UPDATE

Hydrogeologic Conceptual Site Model for Camp Stanley Storage Activity

DEPARTMENT OF THE ARMY • UNITED STATES OF AMERICA •

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Prepared for:

Camp Stanley Storage Activity
Boerne, Texas

August 2008

GEOSCIENTIST CERTIFICATION

Hydrogeologic Conceptual Site Model for Camp Stanley Storage Activity

For

Department of the Army
Camp Stanley Storage Activity
Boerne, Texas

I, W. Scott Pearson, P.G., hereby certify that the for Camp Stanley Storage Activity installation in Boerne, Texas accurately represents the site conditions of the subject area. This certification is limited only to geoscientific products contained in the subject report and is made on the basis of written and oral information provided by the CSSA Environmental Office, laboratory data, and field data obtained during investigations, and is true and accurate to the best of my knowledge and belief.

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EXECUTIVE SUMMARY

BACKGROUND

This update to the Hydrogeologic Conceptual Site Model (HCSM) report incorporates data from groundwater and remedial investigations conducted at Camp Stanley Storage Activity (CSSA) between the years 1992 and 2007. It is an endeavor to bring the findings of multiple environmental investigations into a cohesive "big picture" model that describes the hydrologic setting at CSSA, and how and where contaminants occur within the subsurface, and groundwater in particular.

The CSSA mission is the receipt, storage and issuance of ordnance, materiels, as well as, quality assurance testing and maintenance of military weapons. Maintenance of ordnance materiel included the use of industrial solvents as a degreasing agent from the 1950s through 1990. As a result of past operations, releases of tetrachloroethene (PCE) to the environment have occurred from multiple source areas within CSSA.

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. CSSA is sited over Cretaceous-age deposits of the Travis Peak and Glen Rose Formations of the Trinity Group. The predominant structural feature in the area is the Balcones fault zone (BFZ) escarpment. As part of the BFZ, normal faulting occurs near the central area and southeastern boundary of CSSA.

HYDROGEOLOGY

The primary groundwater source at CSSA and surrounding areas is the Middle Trinity aquifer, consisting of the Lower Glen Rose (LGR) Limestone, the Bexar Shale, and the Cow Creek (CC) Limestone. The average combined thickness of the aquifer members is approximately 460 feet. In the vicinity of CSSA, the LGR portion of the Middle Trinity aquifer derives its recharge from direct precipitation on the outcrop and stream flow infiltration. Likewise, over the same area, the Bexar Shale acts as a hydrologic barrier to vertical leakage except where faulted; therefore, most recharge to the CC Limestone comes from overlying updip formations. The bottom of the CC Limestone forms the base of the Middle Trinity aquifer.

Information regarding the subsurface was compiled from borehole data, geophysics, and surface mapping to create a conceptual stratigraphic model. Nearly 90 percent of the land surface at CSSA is comprised of the basal section of the Upper Glen Rose (UGR) limestone, comprising the upper confining layer of the Middle Trinity aquifer. Data indicate that the underlying LGR is typically an average thickness of 320 feet. The Bexar Shale is normally 60 feet in thickness, whereas the underlying CC Limestone unit is typically 75 feet in thickness.

Extensive drilling indicated that the bulk of the main groundwater body occurred within the basal portion of the LGR and the upper portion of the CC Limestone. The occurrence of groundwater within these units was implicitly related to the massive moldic porosity and karstic features associated with reef-building events and fossiliferous biostromes capable of storing large quantities of water. Occasionally, large volumes of groundwater could also be produced from well-developed reefs above the basal unit, or from significant perched fracture or karstic features. Otherwise, groundwater yields in the UGR and the top 250 feet of the LGR are minimal. Likewise, groundwater production from the BS is minimal at best.

Based on measurements at observation wells, the regional groundwater flow is generally to the south-southeast. The LGR typically has a southward gradient that deviates around mounding which occurs near the central and northern portions of the facility (CS-MW4-LGR). The Bexar Shale exhibits the potential for either northward or southward flow, depending on the season. Likewise, the CC Limestone exhibits erratic flow paths, with seasonally radial flow from mounded areas.

Long-term monitoring shows that groundwater response to precipitation events can be swift and dramatic. Depending on the severity of a precipitation event, the groundwater response will occur within several days, or even hours. Data obtained from the on-post well clusters indicate that for most of the year, a downward vertical gradient exists within the Middle Trinity aquifer. Differences in drainage rates often leave the head of the Bexar Shale well above the head of the LGR and CC Limestone. The large differences in head suggest that the Bexar Shale reacts locally a confining barrier between the LGR and CC Limestone.

The CSSA weather station reported a 31.46 annual average between 1999 and 2006. Annual precipitation ranging from 17 inches to 52 inches has been reported for the same timeframe. In an attempt to estimate an annual water balance, approximately 67 percent of the annual precipitation is expected to be lost to evapotranspiration. Another 29 percent is assumed to be lost to annual surface runoff, while the remaining 4 percent recharges the Middle Trinity aquifer (based on published literature values). Assuming these estimates are valid, CSSA can be expected to consume between 11 percent and 25 percent of its annual recharge.

CONTAMINANT DISTRIBUTION

Solvent contamination (PCE, trichloroethene [TCE], and *cis*-1,2-dichloroethene [*cis*-1,2-DCE]) was first detected in a water supply well at CSSA in 1991. 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 (SWMU) B-3 and O-1 and Area of Concern (AOC)-65 as likely candidates. Starting in 1996, the first of 56 monitoring wells were installed, and well installation has continued through April 2007.

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 method detection limits (MDL) in 30 off-post private and public water supplies.

Contamination from past disposal activities resulted in multiple groundwater units, referred to as Plume 1 (B-3 and O-1) and Plume 2 (AOC-65). Contamination is most widespread within the LGR water-bearing unit. Locally, the Bexar Shale serves as a confining unit between the water-bearing LGR and CC Limestone. Faults of the BFZ structurally influence and re-direct the groundwater flowpaths. Environmental studies demonstrate that most of the contamination resides within the LGR.

Plume 1 has advectively migrated southward towards Camp Bullis, and west-southwest toward CSSA well fields (CS-9, CS-10, and CS-11) and several off-post public and private wells. Volatile organic compounds (VOC) concentrations over 200 µg/L are present in Middle

Trinity aquifer wells near the source area. However, contaminant concentrations are below 1 µg/L over most of the Plume 1 area. In contrast, little to no contamination within the Bexar Shale and CC Limestone 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 spread southward and westward from the post. The greatest concentrations of solvents are reported at the near subsurface adjacent to the source area. Deeper in the subsurface, concentrations in excess of 100 µg/L have been reported in perched intervals above the main aquifer body in the LGR. However, as evidenced by the multi-port wells, 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. Only sporadic, trace concentrations of solvents have been detected in Bexar Shale and CC Limestone wells within Plume 2.

OBSERVATIONS

The style of well completion can affect the amount of concentration detected at a location. At CSSA, monitoring wells were purposely designed to case off contamination present within upper strata in an effort to reduce cross-contamination between water-bearing units. This style of well completion typically results in a groundwater sample from the main portion of the aquifer that has little to no contamination present. In contrast, most off-post wells are designed to maximize yield from all portions of the aquifer, resulting in co-mingling of stratified groundwater with varying degrees of contamination as seen in Plume 2. Within an open wellbore, the net effect is that perched waters with high concentrations of solvents are contaminating relatively pristine groundwater held within the main body of the aquifer.

RECOMMENDATIONS

The geometry of the plumes indicates that multiple advective directional forces are occurring, and possibly at different velocities. Traditionally, quantitative groundwater flow and direction is characterized by “tracer” studies. This analysis will help quantify the velocity and direction of the plumes and qualify underlying controlling features such as karst, faults, and fractures.

To the southwest of CSSA it appears that Plumes 1 and 2 may be co-mingling. To help differentiate the plumes in this vicinity, isotope studies may be performed to chemically “fingerprint” the contaminants in the groundwater. The isotope analysis would find chemical distinctions between the presumed sources of Plume 1 and Plume 2, and thereby correlate and associate the contaminants detected in off-post wells with one of the known source areas.

To the southwest of CSSA near the leading edge of the plume, there have been indications that the contamination is still mobile and dynamic. Some data suggest that contamination may be rapidly flushed in “slugs” during significant precipitation events. It is recommended that additional groundwater monitoring locations to the southwest of Interstate IH-10 be indentified and characterized. This may included utilizing existing wells (public or domestic), or securing access agreements for the installation of monitoring wells.

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°F	Fahrenheit
acre-ft/yr	Acre-feet per year
AEM	Aerial electromagnetic
AFCEE	Air Force Center for Environmental Excellence
AL	Action Level
AMC	Air Mobility Command
AOC	Area of concern
ARAR	Applicable or Relevant and Appropriate Requirements
BFZ	Balcones fault zone
bgs	Below ground surface
BrE	Brackett soils
BS	Bexar Shale
BtE	Brackett-Tarrant Association soils
Cb	Crawford and Bexar stony soils
CC	Cow Creek
CD	Compact disc
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
cm/sec	Centimeters per second
CO_2	Carbon dioxide
COC	Contaminant of concern
CSSA	Camp Stanley Storage Activity
CY	Cubic Yards
DCE	*cis*-1,2-dichloroethene
DNAPL	dense, non-aqueous phase liquid
DO	Delivery Order
DoD	Department of Defense
DQO	Data quality objective
DRO	Diesel-range organics
DTM	Digital terrain model
EAA	Edwards Aquifer Authority
EM	Electromagnetic
EPA	U.S. Environmental Protection Agency
ES	Engineering Science
ft	feet
ft^2	square feet
ft/ft	Foot per foot
ft/sec	Feet per second
FM	Farm to Market
GIS	Geographic information system
gpd/ft	Gallons per day per foot
gpm	Gallons per minute
gpm/ft	Gallons per minute per foot

GPR	Ground Penetrating Radar
GPS	Geographic positioning system
GRO	Gasoline-range organics
GVA	George Veni & Associates
HCSM	Hydrogeologic conceptual site model
HS	Hammett Shale
IH	Interstate Highway
IM	Interim Measure
IP	Induced polarization
Kr	Krum complex soils
LCY	Loose cubic yards
LGR	Lower Glen Rose
LvB	Lewisville silty clay
MCL	Maximum contaminant level
mg/kg	Milligrams per kilogram
µg/L	Micrograms per liter
MSL	Mean sea level
N/A	Not available
NE	Northeast
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resource Conservation Service
NW	Northwest
NWS	National Weather Service
O&M	Operation and Maintenance
P	Precipitation
Parsons ES	Parsons Engineering Science
PCB	Polychlorinated biphenyl
PCE	Tetrachloroethene
PIMS	Phosphate-Induced Metals Stabilization
ppbv	Parts per billion volume
PZ	Piezometer
Q_d	groundwater component of runoff
Q_s	surface component runoff
QA/QC	Quality Assurance/Quality Control
QAPP	Quality Assurance Program Plan
RCRA	Resource Conservation and Recovery Act
RFI	RCRA Facility Investigation
RL	Reporting limit
RMU	Range Management Unit
RRAD	Red River Army Depot
RRS1	Risk reduction standard 1
SAWS	San Antonio Water System
SDWA	Safe Drinking Water Act
SE	Southeast
SH	State Highway

SP	Spontaneous potential
SVE	Soil vapor extraction
SVOC	Semivolatile organic compound
SW	Southwest
SWMU	Solid Waste Management Unit
TaB	Gently undulating Tarrant Association Soils
TaC	Rolling Tarrant Association Soils
TCE	Trichloroethene
TCEQ	Texas Commission on Environmental Quality
TDH	Texas Department of Health
Tf	Trinity and Frio soils
TNRCC	Texas Natural Conservation Commission
TO	Task Order
TOC	Top of casing
TPH	Total petroleum hydrocarbon
TRRP	Texas Risk Reduction Program
TWDB	Texas Water Development Board
UGR	Upper Glen Rose
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator
VC	Vinyl Chloride
VEW	Vapor extraction well
VLF	Very low frequency
VMP	Vapor monitoring point
VOC	Volatile organic compound

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SECTION 1
INTRODUCTION

1.1 PURPOSE OF REPORT

Camp Stanley Storage Activity (CSSA) is located in northwestern Bexar County, Texas about 19 miles northwest (NW) of downtown San Antonio and 11 miles southeast (SE) of Boerne (Figure 1.1). Solvent contamination was detected in groundwater beneath CSSA in August 1991. At that time, the unidentified release(s) were discovered to have affected the Middle Trinity aquifer, which is a primary drinking water source. CSSA engaged in a series of environmental investigations during the ensuing 16 years to aid in the horizontal and vertical delineation of solvent contamination source areas within the aquifer. This report compiles those data into a cohesive Hydrogeologic Conceptual Site Model (HCSM) to describe and quantify the processes, which dictate the occurrence, fate, and transport of contaminants beneath and beyond CSSA borders.

1.2 PROJECT AUTHORIZATION

Initiation of this HCSM was authorized under Air Mobility Command (AMC) Contract F11623-94-D-0024, Delivery Order (DO) RL83, and subsequent work was authorized under the Air Force Center for Environmental Excellence (AFCEE) contract F41624-00-D-8024, Task Order (TO) 42. This current HCSM update is authorized under AFCEE contract F41624-03-D-8613, Task Order (TO) 0008. The work was conducted by Parsons under the technical supervision of AFCEE and was also overseen by U.S. Environmental Protection Agency (EPA) Region VI, Resource Conservation and Recovery Act (RCRA)-Enforcement Section, and the Texas Commission on Environmental Quality (TCEQ) since October 1993.

This HCSM combines work associated with numerous environmental investigations and remediation contracts under DOs issued by AFCEE and AMC, and represents the second issue of an iterative document that will be updated and refined as new data and information are discovered. The HCSM will provide the framework for an eventual numerical simulation of the hydrologic conditions at CSSA.

1.3 REGULATORY BASIS

Upon verification of solvent contamination in Well CS-16 on August 23, 1991, CSSA deactivated the well and notified water users as required by state and federal regulations. CSSA then initiated groundwater investigations, including installation of wells described in this report. In January 1993, preliminary evaluation data were presented to the Texas Department of Health (TDH), TCEQ (known at the time as the Texas Natural Resource Conservation Commission [TNRCC]), and EPA Region VI-RCRA Permitting Section, at a technical interchange meeting. The project plans of actions were submitted to EPA and TNRCC in May 1993.

On June 30, 1993, the EPA notified CSSA that an Administrative Order on Consent (Order) would be issued to CSSA. This Order, issued under Section 3008(h) of RCRA on May 5, 1999, required CSSA to investigate groundwater contamination, as well as solid waste management units (SWMUs) and areas of concern (AOCs) at the facility. Groundwater investigations conducted at CSSA, including the hydrogeologic investigations described in this report, are

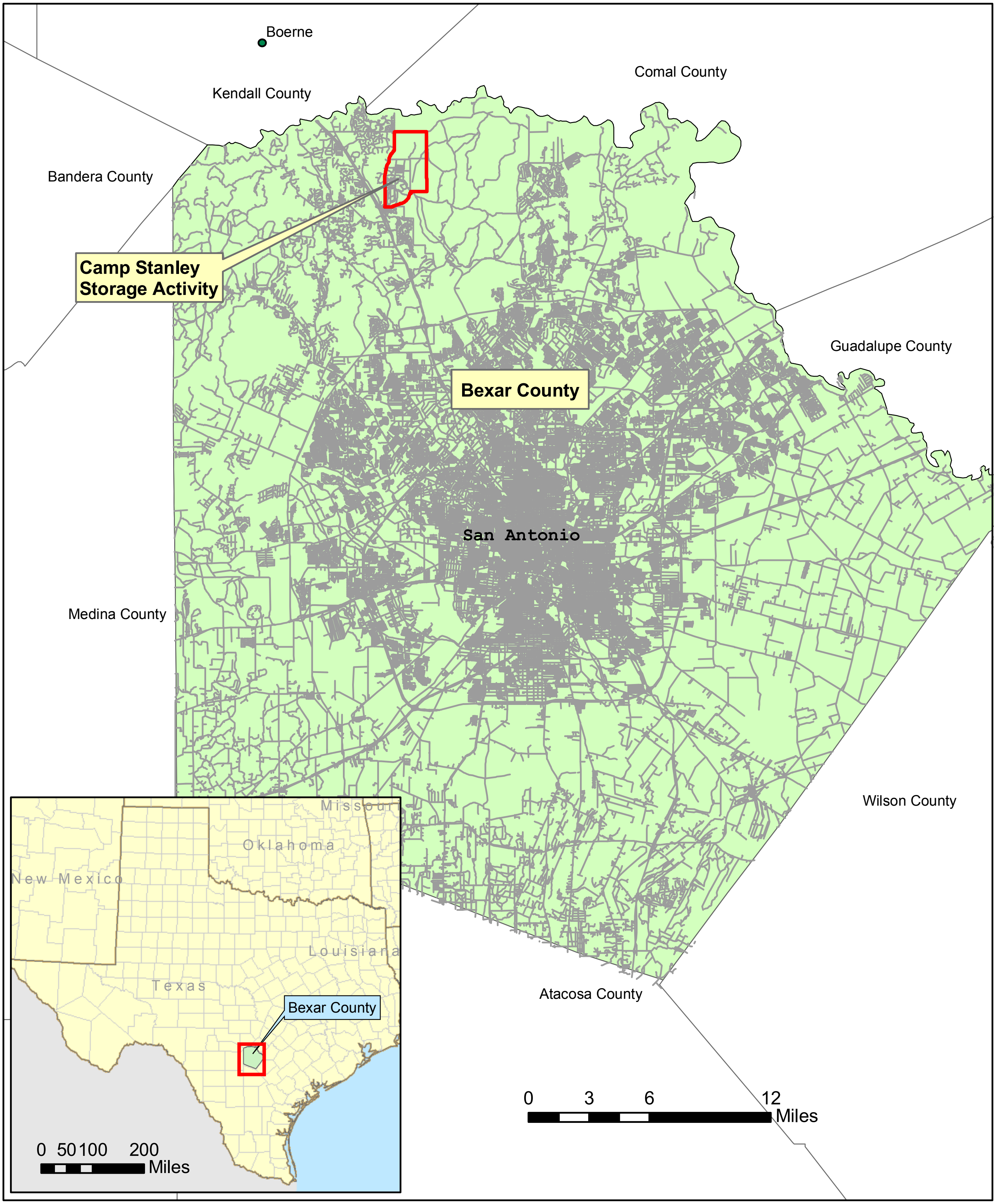

Figure 1.1

Site Location Map

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performed in accordance with the Resource Conservation and Recovery Act, as amended (RCRA), USEPA's RCRA regulations (including 40 CFR Part 265), and EPA's corrective action policies and guidance as appropriate for use at RCRA facilities with interim status.

1.4 OBJECTIVES AND SCOPE

Construction of a complete HCSM is an iterative process that defines and quantifies the hydrologic regime at CSSA. Throughout the process, a preliminary HCSM was progressively tested and refined as additional data were integrated to yield a more detailed understanding of the physiographic, geologic, hydrologic, and geochemical processes that, in sum, control groundwater flow and contaminant migration within the aquifer. As the model evolved, the characterization program was tailored to address the specific data needs identified. In general, development of the HCSM involved the following work elements:

1. Combining the well and borehole information (physical, chemical, and geophysical) from selected domestic, stock, municipal, and industrial wells into a mappable database. This HCSM includes the available wells at CSSA and in the immediate vicinity;
2. Generating structure maps for each of the geologic layers from borehole information. This involved inputting elevation picks for each of the layers, grouping stratigraphic lenses defined in the correlations, and defining a grid to delineate the tops and bottoms of the layers. Also, attempting to identify major structural features that could dictate flow paths of groundwater and contaminant propagation;
3. Where sufficient data were available, performing selected stratigraphic correlations with regard to mineralogy, structure, fossil content, dissolution, water availability, and geochemistry. The correlations will be represented in cross-sections and fence diagrams. Evaluate/modify the stratigraphic geometric boundaries of the proposed HCSM;
4. Preparing new water level maps and water level difference maps for the water-bearing units (Lower Glen Rose [LGR], Bexar Shale [BS], and Cow Creek [CC] Formation) and correlating rainfall data with groundwater levels and response;
5. Preparing a generalized water budget for the HCSM area based on precipitation data, published recharge infiltration rates, and discharge from water supply wells and other parameters;
6. Defining and diagramming the contamination within the HCSM model layers; and
7. Evaluating migration pathways and potential receptors with respect to the CSSA contaminant plume(s).

1.5 REPORT ORGANIZATION

This report is organized in six sections. **Section 1** presents an overview of the report, including project purpose, regulatory basis, authorization, and objectives of the HCSM. **Section 2** describes the background, history, and environmental setting of CSSA. Contaminant source characterization is discussed in **Section 3**. Components of the HCSM are identified and built through narrative text and conceptual diagrams in **Section 4**. Building on the elements of the HCSM, **Section 5** discusses the fate and transport of contaminants within the groundwater system. Finally, conclusions and recommendations are presented in **Section 6**. Supporting data are found in the appendices.

SECTION 2
BACKGROUND

2.1 SITE SUMMARY

2.1.1 Site Description

The CSSA installation consists of 4,004 acres immediately east of Farm to Market Road (FM) 3351, and approximately half a mile east of Interstate Highway (IH) 10 (Figure 2.1). Camp Bullis borders CSSA on the north, east, and southeast (SE). 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.

Land surrounding CSSA is primarily residential or used for ranching. The area between CSSA and the nearby community of Leon Springs is primarily residential, composed of Leon Springs Villa, Hidden Springs Estates, and The Dominion developments. Some ranching/agricultural land is intermingled within those developed communities.

The western side of Ralph Fair Road and to the north of CSSA, has been primarily ranch land with some ranch-style dwellings. A few businesses that serve the city of Fair Oaks community are located in a strip center at the NW corner of CSSA. Fair Oaks development consists of approximately 2,000 houses and takes up most of the northwest (NW) quadrant of the CSSA vicinity. The development is located at the convergence of Bexar, Comal, and Kendall Counties and extends northward well beyond Cibolo Creek.

The vicinity immediately west of CSSA is composed of a mixture of residential and ranching acreage. Several large-acreage properties are to the west of CSSA and contain multiple ranch-style dwellings. The residential community of Jackson Woods is also adjacent to the west perimeter of CSSA, and consists of approximately 40 multi-acreage tracts. Historically, the southwest (SW) quadrant was primarily ranching property with the exception of the IH 10 and Ralph Fair Road intersection where commercial activities are found. However, in the past two years large ranch tracts adjacent to CSSA to the west and southwest have yielded to urban sprawl, and are being developed as residential subdivisions.

Further information regarding the site description of CSSA is provided in the CSSA Environmental Encyclopedia **(Volume 1-1, Background Information Report)**.

2.1.2 Historical Information

CSSA was a segment of the original Leon Springs Military Reservation and was transferred to the jurisdiction of the Chief of Ordnance as an ammunition depot for the San Antonio Arsenal in 1933. In June 1949, CSSA was transferred to the Red River Army Depot (RRAD). CSSA is now under McAlester Army Ammunition Plant, US Army Field Support Command, Army Materiel Command (CSSA, McAAP, US AFSC, AMC). Historically, its mission was training, evolving to ordnance storage, maintenance, and testing. CSSA currently consists of operations buildings, igloo storage magazines, U. S. Department of Agriculture (USDA) grazing acreage, and unused land.

Figure 2.1

Camp Stanley and Surrounding Area

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General information regarding the history of CSSA is provided in the CSSA Environmental Encyclopedia **(Volume 1-1, Background Information Report).**

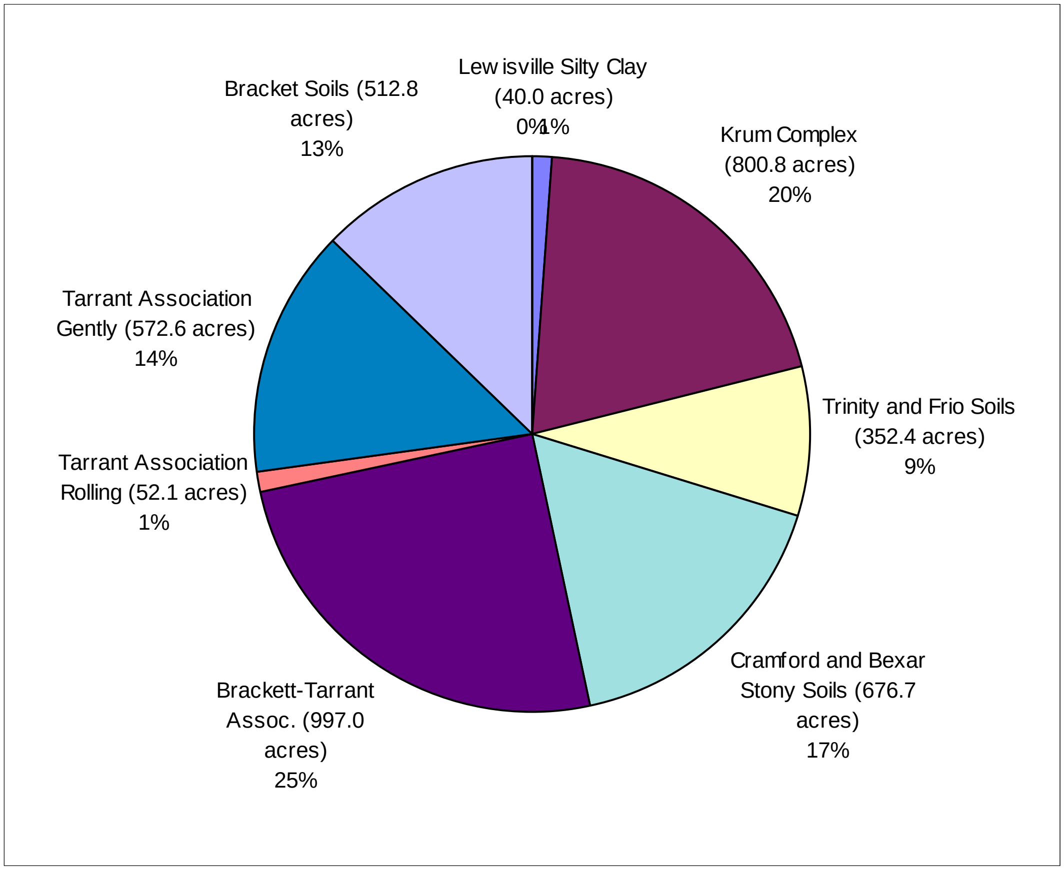
2.2 ENVIRONMENTAL SETTING

It is recommended that the **Soils and Geology** and **Groundwater Resources** sections of the CSSA Environmental Encyclopedia **(Volume 1-1, Background Information Report)** be reviewed for understanding of the local physiography, geology, stratigraphy, structure, and hydrology. Specific knowledge of the environmental conditions is beneficial to understanding the development of the local groundwater resources near CSSA. For completeness, pertinent sections are briefly summarized below for this report.

2.2.1 Soils

In general, soils at CSSA are thin, dark-colored, gravelly clays and loams. The soil types are strongly influenced by topography and the underlying limestone. The soil classifications used for this report are taken from the USDA Soil Conservation Service (now the Natural Resource Conservation Service (NRCS) soil survey series for Bexar County, Texas (USDA, 1991). A total of eight soil types occur at CSSA. Figure 2.2 shows the portion of CSSA each soil type covers.

Figure 2.2 CSSA Eight Soil Types by Area Percentage



Brackett Soils

Brackett (BrE) soils occur over 12.8 percent (512.8 acres) of the CSSA lands. These soils cover a large portion of the east pasture and the inner cantonment at CSSA. These loamy and clayey soils are thin (about 4 inches thick), grayish-brown, and strongly calcareous. Gravel and cobblestone lithics occur at the surface and shallow subsurface. The soils can develop over soft limestone and are underlain by hard limestone, which gives the slopes a stairstep appearance.

Tarrant Soils

At CSSA the Tarrant soils occur along the outer edges of the Salado Creek floodplain. The soils are thin and form over hard, fractured limestone. The surface layer is usually about 10 inches thick and is a dark grayish-brown, calcareous, clay loam with scattered gravel and cobblestones within and on the surface layer. Two types of Tarrant soils occur at CSSA: Gently undulating Tarrant soils (TaB) and rolling Tarrant association soils (TaC).

The TaB areas are typical of prairie and plateau topography. They occur primarily in areas not occupied by streams, such as the north-central area of the inner cantonment at CSSA. This soil type covers 14.3 percent (572.6 acres) of CSSA. The soils are dark colored, very shallow, calcareous, and clayey, and are best suited for native grasses and range use.

The TaC is found on the eastern sides of hills in areas not occupied by streambeds. This soil type occurs over only 1.3 percent (52.1 acres) of CSSA lands. The slopes tend to have a gradient of 5 to 15 percent. The soils are dark colored, very shallow, clayey, weakly calcareous, and typically more stony than TaB.

Brackett-Tarrant Association

Brackett-Tarrant association soils (BtE) cover 24.9 percent (997.0 acres) of CSSA. At CSSA, this soil type is found north of the inner cantonment in the north pasture. The slopes of ridges are Tarrant soils which are clayey, calcareous, and very dark grayish-brown. The BrE soils are light grayish-brown and calcareous. Tarrant soils make up 65 percent of the association and BrE make up 20 percent.

Crawford and Bexar Stony Soils

Crawford and Bexar stony soils (Cb) occupy portions of both the inner and outer cantonments, for a total of 16.9 percent (676.7 acres) of CSSA. They occur in broad, nearly level to gently undulating areas. The soils are stony, very dark gray to dark reddish-brown, noncalcareous clay, about 8 inches thick. Bexar soils range from a cherty clay loam to gravelly loam.

Trinity and Frio Soils

The Trinity and Frio soils (Tf) cover 8.8 percent (352.4 acres) of CSSA. The soils are frequently subjected to flooding, and are the main channel soils for Salado Creek and a large tributary that joins the creek in southwestern CSSA. Some areas are subject to thin sediment depositions, while other areas are scoured. Channels are poorly defined and are of small capacity. Trinity soils are 3 to 5 feet (ft) deep and are composed of clayey to gravelly loam. Frio soils are a dark grayish-brown clay loam, 3 to 4 ft deep.

Krum Complex Soils

The Krum Complex soils (Kr) make up the remaining soils covering the streambeds and floodplains, 20.0 percent (800.8 acres) of CSSA. The soils are dark grayish-brown or very dark grayish-brown, calcareous, and approximately 30 inches thick. The soils developed from slope alluvium of the limestone prairies. The Kr receives sediments and runoff from higher elevation soils and is highly prone to hydraulic erosion if unprotected.

Lewisville Silty Clay

A minor soil type found at CSSA is the Lewisville silty clay (LvB). This soil type covers only 1.0 percent (40.0 acres) of CSSA. It typically occupies long, narrow, sloping areas separating nearly level terraces from upland soils. Surface soils are dark grayish-brown about 20 inches thick. This is a highly productive soil but is also susceptible to hydraulic erosion if unprotected.

2.2.2 Physiography

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 SE. Normal faulting has occurred near the central area and the southern boundary of the installation. Regionally however, two major trends of fractures extend NW-SE and northeast (NE)-SW. Faulting in the limestone units has juxtaposed strata of different ages, but fault scarps and traces are almost absent because many of the various calcareous lithologies weather similarly. The faults are NE-SW trending, but most are not as continuous as the fractures. Soil cover is relatively thin, and bedrock is frequently exposed in most areas other than stream valleys.

River and stream dissection of limestone is the major surface feature at CSSA. Most major rivers and streams originating in the Edwards Plateau NW of CSSA tend to follow the NW-SE regional fracture patterns. Resistive limestone beds crop out as topographic highs, but none of these beds form buttes or mesas. Rather, the predominant physiography is hills and “saddles” which lead to stream valleys. Topographic relief across the area ranges from about 1,100 to 1,500 ft above sea level (Figure 2.3).

2.2.3 Geology

Stratigraphy

The oldest and deepest known rocks in the HCSM area are Paleozoic age (225 to 570 million years ago) schists of the Ouachita structural belt. They underlie the predominant carbonate lithology of the Edwards Plateau. The Cretaceous-age sediments were deposited as onlapping sequences on a submerged marine plain and, according to well logs and outcrop observations, these sediments thicken to the SE. Figure 2.4 summarizes the Cretaceous System stratigraphy, which represents the Edwards and Trinity Groups’ shallow marine deposits. Within the Trinity Group, the Travis Peak Formation attains a maximum thickness of about 940 ft and is divided into five members, in ascending order: the Hosston Sand, the Sligo Limestone, the Hammett Shale, the Cow Creek (CC) Limestone, and the Hensell Sand (and Bexar Shale (BS) facies). Overlying the Travis Peak Formation, but still a part of the Cretaceous-age Trinity Group, is the Glen Rose Limestone. For this HCSM, the units of interest are the Glen Rose Limestone, BS, and CC Limestone that form the Middle Trinity aquifer.

Figure 2.3

Physiographic Map of Camp Stanley

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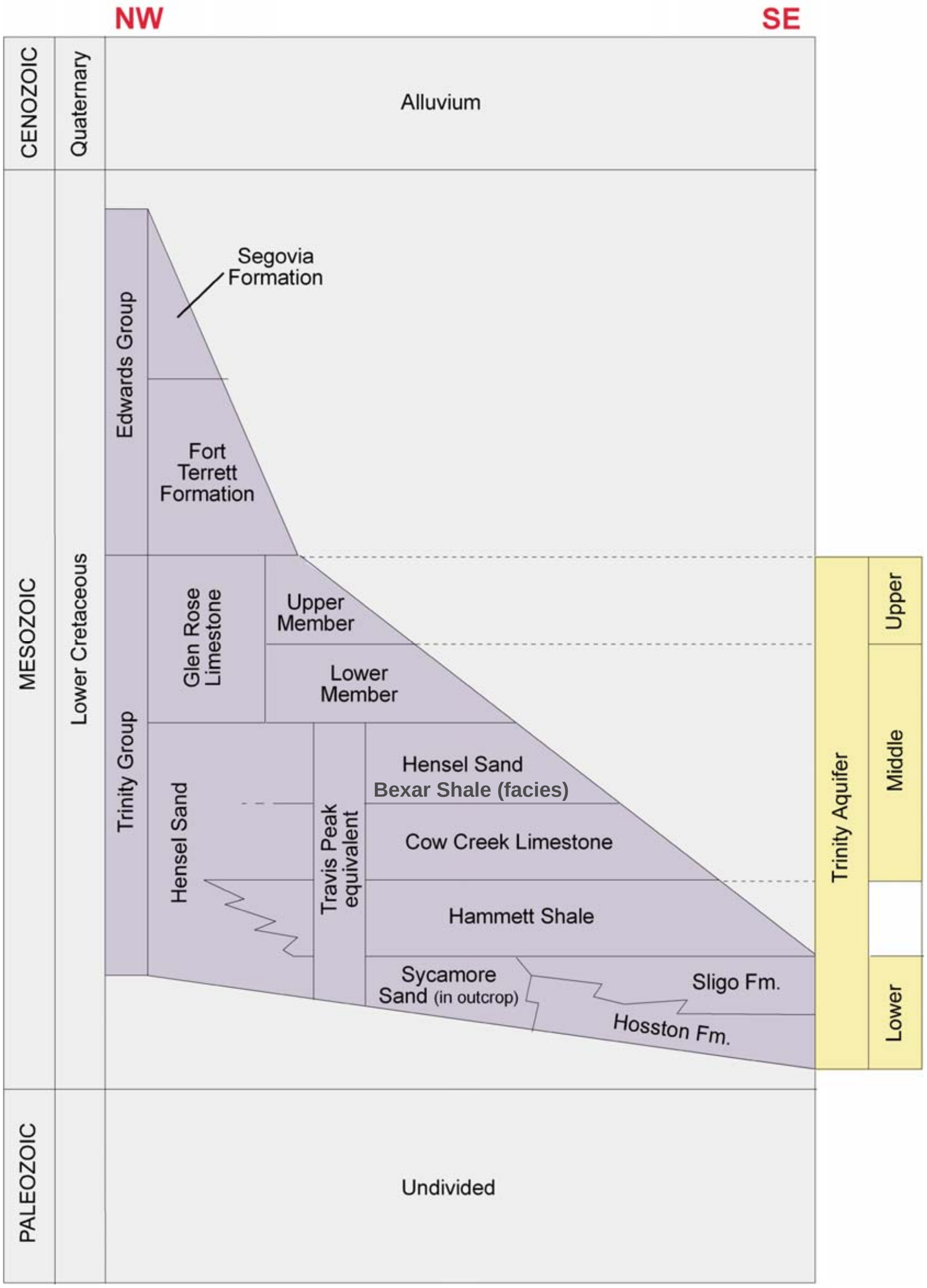
Figure 2.4 Stratigraphic and Hydrostratigraphic Section of the Hill Country Area



(modified after TWDB Report 353, September 2000 – [after Ashworth, 1983; Barker and others, 1994])
Note: In some areas, including CSSA,, the Bexar Shale is present instead of the Hensel Sand

The Hammett Shale (HS), which overlies the Sligo Limestone, has an average thickness of 60 ft. It is composed of dark blue to gray fossiliferous, calcareous, and dolomitic shale. It pinches out north of the HCSM area and attains a maximum thickness of 80 ft to the south. Above the HS is the CC Limestone, which is a massive fossiliferous, white to gray, shaley to dolomitic limestone that attains a maximum thickness of 90 ft down dip in the area. The youngest member of the Travis Peak Formation is the Hensell Sand, locally known as the BS. The shale thickness averages 60-80 ft, and is composed of silty dolomite, marl, calcareous shale, and shaley limestone, and thins by interfingering into the Glen Rose Formation.

The upper member of the Trinity Group is the Glen Rose Limestone. The Glen Rose Limestone was deposited over the Travis Peak BS and represents a thick sequence of shallow water marine shelf deposits. This formation is divided into upper and lower members. At CSSA, the Glen Rose is exposed at the surface and in stream valleys (Figure 2.5).

The Upper Glen Rose (UGR) 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 ft in Bexar County. The thickness of this member at CSSA is estimated from well logs to be between 20 and 150 ft.

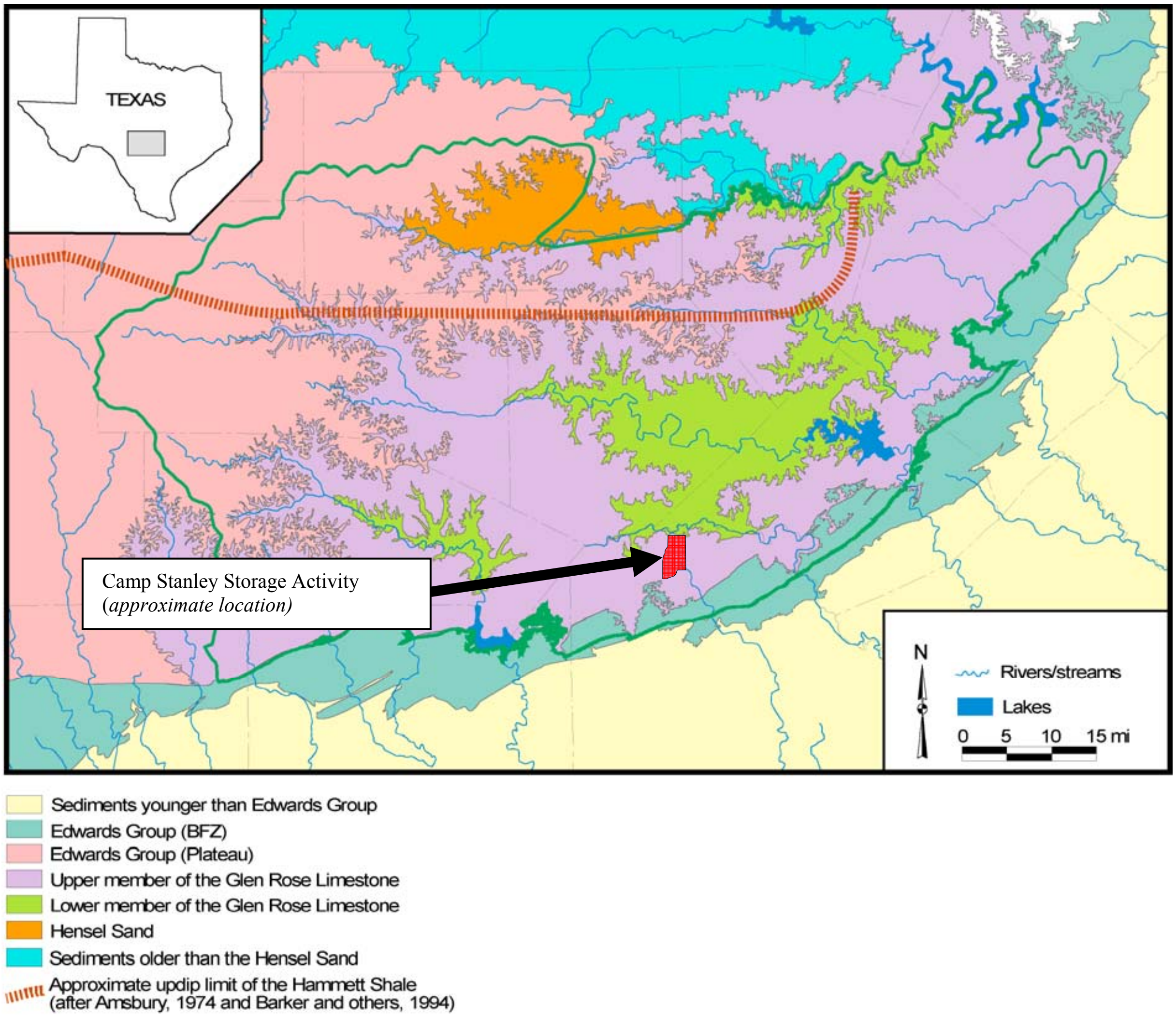
The Lower Glen Rose (LGR), underlying the UGR, consists of a massive fossiliferous limestone, grading upward into thin beds of limestone, marl, and shale (Ashworth, 1983). The lower member, according to area well logs, is approximately 300 ft thick at CSSA. Isolated areas of reef rock have also been identified in the LGR. The boundary between the upper and lower members of the Glen Rose Limestone is defined by a widespread fossil stratigraphic marker known as the Corbula bed (Whitney, 1952). The Corbula bed is 0.5-5 ft thick and contains small pelecypod clamshells, which are three to five millimeters in diameter. Presence of the Corbula fossil indicates a slightly more saline depositional environment than fossils found above and below the Corbula. A gypsum bed has also been identified close to the Corbula bed.

Structure

The predominant structural features in the area are regional vertical fractures, the regional dip, and the Balcones fault zone (BFZ) escarpment. Regional fractures are the result of faulting in the Cretaceous sediments and in the deeper Paleozoic rocks. The two sets of fracture patterns trend NW-SE and NE-SW across the region. The regional dip is to the east and SE at a grade of about 100 ft per mile near the fault zone in Bexar and Comal Counties, decreasing 10-15 ft per mile NW of CSSA.

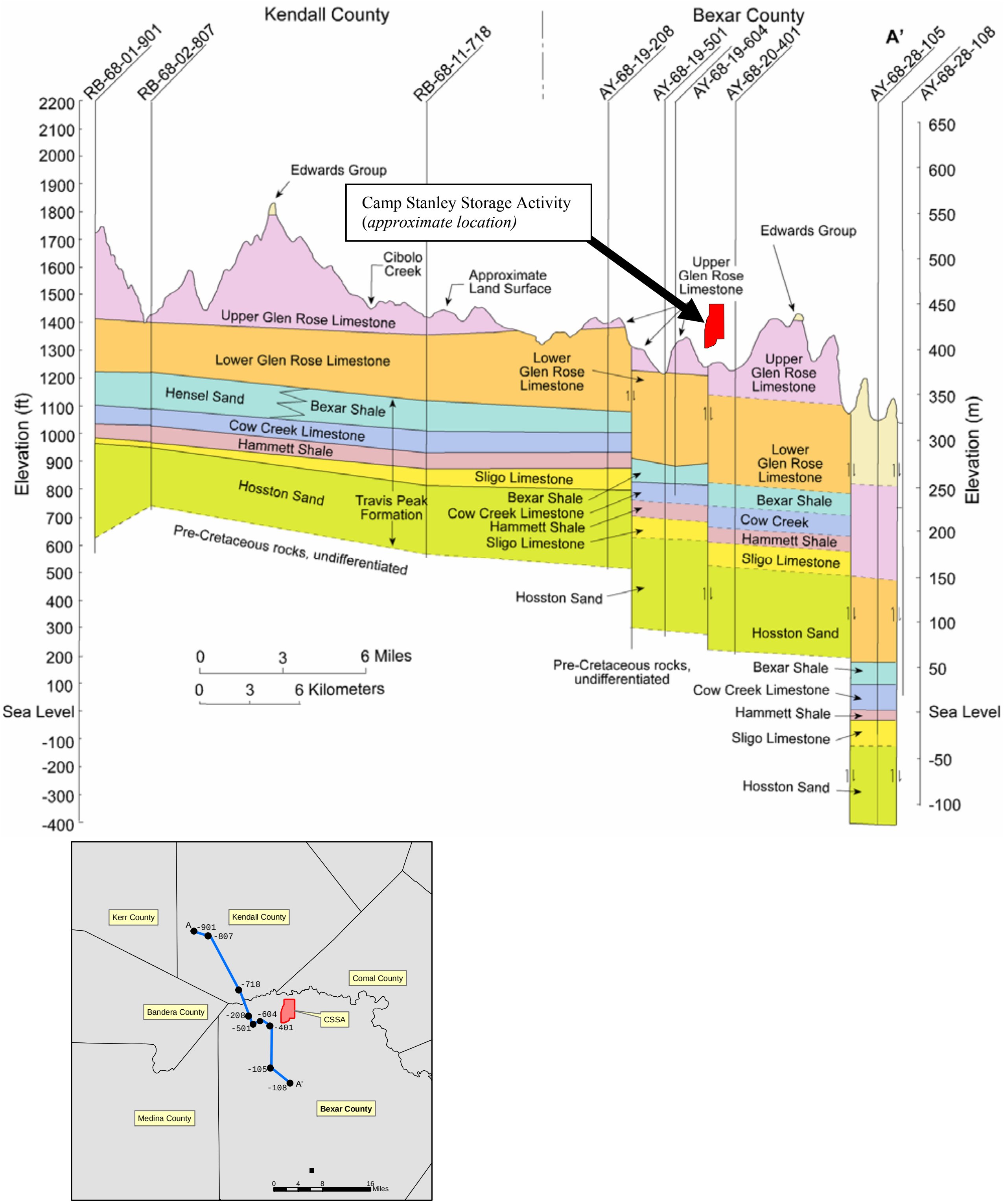
The BFZ is a series of high-angle normal faults that generally trend NE and SW. Total displacement in NW Bexar County is approximately 1,200 ft. The faulting is a result of structural weakness in the underlying Paleozoic rocks and subsidence in the Gulf of Mexico basin to the SE. The down drop blocks outcrop as progressively younger strata from NW-SE across the fault zone. In addition to major faulting along the BFZ, numerous minor NW-SE-trending faults also occur. These faults are laterally discontinuous and their displacement is small. Figure 2.6 generically diagrams the regional geology and structure based on the groundwater modeling efforts performed by the Texas Water Development Board (TWDB) (2000).

Figure 2.5 Surface Geologic Map



(modified after TWDB Report 353, September 2000)

Figure 2.6 Geologic Cross Section through the Study Area



(modified after TWDB Report 353, September 2000 - after Ashworth, 1983, fig. 6)

2.2.4 Groundwater Hydrology

Groundwater occurrence and movement at CSSA have been studied since 1992, and continue to be studied due, in part, to the complex geologic environment. Results of a preliminary evaluation of groundwater contamination in 1992 were included in a report entitled **Hydrogeologic Report for Evaluation of Groundwater Contamination at Camp Stanley Storage Activity, Texas** (Engineering Science [ES], 1993). This work was updated in the **Groundwater Investigation and Associated Source Characterizations** (Parsons Engineering Science [Parsons ES], 1996).

Three aquifers are present in the area of CSSA: the Upper, Middle, and Lower Trinity aquifers. These divisions are based on hydraulic continuity. The Travis Peak Formation and the Glen Rose Formation are the principle water-bearing units. Beneath these are metamorphosed Paleozoic rocks, which act as a lower hydrologic barrier. Only the Middle and Upper Trinity aquifers are addressed for this HCSM.

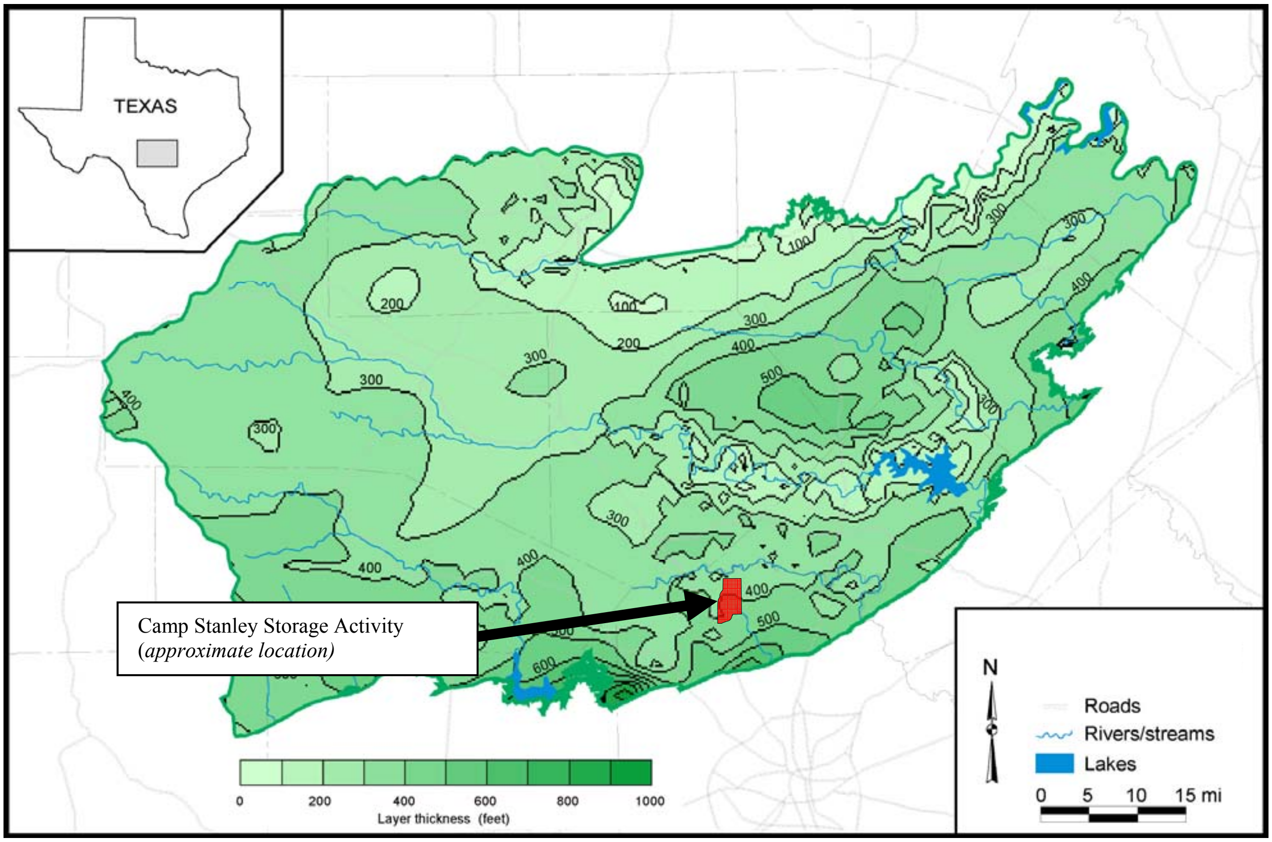
Middle Trinity aquifer

The primary groundwater source at CSSA is the Middle Trinity aquifer, the most prolific producer with the best quality of water of the three Trinity aquifers. Typical wells in this formation are completed as open holes without well screens. The Middle Trinity aquifer consists of the CC Limestone, the BS (Hensell Sand), and the LGR Limestone. The average combined thickness of the aquifer members is approximately 460 ft (Figure 2.7). The only member found in outcrop at CSSA is the LGR, which has been mapped north of CSSA along Cibolo Creek and within the central and SW portions of CSSA (Figure 2.5).

The LGR portion of the Middle Trinity aquifer derives its recharge from direct precipitation on the outcrop and stream flow infiltration. Stream flow loss has been observed in Cibolo Creek, which is north of CSSA, between the towns of Boerne and Bulverde, where stream flow is diverted underground via sinkholes except during flood stages. This is the only area of the LGR that is considered to be part of the recharge zone for the Edwards Aquifer (Edwards, 1987). In other portions of the Texas Hill Country, the upper member of the Glen Rose Limestone (UGR) is sometimes considered to be a confining unit below the Edwards Aquifer.

In the area of CSSA, the BS acts as a hydrologic barrier to vertical leakage except where faulted; therefore, most recharge to the CC Limestone comes from overlying up dip formations. On a regional scale, it is inferred that the CC is in natural hydraulic communication with the LGR due to extensive faulting in the area. The bottom of the CC Limestone forms the base of the Middle Trinity aquifer (Figure 2.8). The Middle Trinity aquifer appears to be unconfined in the CSSA area.

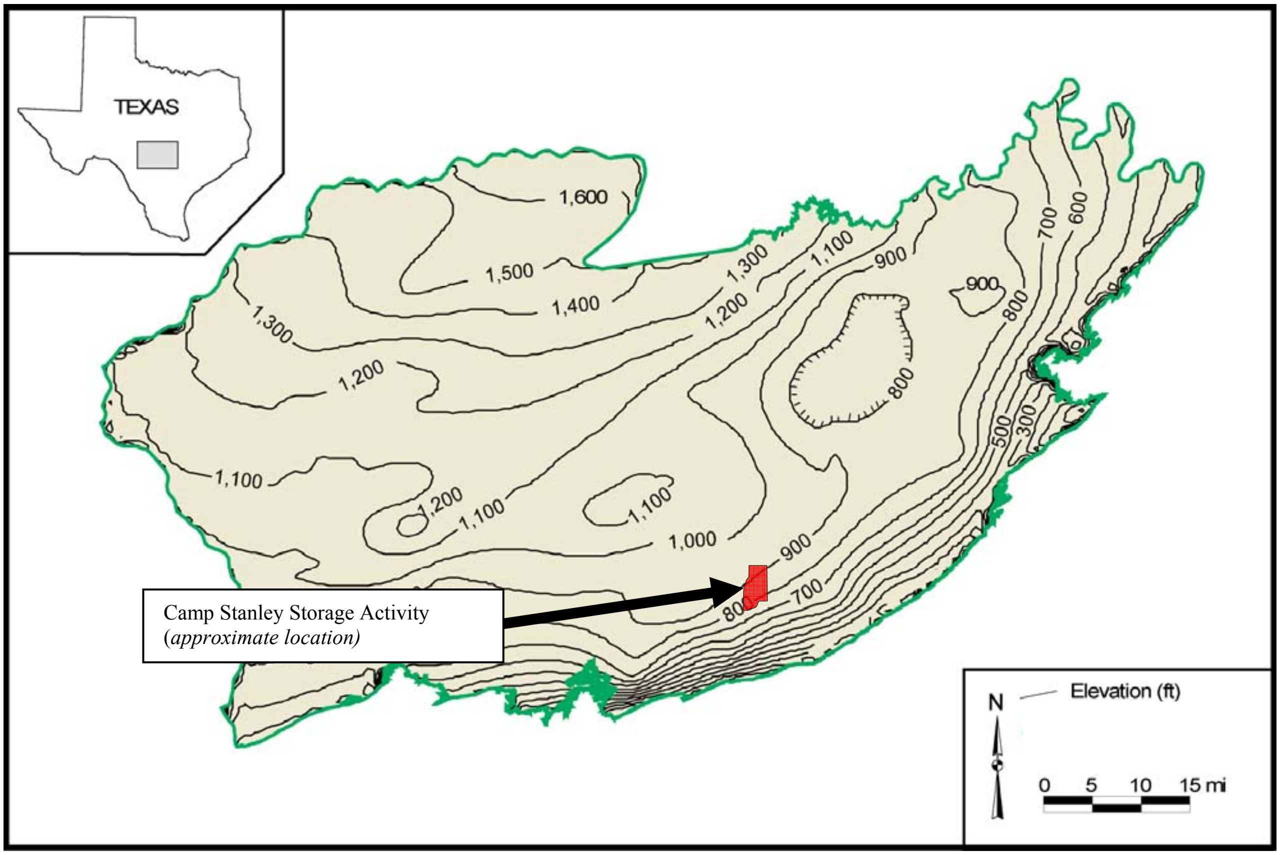
Figure 2.7 Approximate Thickness of the Middle Trinity aquifer



Camp Stanley Storage Activity
(*approximate location)*

(modified after TWDB Report 353, September 2000)

Figure 2.8 Elevation of the Base of the Middle Trinity aquifer



Camp Stanley Storage Activity
(*approximate location)*

(modified after TWDB Report 353, September 2000)

The Middle Trinity aquifer yields fresh to slightly saline water throughout the area and is the most widely used source of water in the area. Although high in mineral content, water in the lower member of the Glen Rose Limestone is normally very good quality. The water increases in dissolved solids content near the BFZ owing to an increase in sulfate ions. No drinking water wells are known to have been completed only in the CC Limestone near CSSA; therefore, the water quality of that limestone member has not been documented in research literature. Wells that draw from the CC only are located significantly up dip of the CSSA vicinity. Most water wells in the area obtain Middle Trinity water for public supply, irrigation, domestic, and livestock purposes.

Upper Trinity aquifer

The Upper Trinity aquifer consists of the UGR Limestone. Recharge to the Upper Trinity aquifer is from direct precipitation to UGR Limestone outcrop and from stream flow infiltration. Movement of groundwater in the Upper Trinity is restricted to lateral flow along bedding planes between marl and limestone, where solution has enhanced permeability. Static water levels in adjacent wells completed in different beds within the UGR are often different, demonstrating the possibility that beds are not hydraulically connected by avenues of vertical permeability. The only place where extreme development of solution channels is reported is in evaporite layers in or near the outcrop of the UGR Limestone. Discharge from the Upper Trinity aquifer is predominantly from natural flow through seeps and springs and from pumping. The Upper Trinity aquifer is, in general, unconfined. Fluctuations in water levels in the Upper Trinity are predominantly a result of seasonal rainfalls and in some areas, may be impacted by pumping from domestic and public wells. Figures 2.9 and 2.10 show the thickness and mapped basal contact of the Upper Trinity aquifer.

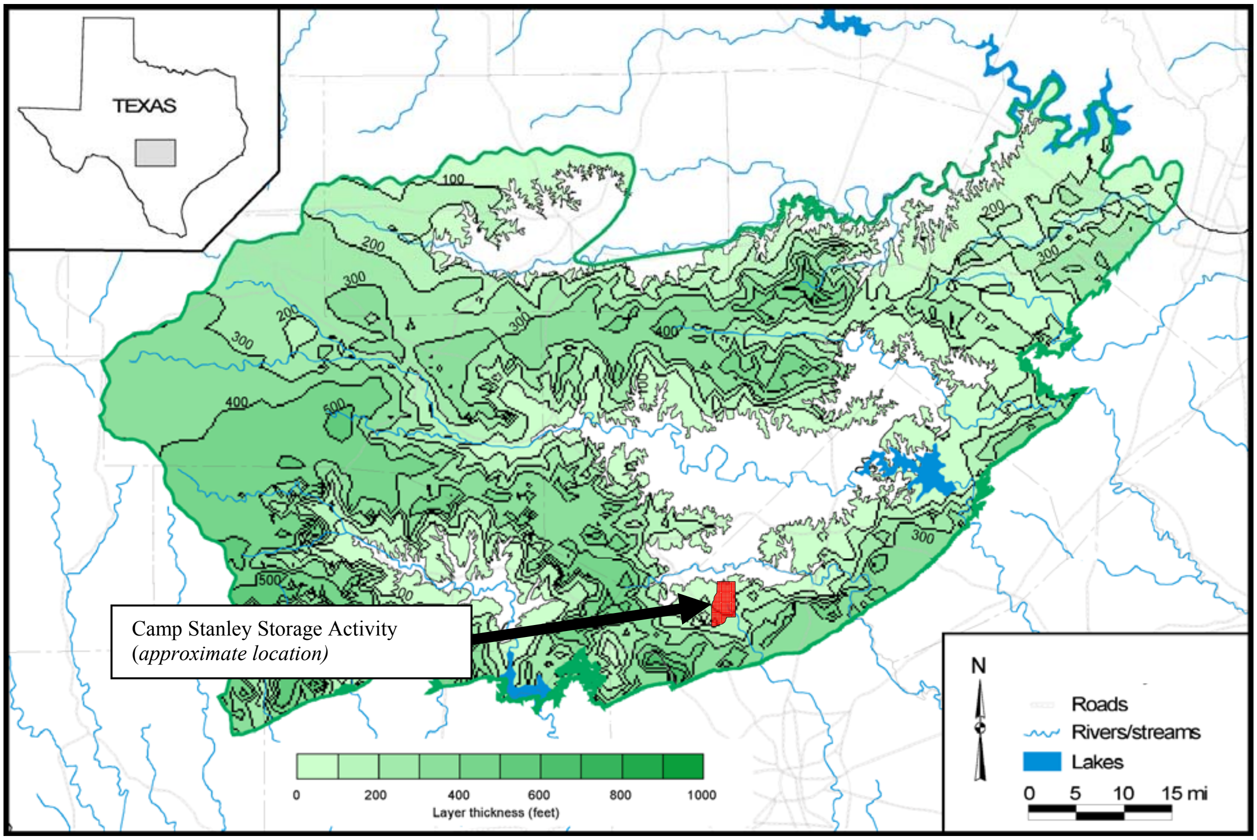
Upper Trinity water is generally of poor quality and most wells achieve only low production. Evaporite beds in the Upper Trinity introduces excessive sulfate into the water. Few wells obtain water solely from the Upper Trinity aquifer.

2.2.5 Surface Water Hydrology

The CSSA area can be characterized as hilly with stony soils and high runoff potential. Natural stream channels on CSSA generally have broad floodplains, and portions of CSSA are within the 100-year floodplain. Salado, Leon, and Cibolo Creeks drain surface water from CSSA. Approximately 75 percent of CSSA is in the Salado Creek watershed, 15 percent in the Cibolo Creek watershed, and 10 percent in the Leon Creek watershed. Most of the active-use areas of CSSA are in the Leon Creek watershed, including a wastewater treatment plant, which drains into a tributary of Leon Creek at the southern boundary of CSSA. All of these streams are intermittent at CSSA.

The Salado Creek watershed, with its headwaters located in the adjacent City of Fair Oaks extends in a broad swath across CSSA from NW to SE. Impervious cover in Fair Oaks is currently estimated at 5 to 10 percent. Drainage from Camp Bullis to the east also flows across CSSA to Salado Creek. Impervious cover for CSSA within the Salado Creek watershed is substantially less than 5 percent, with much of the area undeveloped except for dirt and gravel roads.

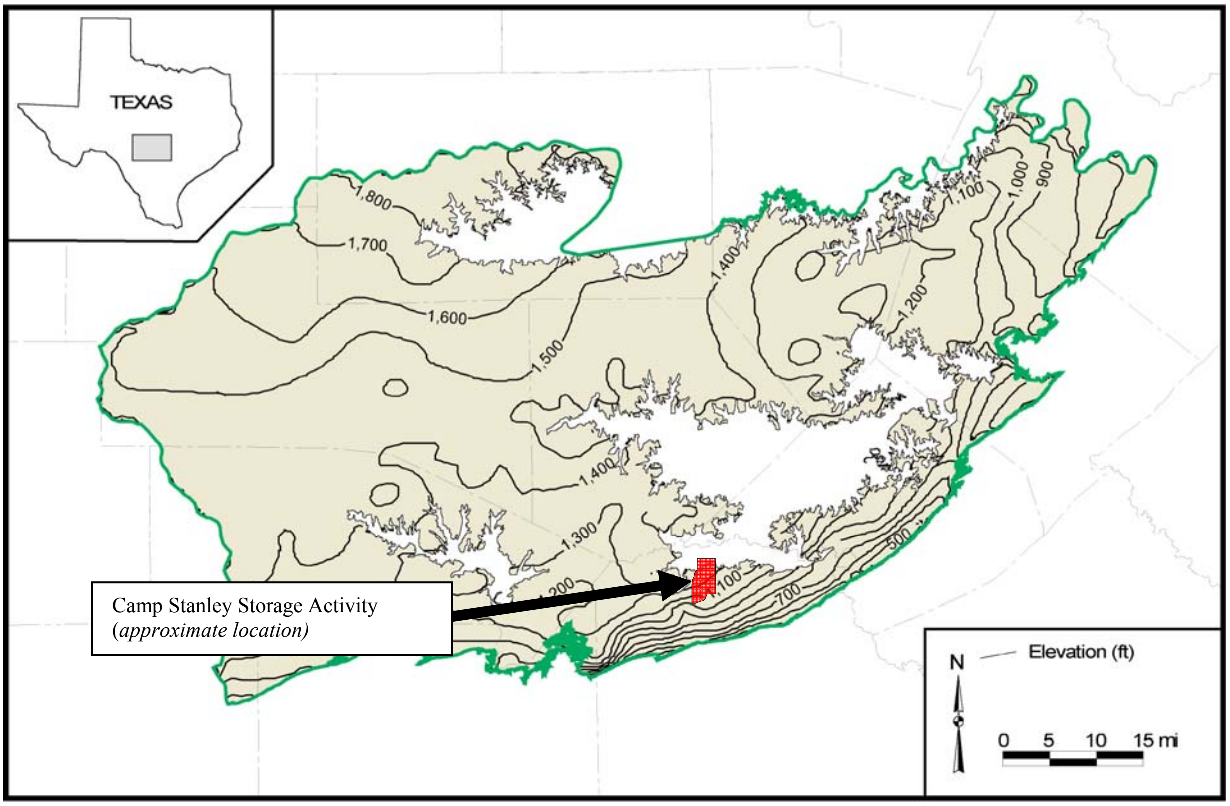
Figure 2.9 Approximate Thickness of the Upper Trinity aquifer



Camp Stanley Storage Activity
(*approximate location)*

(modified after TWDB Report 353, September 2000)

Figure 2.10 Elevation of the Base of the Upper Trinity Aquifer



(modified after TWDB Report 353, September 2000)

Three tributaries of Cibolo Creek, which originate on CSSA, drain the northeastern part of the outer cantonment. The area of the Cibolo Creek watershed within CSSA is undeveloped except for dirt and gravel roads. Impervious cover in the Cibolo Creek watershed is minimal.

A tributary of Leon Creek, originating on CSSA, drains the SW quarter of the inner cantonment. Overall, impervious cover within the Leon Creek portion of CSSA is estimated at approximately five percent or less, much of which is located along Tompkins Road and McElroy Drive.

Rainfall runoff is conveyed to natural stream flow channels by ditches and sheet flow in the developed areas of CSSA. CSSA has sufficient relief to allow rapid conveyance of runoff from developed areas, and in the undeveloped areas, runoff flows overland to natural channels.

2.2.6 Meteorology and Climate

CSSA is located in the south-central part of Texas on the Balcones escarpment. NW of the installation, the terrain slopes upward to the Edwards Plateau; to the SE, the terrain slopes downward to the Gulf Coastal Plains. This results in a modified subtropical climate, predominantly marine during the summer months and continental during the winter months. The resulting weather is characterized by hot summers with daily temperatures above 90 degrees Fahrenheit (°F) over 80 percent of the time and mild winters with below-freezing temperatures occurring on an average of only about 20 days per year. Average annual temperature is 69°F. The highest average daily maximum temperature is 95°F in July, and the lowest average daily minimum temperature is 39°F in January. Temperature extremes for the period of weather records range from 0°F to 108°F.

CSSA is situated between a semi-arid region to the west and the coastal area of heavy precipitation to the east. Between the years of 1934 and 1999, the annual rainfall at Boerne averages 33.66 inches (Esquilin, *et al*., 2000). Precipitation is fairly well distributed throughout the year, with the heaviest amounts occurring in May and September. Approximately 61 percent of the rainfall occurs over the period from April through September and is primarily due to thunderstorms. Damaging hail seldom occurs, but light hail is common with springtime thunderstorms. Since CSSA is only 140 miles from the Gulf of Mexico, tropical storms occasionally affect the post with strong winds and heavy rains. Spring rainfalls are associated with frontal systems while summer rainfalls are associated with thunderstorms and tropical weather. Measurable snowfall occur only once every 3 or 4 years.

2.3 PREVIOUS AND CURRENT INVESTIGATIONS

2.3.1 Regional Studies

Several studies on groundwater development and availability within the Trinity aquifer have been produced over the past 20 years. These studies range from graduate-level thesis to major governmental projects. Described below are regional studies widely regarded as a definitive body of work conducted within the hydrostratigraphy of interest.

Ground-Water Availability of the Lower Cretaceous Formations in the Hill Country of South-Central Texas (Ashworth, 1983)

Ashworth (1983) performed a study to describe the hydrologic characteristics of the Trinity Group Formations of the south-central Texas Hill Country. The study area encompassed approximately 5,800 square miles at the edge of the Edwards Plateau, along the BFZ. The study area included Kendall, Kerr, Real, and Bandera Counties and portions of Hays, Gillespie, Comal, Bexar, Medina, Uvalde, and Blanco Counties. CSSA is located in the northern portion of Bexar County. Drainage basins within the study area include the Guadalupe, San Antonio, Nueces, and Colorado River drainage basins.

Ashworth collected hydrologic data from high-capacity public supply, irrigation, and industrial wells and attempted to gather data from perennial springs. Wells completed within the Middle Trinity aquifer, the portion of the Trinity Group that is present at CSSA, yielded slightly saline water. Water from the LGR Limestone was hard, but of good quality, as was water from the Hensell Sand (geologic facies to the BS) and CC Limestone. The Hensell Sand water had high iron concentrations in some localities. Water quality decreased toward the south and southeastern edges of the study area where the total dissolved solids increase substantially.

The primary recharge source for the Trinity Group is from rainfall and seepage from lakes and streams. Within the study area, the Glen Rose Limestone and the Hensell Sand outcrops receive direct recharge. Underlying units, such as the CC Limestone, derive recharge from vertical leakage. Water that recharges the Trinity Group flows down dip, south-SE, at a hydraulic gradient of 0.005. Hydraulic gradient is a dimensionless number or ratio that can be represented in any unit of measure such as feet per foot, meters per meter or miles per mile. Groundwater flow paths generally follow decreasing topography, except in areas of continuous pumpage or springs.

Predicated on base flow received by the Guadalupe River, the effective recharge to the Trinity Group aquifer is estimated at 200,000 acre-feet per year (acre-ft/yr). Base flow was measured at a gauging station located in an area of little groundwater pumpage derived from groundwater discharge into the river. This discharge amount should match the recharge amount assuming the aquifer remains nearly filled.

Most of the streams in the study area traversed the Middle Trinity aquifer units and are effluent streams, gaining water from the units they traverse. The exception to this rule is Cibolo Creek, which is influent, losing its water to sinkholes unless flood periods are occurring. The largest water loss from Cibolo Creek was observed along its path from Boerne to Bulverde, where it flows over the Glen Rose Limestone. CSSA lies directly south of Cibolo Creek, within a few miles of Boerne.

Pumping tests were performed for several Trinity Group wells. For the Middle Trinity aquifer, a transmissivity coefficient of 1,700 gallons per day per foot (gpd/ft) [21.1 square meters per day (m^2/day)] was calculated. Groundwater in the Trinity Group is under artesian (confined) and water table conditions. Wells under artesian conditions have a storativity range of 10^{-5} to 10^{-3}, whereas wells under water-table conditions have a storativity range of 0.1 to 0.3. Storativity, also known as the coefficient of storage, is a dimensionless number used to express the storage capacity of an aquifer. It is briefly defined as the volume of water taken into or released from storage per unit change in head per unit area.

Wells in the Trinity Group are usually under artesian conditions, except for shallow wells. Confined or artesian conditions are present in units that are overlain by confining units such as the Bexar or Hammett Shales. Glen Rose Limestone outcrops over much of the study area and over the whole CSSA area. Shallow wells that only penetrate the Glen Rose Limestone are under water-table conditions.

Hydrogeology of the LGR Aquifer, South-Central Texas (Hammond, 1984)

Hammond (1984) completed his doctoral thesis on the hydrogeology of the LGR aquifer. The study area included Blanco, Comal, Kendall, Kerr, Bandera, Uvalde, Medina, and Bexar Counties. Hammond found that the hydrologic properties of the LGR Limestone varied widely over short distances and that the groundwater had regional and local flow systems.

The LGR consists of biomicrite, dolomite, micritic marl, and reef deposits. The unit reaches its maximum thickness of approximately 400 ft in the eastern portion of the Edwards Plateau area. Early Miocene uplift of the eastern Edwards Plateau subjected the LGR to sub-areal weathering, which developed secondary permeability through carbonate dissolution in fracture zones.

The regional groundwater flow system in the LGR is controlled by syndepositional permeability and primary porosity. Hydrologic parameters for the regional groundwater system were 240 to 3,220 gpd/ft (2.98 to 40 m^2/day) for transmissivity and 0.721 to 21.2 gpd/ft^2 (0.294 to 0.864 m/day) for hydraulic conductivity.

Groundwater Availability of the Trinity aquifer, Hill Country Area, Texas: Numerical Simulations through 2050 (TWDB, 2000)

A three-dimensional, numerical groundwater flow model of the Middle Trinity aquifer in the Hill Country area of south-central Texas was developed to help estimate groundwater availability and water levels in response to pumping and potential future droughts. The model included historical information on the aquifer and incorporated results of new studies on water levels, structure, hydraulic properties, and recharge rates. A steady-state model was calibrated for 1975 hydrologic conditions when water levels in the aquifer were near equilibrium, and a transient model was calibrated for 1996 through 1997 when the climate transitioned from a dry to a wet period.

Using the model, values of recharge, hydraulic conductivity, specific storage, and specific yield were calibrated for the aquifer. The model was used to predict future water levels and saturated thickness under drought-of-record conditions using estimates of future groundwater demands based on demand numbers from the Regional Water Planning Groups. The model predicts that the area near Cibolo Creek in northern Bexar, southern Kendall, and western Comal Counties were the most susceptible to future water level declines due to increased demand and potential droughts.

If a drought similar to the drought-of-record were to occur, the model suggested that water levels may decrease as much as 100 ft in this area by the year 2010 and that a large part of the aquifer may be depleted in this area by the year 2030. Hays, Blanco, Travis, southeastern Kerr, and eastern Bandera Counties could experience moderate water level declines (50-100 ft) in response to projected demands and potential drought as early as 2010. The model suggested that major rivers may continue to flow seasonally even with increased pumping and under drought conditions.

2.3.2 Camp Stanley Environmental Studies

CSSA Groundwater Investigation Summary (1991 to Present)

Contaminants were initially detected in CSSA Well CS-16, shown in Figure 2.11, during routine water supply testing in April 1991. Drinking water withdrawals at CS-16 ceased immediately. Follow-up sampling confirmed concentrations of trichloroethene (TCE) and tetrachloroethene (PCE) above drinking water maximum contaminant levels (MCLs) and the well was permanently taken out of service. Comprehensive investigation of groundwater contamination at CSSA began in 1992. The effort started with preliminary evaluations to establish the extent of the problem without invasive field techniques, namely analyzing groundwater samples from existing CSSA wells and geophysical surveys to identify potential contamination source areas. Samples from Well CS-D, located west of Well CS-16, also exhibited concentrations of PCE and TCE that exceeded MCLs. Camera surveys were also performed at CSSA wells to inspect the integrity of existing casings and to document general conditions inside the wells. Following this effort, the **Hydrogeologic Report for Evaluation of Groundwater Contamination** (ES, 1993) was submitted to the appropriate regulatory agencies for comment and approval.

A groundwater monitoring and reporting program was initiated in 1994 and established that groundwater flow gradients generally varied from south-southwest to south-southeast. The monitoring continued to show above-MCL volatile organic compound (VOC) contamination in Wells CS-16 and CS-D. Attempts to identify specific contaminated zones in several CSSA wells through discrete groundwater sampling proved inconclusive. Nevertheless, after review of geophysical and video logs, additional surface casing was installed to 200 ft below ground surface (bgs) in Wells CS-2, CS-3, CS-4, CS-16, and CS-D to seal off shallow water-bearing zones that could have been contributing to migration of VOC contamination through open boreholes. Investigation activities continued in 1995, including additional downhole geophysical logging, discrete interval sampling, and well upgrades. In addition, periodic monitoring of several off-post domestic water supply wells was eventually initiated. At that time, none of the offsite wells sampled showed evidence of contamination.

Other work in 1995 relating to groundwater contamination issues focused on source characterization. To help identify potential sites, historical records were examined and interviews with CSSA employees were conducted to locate potential SWMUs and other AOCs. Sites were examined throughout CSSA where waste had been dumped and/or burned during past disposal activities. Areas showing unusual topography were also considered possible waste burial locations. Electromagnetic (EM) and ground penetrating radar (GPR) surveys were conducted at some of these sites in early 1995, followed by soil-gas surveys in areas where anomalies were identified.

Subsequently, SWMU B-3 and the abandoned oxidation pond SWMU O-1, located in the NE corner of the Inner Cantonment, were identified as potential VOC source areas. The pond once held waste fluids and sludge from CSSA's weapons bluing operations. The pond was abandoned and filled in 1985. At SWMU B-3 there had been a wide trench where solid and

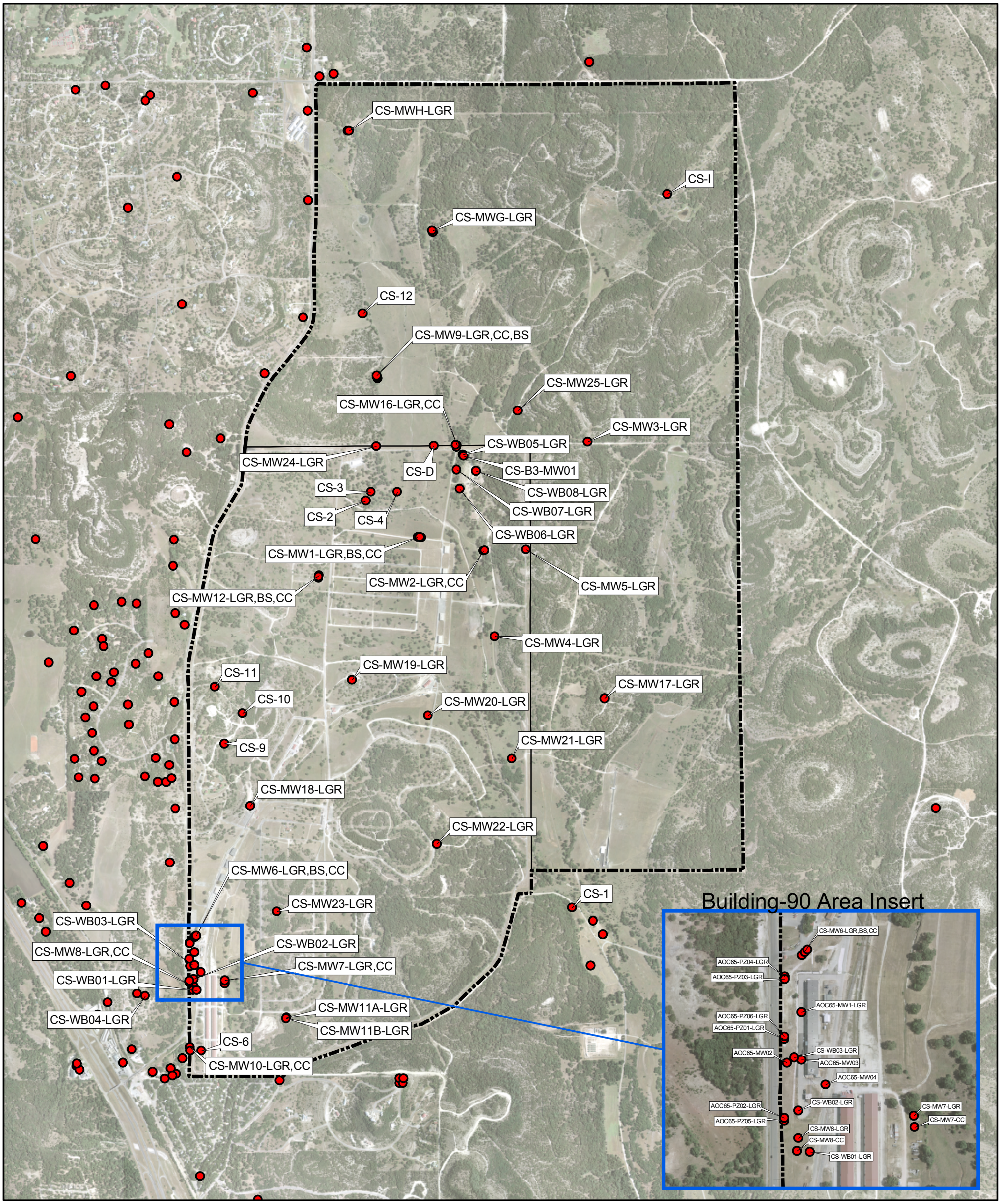


Figure 2.11

Groundwater Sampling Locations within the HCSM Area

PARSONS

J:\736\736071\GIS\csm_groundwater_sampling_locations.mxd liquid wastes were apparently burned. The trench was backfilled in the early 1990's. Additional geophysical surveys, soil gas sampling, soil boring, and sampling continued at CSSA. Results indicated that SWMU B-3 and O-1 contained significantly higher concentrations of VOC contaminants than other sites. Analytical results showed PCE in SWMU O-1 soil samples and PCE, TCE, and *cis*-1,2-dichloroethene (DCE) in soil at SWMU B-3. Results of these investigations are provided in the **Technical Memorandum on Soil Boring Investigations** (Parsons ES, 1995b), the **Technical Memorandum on Surface Geophysical Surveys at High Priority Sites** (Parsons ES, 1995c), and the **Technical Memorandum on Surface Geophysical Surveys, Well 16 Source Characterization** (Parsons ES, 1995a).

Other activities completed at about this time included mapping of two fault zones through CSSA by Parsons. One narrow fault zone courses through the southern portion of CSSA trending SW-NE. A second, wider fault zone bisects CSSA immediately south of CS-16, trending west to east. At an October 1995 meeting involving EPA, TCEQ, AFCEE, CSSA, and their consultants, it was agreed that groundwater work at CSSA would continue to focus on source characterization. Quarterly groundwater monitoring and reporting continued.

In 1996, CSSA initiated additional source characterization at SWMU B-3 and O-1 in preparation for source removal. Additional detailed geophysical work was completed in areas around CS-16 and south to CS-1. CSSA had two monitoring wells (CS-MW1-LGR and CS-MW2-LGR) installed south of CS-16. The wells were drilled into the bottom of the LGR Formation (320 to 361 ft bgs) and completed with 140 and 141 ft of casing, respectively in 1999. These wells were recompleted with a 20-screen section in the bottom of the LGR. Periodic TCE concentrations above MCLs were found in both wells. The **Groundwater Investigation and Associated Source Characterization Report** (Parsons ES, 1996), which includes source characterizations of SWMU B-3 and O-1, was submitted to the regulatory agencies.

CSSA began groundwater monitoring using a QED MicroPurge® Low-Flow system in early 1997. Camera surveys were completed in CS-1, CS-9, and CS-11, followed by upgrading that included carbon dioxide (CO_2) rehabilitation treatments. Ongoing work for SWMU and AOC site characterizations did not reveal additional potential sources contributing to the CS-16 area plume. However, past use of solvents in CSSA Building 90 was suspected as a potential source of contamination in the SW corner of the post. From 1998 through January 2004, CSSA continued monitoring water levels and conducting groundwater sampling on a quarterly schedule. Groundwater monitoring reports are included in **Volume 5** of the **CSSA Environmental Encyclopedia.**

In 1998 planning for the installation of several clustered monitoring wells throughout CSSA was also initiated. The intention of the well clusters was to assist in the ongoing characterization of groundwater contamination at CSSA. The wells provided for monitoring of the major water-bearing zones in the LGR, BS, and CC portions of the Middle Trinity aquifer. To date, 30 new monitoring wells and six piezometers (PZs) have been installed within the LGR, BS, or CC portions of the Middle Trinity aquifer (Figure 2.11).

In 1999, an offsite well survey was conducted in the areas surrounding the CSSA facility. As many as 130 private or public supply wells were tentatively identified within one mile of CSSA. Of these, nearly 100 wells were positively identified and mapped. Most wells in the locality developed their water resources from the Middle Trinity aquifer. The typical well construction for the area includes an open borehole completion through the LGR, BS, and CC portions of the aquifer with minimal surface casing. This methodology ensured adequate yield, but could enhance the likelihood of cross-contamination between water-bearing units. As part of the quarterly monitoring program, select offsite wells were sampled for the presence of target contaminant analytes.

As a result of the 1999 well survey, CSSA initiated an offsite well sampling program in December 1999 (Figure 2.11). Based on this sampling, it was discovered that PCE and/or TCE was present in both public and private drinking water wells to the west and SW of the facility. These events lead to the search for another area of contaminant release, which ultimately lead to AOC-65, a solvent vat area in Building 90 where solvent had been used in the past.

Investigations performed at AOC-65 included soil borings, soil-gas surveys, multiple geophysical sensing techniques, and shear-wave seismic surveys. The objectives of those investigations were to identify pathways for migration specifically related to stratigraphic and structural features. Results of these investigations culminated with the installation of two pilot study vapor extraction systems. A weather station and transducers were installed at the site to aid in a groundwater recharge study.

In July and August 2001, two pumping tests were performed on CSSA wells CS-10 and CS-16. The tests were conducted to get a better sense of the hydraulic character of the Middle Trinity aquifer. The tests were conducted in wells that were open to both producing intervals of the aquifer: the Glen Rose Limestone and the CC Limestone. Groundwater pumping rates between 45 and 80 gallons per minute (gpm) were achieved, and measurable drawdown was observed at distances up to 700 ft away. Transmissivity values ranged between 1,600 and 2,300 gpd/ft (19.9 to 28.6 m^2/day), and aquifer storativity between 0.00008 and 0.005. Storativity, also known as the coefficient of storage, is a dimensionless number used to express the storage capacity of an aquifer. It is briefly defined as the volume of water taken into or released from storage per unit change in head per unit area. The resultant hydraulic conductivity ranged between 8.9 and 9.96 gpd/ft^2 (0.363 and 0.406 m/day).

Starting in 1996, the first of 47 environmental monitoring wells (defined as wells with casing and screen) were installed, and has continued through April 2007. With the exception of 10 shallow piezometers (AOC-65) completed within the UGR, the remainder (37) of the observation wells monitor the LGR (24), BS (4), or CC (9) components of the aquifer. Twenty-three of these monitoring wells are arranged in 10 clusters of 2 or 3 wells each to observe different intervals of the Middle Trinity aquifer (e.g., LGR, BS, and CC wells). The remaining 14 monitoring wells are individually located throughout the base to monitor the LGR exclusively.

Another 8 multi-port (Westbay) wells have been installed to discretely measure multiple zones throughout the Middle Trinity aquifer using single boreholes. These wells use an inflatable packer technology to isolate various sampling ports throughout the length of the borehole. The well design allows discrete measurements of hydraulic head and contaminant composition to be profiled throughout the length of the borehole. These multi-port wells are installed at the AOC-65 and SWMU B-3 remediation sites.

Additionally, 6 unused agricultural wells, 2 unused water supply wells, and 3 active water supply wells are also used in monitoring the bedrock groundwater system. These wells are generally described to have an open borehole construction that uses a limited amount of surface casing to manage near-surface borehole instability and prevent less desirable upper strata groundwater from entering the well.

A chronology of work conducted in association with the groundwater investigation is provided in **Volume 1-1** of the **CSSA Environmental Encyclopedia.**

USGS Surface and Aerial Mapping

In 2003 CSSA contracted the U.S. Geological Survey (USGS) to perform surface geologic and EM mapping at the facility. Much of the planned activities will build upon, or be performed in conjunction with Camp Bullis. Other regional entities also contributing to the effort include the San Antonio Water System (SAWS) and the Edwards Aquifer Authority (EAA).

Surface Mapping

In 2004, the USGS published the *"Geologic Framework and Hydrogeologic Characteristics of the Glen Rose Limestone, Camp Stanley Storage Activity, Bexar County, Texas" (Scientific Map 2831).* This report describes the hydrogeologic units exposed at the ground surface at CSSA, and presents a map of these units. This geologic survey is a continuation of the mapping previously performed at the neighboring Camp Bullis facility. It is noteworthy to mention that this report primarily addresses the UGR, which comprises almost 90 percent of the exposed surface at CSSA. Except for the uppermost exposed interval, the LGR is not addressed in this report.

Based on mapping to the east on the Camp Bullis military installation, the UGR has been subdivided into 5 intervals (A-E) by the USGS. Of these intervals, E and C, are responsible for much of the near surface lateral movement of ground-water within the study area. A biostrome in interval D appears to have high porosity and permeability associated with fractures and molds which allow for substantial groundwater recharge from precipitation and run-off.

Interval A, which is a very permeable interval east at Camp Bullis (USGS, 2003), is mostly absent at CSSA due to erosion and plays a very minor role in recharge at/or near CSSA. Intervals B and C are also not present except upon the higher elevation hilltops. Faulting within and adjacent to CSSA is associated with the northeast-southwest extensional BFZ. This fault zone has resulted in high-angle normal down to the coast faulting. The displacement on most faults is 10 to 20 feet. Also present in the study area are fractures that are both parallel and perpendicular to the BFZ. The northwest-southeast fractures, which are perpendicular to the Balcones fault trend, appear to be the most permeable, probably due to east-west extension. Also presented is information about faults and fractures in the study area.

Aerial Mapping

CSSA and Camp Bullis also contracted with the USGS Crustal Imaging Team to perform an aerial EM (AEM) survey of both U.S. Army facilities and private entities (SAWS/EAA). The process utilizes an EM drone towed in linear flight paths above the land surface by a helicopter. The method employs the same geophysical principles utilized by the resistivity surveys conducted at AOC-65, but at a regional scale. Research by the USGS in other parts of Central Texas (Seco Creek) demonstrates that the method is able to identify the major stratigraphic and structural features affecting the regional groundwater regime in the Edwards Aquifer. The CSSA survey was completed in the fall of 2003 and to date only preliminary data has been received.

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SECTION 3
SOURCE CHARACTERIZATION AND POTENTIAL EXPOSURE

Over the past decade, a total of 84 sites, including 39 SWMUs, 40 AOCs, and 5 Range Management Units (RMUs) have been identified at CSSA. The scale of the sites ranges from localized areas of surficial debris or burn areas to multi-acre disposal trenches. Analytical data suggest that PCE, TCE, and *cis*-1,2-DCE are the primary contaminants of concern (COC) in groundwater, and metals are the primary COCs in soil. Figure 3.1 depicts locations of currently identified SWMUs, AOCs, and RMUs.

As of December 2004, a total of 43 sites have been closed, with another 4 sites with closures pending. The remaining sites are being evaluated under the Texas Risk Reduction Rules and the Texas Risk Reduction Program (TRRP). Thus far, a total of 69 sites have been investigated, with ongoing investigations and/or remediation being conducted at 22 sites. However, only a few sites investigated are considered to be likely sources for the VOC contamination within the Middle Trinity aquifer. These include two SWMUs (B-3 and O-1) located near Well CS-16 and AOC-65 located near the SW corner of the post.

3.1. SWMU B-3

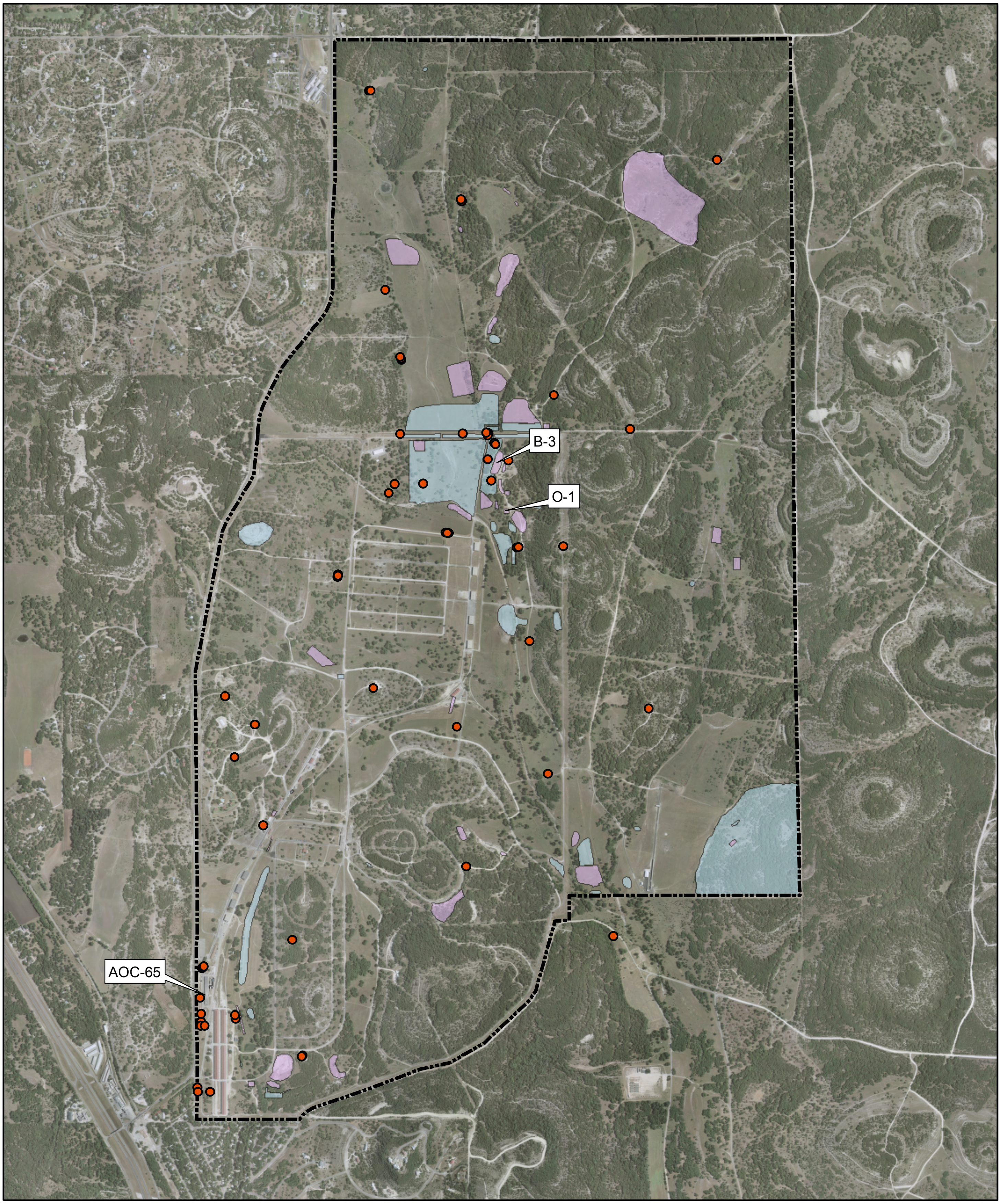
3.1.1 B-3 Background

Presumably during the 1980's, SWMU B-3 was a landfill area thought to have been used primarily for garbage disposal and trash burning. The trench areas were reportedly closed in 1990-1991. In 1991, chlorinated hydrocarbons were detected in groundwater from Well CS-16 approximately 500 ft north-northwest of SWMU B-3. The VOC concentrations, which were above drinking water standards, prompted several investigations aimed at identifying possible source areas that could have contributed to the contamination.

Background information regarding the location, size, and known historical use of the site is included in the CSSA Environmental Encyclopedia (**Volume 1-2, SWMU B-3)**. This volume includes a Chronology of Actions and a Site-Specific Work Plans for SWMU B-3. Results for a geophysical survey, soil gas survey, soil boring investigation, groundwater sampling, and a treatability study are also included as part of the CSSA Environmental Encyclopedia **(Volume 3-1, SWMU B-3)**.

3.1.2 B-3 Characterization Activities

Source characterization began with surface geophysical surveys performed during January through March 1995 at seven potential source areas. Two large anomalous areas were detected at SWMU B-3 during the EM survey as discussed in the technical memorandum (Parsons ES, 1995b). Based on this geophysical data, soil borings were drilled at potential areas including SWMU B-3 to investigate the portions of each area exhibiting geophysical anomalies. A subsequent soil gas survey of SWMU B-3 identified PCE and TCE associated with the geophysical anomalies, with occasional detection of *cis*-1,2-DCE. The presence of these chlorinated hydrocarbons implicated SWMU B-3 as a likely source area for the contamination detected in well CS-16. Figure 3.2 is the 1996 Soil Gas Plume Map.



CSSA Boundary

Areas of Concern

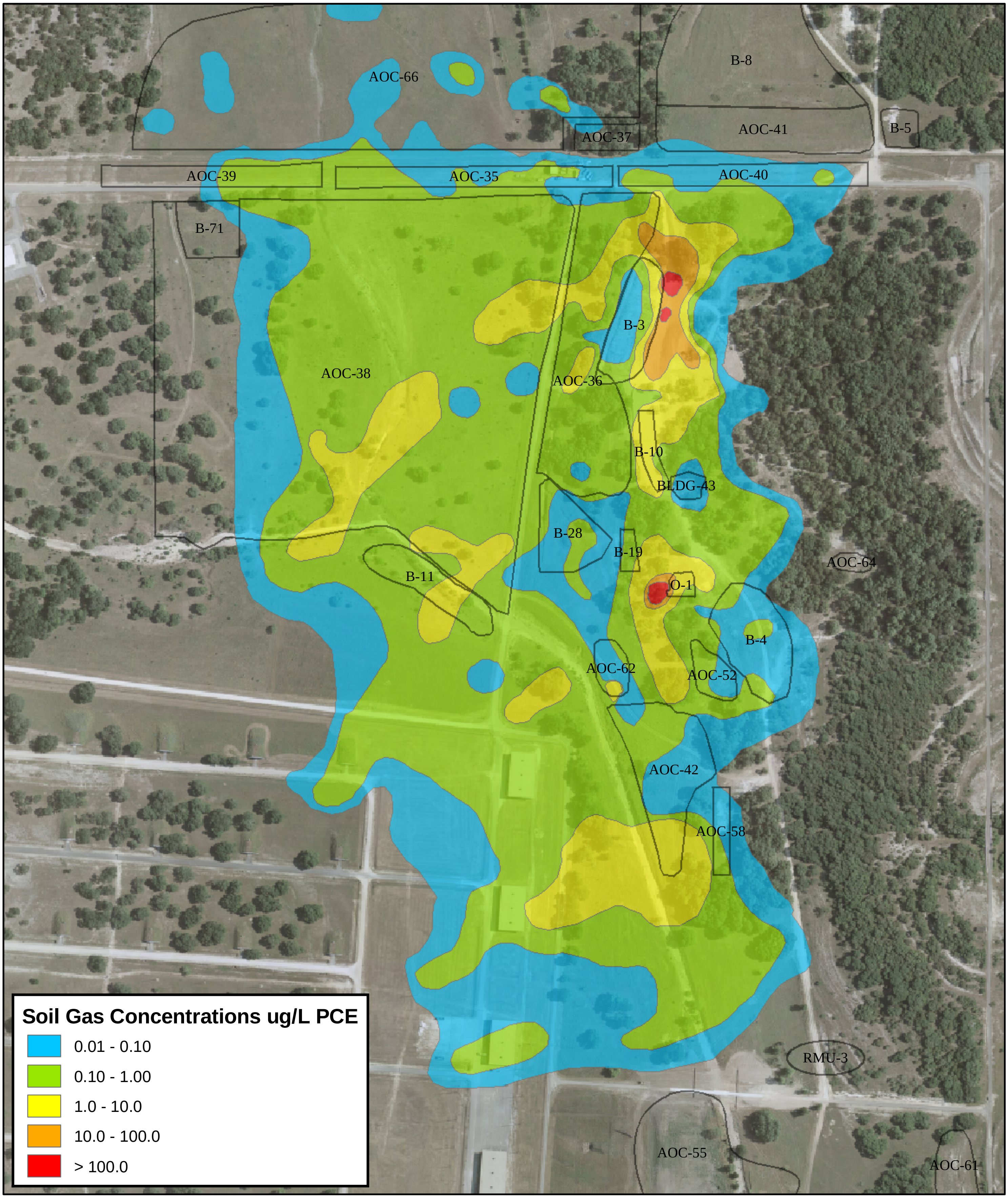
Solid Waste Management Units

● On-Post Water Wells

Figure 3.1

SWMU Location Map

PARSONS



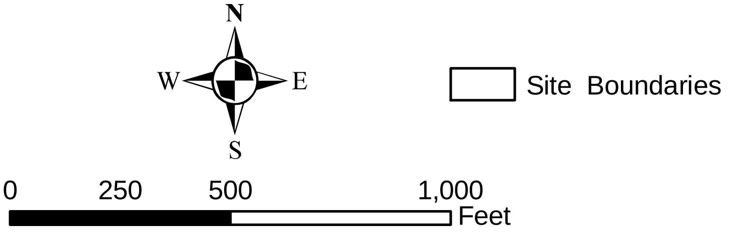


Figure 3.2

Soil Gas Plume Map

Camp Stanley Storage Activity

PARSONS

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A soil vapor extraction (SVE) pilot test was recommended at SWMU B-3 for removal of soil VOC contamination. The primary objectives of the pilot test were to determine if SVE is a viable remediation alternative and to collect data to design a full-scale SVE system. Borings drilled for construction of the SVE pilot test system were also used to collect soil samples in the soil gas "hot spots" to determine VOC concentrations. These samples were also tested for total metals and soil physical characteristics to assist in evaluating potential remedial options. SVE was the primary treatment technology selected for the pilot study because of the volatility of PCE, TCE, and *cis*-1,2-DCE.

3.1.3 B-3 Soil Vapor Extraction

SWMU B-3 consists of multiple trenches that cover approximately one-half acre. Tests identified PCE and TCE in the trench area, indicating this is a likely source for the VOCs detected in Well CS-16. CSSA installed 18 SVE wells to cleanup VOCs in the soils and limestone in 1995.

After installation, a limited, 2-week initial pilot test demonstrated that an SVE system operated at the site could reduce the VOC concentrations present in the trench area. The results also indicated that the subsurface soils at the site are very complex, and that it would be difficult to extrapolate pilot test results across the entire site without the collection of additional data. Some of this complexity was uncovered during an interim removal action and pre-excavation investigation of the SWMU B-3 trenches conducted in 2002 (Foster Wheeler Corporation, 2003), which discovered that the west trench is actually composed of multiple trenches aligned parallel to each other.

Beginning in December 2001, samples were collected from the site VEWs after periods of heavy rainfall had collected groundwater in the perched wells. When groundwater is present, results have indicated the presence of *cis*-1,2-DCE in excess of 24,000 µg/L, and trace amounts of vinyl chloride. The results indicate that presence of contaminated media with B-3 may continue as a persistent source area for the continual development of Plume 1.

In addition, CSSA initiated further cleanup actions at SWMU B-3 in August 2002 to remove source areas of contaminated soil and debris in the east trench of the former disposal area. The B-3 SVE system was taken out of service during the removal action to facilitate excavation of the contaminated material. The impacts of the actual configuration of the multiple trenches on the SVE performance were not evaluated during the 1995 study.

Based on the initial pilot test and the first 12 months of operations and maintenance (O&M), operation of the SVE system at SWMU B-3 resulted in the removal of approximately 290 pounds of VOCs. Based on these findings, SVE appears to be an effective method for removing VOCs from the SWMU B-3 trenches. Additionally, SVE has been identified as a possible remedial alternative to reduce levels of residual contaminant in bedrock.

3.1.4 B-3 Interim Measures

Excavation and off-site disposal was selected as an interim measure (IM) at SWMU B-3. The area at SWMU B-10 formerly occupied by the Phosphate-Induced Metals Stabilization (PIMS) pilot scale field demonstration project was used to stage and stockpile waste from SWMU B-3. The removal and stockpiling of cover soil at SWMU B-3 began on August 28, 2002. Samples were collected to characterize the soil media in the SWMU B-3 west trench on September 12, 2002, and larger volumes of potential waste material were encountered. Results indicated some portions of the media within the west trench contained lead (D008) and TCE (D039) above RCRA hazardous waste criteria. Additional testing will be necessary to delineate the extent of contamination at this part of the site.

The SWMU B-3 east trench investigation and excavation was initiated September 16, 2002. Waste material, including three drums of unknown origin, were removed and placed in a lined waste accumulation area. Excavated wastes from the east trench were characterized according to the established data quality objectives (DQO). Waste characterization results of the excavated east trench material indicated the material exceeded RCRA hazardous waste criteria levels for PCE (D040) and TCE (D039). In addition, analytical results of several sidewall samples from the east trench were above established inorganic background criteria (non-detect for organic compounds). Over-excavation of the affected portions of the east trench was performed. Partial backfilling of the east trench was initiated on September 25, 2002 in those portions of the excavation where data indicated no contaminants above background.

A total of 22 confirmation samples were collected from the east trench at SWMU B-3. The established waste characterization DQOs for SWMU B-3 were followed in determining the proper characterization of contaminated and cover soils. A total of 22 waste characterization samples were collected, and 10 backfill samples were collected and analyzed for COCs. Five additional samples of the cover material were analyzed for total zinc and mercury to determine if it was appropriate for use as backfill. Additionally, six of the waste characterization samples were reanalyzed for COCs to confirm that the soil could be used as backfill.

A total of 732 loose cubic yards (LCY) (916 tons) of D039/D040 hazardous media from the east trench were transported to Onyx Environmental Services (Onyx), Port Arthur, TX facility for treatment and disposal (EPA ID# TXD000838896 and TCEQ ID# 50212). Approximately 1,242 LCY of Class 2 non-hazardous materials were transported to the Waste Management Covel Gardens (TCEQ ID#2093) facility for disposal. In addition, over 5,500 LCY of cover soil were properly characterized and stockpiled for use as backfill.

3.1.5 B-3 Well Installations

A total of five groundwater monitoring wells were drilled and installed at SWMU B-3. Four wells were designed to monitor selected, discrete-depth intervals within the aquifer and were completed with Westbay® (WB) MP-38 Multi-port Systems. The main purpose of these wells is to generate data from the Pilot Study substrate injection and monitor the effects of subsequent interim remedial efforts against the solvent plume associated with SWMU B-3. A fifth well was constructed as a conventional monitoring well, monitoring only one screened interval, and will serve a dual purpose as an injection well and monitoring well.

3.1.6 B-3 Bioreactor

As part of the RCRA Administrative Consent Order, a pilot study using a bioreactor was conceptualized, designed, and constructed at SWMU B-3. The design included the excavation, removal, and offsite disposal of approximately 15,000 cubic yards of affected soil, debris, and waste contained within six trenches in Summer 2006. The waste is believed to be a likely source of contaminants impacting the underlying fractured limestone (bedrock) and groundwater.

The pilot study is intended to determine if the bioreactor technology is applicable corrective measure to remediate the affected groundwater and unsaturated zone underlying SWMU B-3. The bioreactor is intended to create a reducing (anaerobic) condition in which the desired microbial organisms, both naturally occurring and introduced, will flourish and thereby complete the metabolic reduction of contaminants in the vadose zone.

The general concept of the bioreactor is to pump water approximately 400 feet from recovery wells CS-MW16-LGR and CS-MW16-CC to a 5,000-gallon storage tank. Level switches within the storage tank are set to communicate directly with the two water delivery wells to maintain an available water supply in the water tank for the bioreactor. A transfer pump is used to pump water from the storage tank to the network of pipes buried approximately 1.5 ft below a gravel surface which overlay's the SWMU B-3 gravel/mulch filled trenches. Water from the storage tank is sprayed into the gravel/tree mulch mixture in each trench through downward-pointing discharge nozzles located at 10-foot centers along 1.5-inch flexible high density polyethylene (HDPE) pipe.

The injected groundwater percolates throughout the nutrient-laden mulch bed, stimulating aerobic bacteria to consume the available oxygen content, and thereby driving the mulch bed to an anaerobic condition. The result of the aerobic metabolic reaction is the formation of available hydrogen acceptors that are then carried downward within the oxygen-deficient groundwater along the presumed preferential pathways that originally distributed the vadose contamination. In the presence of anaerobic groundwater with available hydrogen, the metabolic reduction of chlorinated VOCs can occur.

Authorization for a Class V Underground Injection Control permit was approved July 20, 2006 with TCEQ Authorization Number 5X2600431; WWC 12002216; CN602728206/RN104431655 was assigned to the SWMU B-3 injection system. The pilot study began shortly thereafter, and performance monitoring continues to date (August 2008).

3.2 SWMU O-1

3.2.1 O-1 Background

The oxidation pond, also referred to as SWMU O-1, was reportedly constructed in 1975 (CSSA, 1992). The pond, measuring approximately 42 ft by 60 ft by 2.5 ft deep, was lined with vinyl butyl plastic. Wastes from Building 90-1 (spillage, change-out, *etc*.) were trucked to the oxidation pond from an exterior 1,000-gallon settling tank. The frequency of delivery to the pond varied upon the level of bluing activity. In 1982, an estimated 24,000 gallons were contained in the pond (CSSA, 1992).

During Fall 1985, the pond liner was damaged during bulldozing. No records are available to indicate whether or not disposal of the sludge or residue contained in the oxidation pond occurred before destruction of the liner. A chronology of activities at SWMU O-1 is provided in **Volume 1-2, SWMU O-1**.

3.2.2 O-1 Characterization Activities

Results of previous studies are discussed in the Environmental Encyclopedia **(Volume 1-2, SWMU O-1)**, and in **(Volume 5-2, Groundwater and Associated Source Characterization Report)**. A general overview is presented below.

Due to its proximity to contaminated well CS-16, investigations were initiated at SWMU O-1 in 1995. Surface geophysical surveys were performed during January through March 1995 at potential source areas. A large anomalous area was detected at SWMU O-1 during the EM and GPR surveys.

Based on this geophysical data, four soil borings were drilled within SWMU O-1 to investigate the portions of each area exhibiting apparent geophysical anomalies. Results of analytical data gathered from the investigation indicated levels of PCE, chromium, and cadmium above background level concentrations.

A subsequent soil gas survey of SWMU O-1 during Summer and Fall 1995 identified PCE concentrations as high as 80,000 parts per billion volume (ppbv). Depths of sampling were 1.0 to 3.5 ft bgs. Additional surface soil sampling was accomplished during subsequent periods after 1995.

A liner investigation was initiated in January 1996. The investigation was designed to use a backhoe to dig a test pit above the existing liner, without disturbing the liner. However, it became apparent that the liner had been previously destroyed. A decision was made in the field to excavate to the limestone bedrock in order to find visual evidence of any potential limestone fractures. Approximately 80 cubic yards (CY) of soil material were excavated during the liner investigation.

The soils excavated during the liner investigation were replaced in their original location and an additional soil gas survey was completed to identify “hot spots” for which to perform an electrokenitic treatability study. The study was designed to test the efficacy of contaminant removal via electroosmosis, electromigration and electrophoresis effects. The field treatability study on SWMU O-1 soils were initiated in September 1997 and completed in December 1997. Test methods employed and results of the treatability study are included in the Environmental Encyclopedia (**Volume 4.1-2, Electrokinetic Treatability Study**). In general, use of the electrokinetic remedial technology was found not to be cost effective due to the large buffering capacity of the soils.

Soils in the oxidation pond area are predominantly fill, consisting of gravelly clay with marly limestone and caliche fragments, along with an identified sand layer, presumably liner bedding. Based on excavation activities associated with the liner integrity investigation, depth to limestone was approximately 3.5 to 4 ft. Clayey gravel soil in the fill material is similar to logged surrounding soils.

The most recent investigations provide data that indicate COCs for the SWMU O-1 area are PCE, cadmium, and chromium, at 1,390 milligrams per kilogram (mg/kg), 4.8 mg/kg, and 1,300 mg/kg, respectively. Samples collected at 26.5 to 27.5 ft bgs contained trace concentrations of PCE, toluene, and xylene above laboratory detection limits.

3.2.3 O-1 Interim Measures

The objective of IMs was to ensure corrective actions were designed to control or abate threats to human health and/or the environment. The other objective of the IM was to prevent or minimize the further spread of contamination while long-term remedies were being pursued. The goals of the IM activities were to define the lateral and vertical extent of contamination, remove those contaminated soils, and backfill and cap the excavation with clay. IM activities were initiated in November 1999 which included defining the lateral and vertical extents of contaminants and removal of surface soils to the defined lateral extent for off-post disposal.

Twenty-one shallow subsurface soil borings, generally to a depth of 4 ft or until limestone was encountered, were drilled in locations surrounding the known geophysical anomaly in the SWMU O-1 area. Composite samples from the shallow subsurface soil borings were collected and analyzed to determine the lateral extent of contamination. Upon review of the results in combination with previous investigation results, it was determined that the lateral extent of contamination could be accurately defined.

Five borings were drilled in the center of SWMU O-1 to a depth of approximately 27 ft bgs, identified as O1-SB5 through O1-SB9. Grab samples were collected at the soil/rock interface and at total depth. Analytical results of the vertical extent investigation indicated that PCE and , toluene were present at depths greater that 27 ft bgs (see Environmental Encyclopedia **Volume 3.1-7 SWMU Oxidation Pond**) . Therefore, the vertical extent of contamination is not currently defined. No further investigations of the vertical extent of contamination were performed, and the remaining IM activities were associated with the surface soils at SWMU O-1.

Excavation of the subsurface soils from the known extent of contamination within SWMU O-1 began on July 24, 2000. Excavation and removal of contaminated soils were completed with approximately 1,515 CY of soil material transported and disposed in Waste Management Inc.'s Covel Gardens facility. The area of excavation encompassed approximately 7,000 square feet (ft^2). Excavation was continued until the soils were removed within and slightly beyond the lateral extent of contamination to a depth where bedrock was encountered. The resulting excavation was approximately 5 ft deep.

After confirmation samples had been collected, backfilling was performed to fill the excavation and to create a solid foundation for the overlying clay cover. The backfill material was a dense, clay-rich soil, placed in 1-foot lifts and compacted. A low-permeability clay liner was constructed over the site. The clay liner was a minimum of 2 ft thick and constructed in 6-inch lifts to a slope of approximately 4 percent. Six inches of topsoil were placed on top of the clay liner, and a vegetative surface was established on the topsoil.

CSSA sought a partial facility closure of the surface soil zone located within the boundaries of SWMU O-1. The underlying limestone and the groundwater bearing zones were not included as part of that partial facility closure. The limestone/groundwater zone is to be addressed when a final remedy solution is available for those operable units. The cover will serve to prevent infiltration of precipitation into and through the bedrock and remaining contaminated groundwater, thereby serving to mitigate, control, abate, and minimize spread of contamination in the groundwater below. The partial facility closure was approved by the TCEQ in April 2002.

3.3 AOC-65

3.3.1 AOC-65 Background

AOC-65 includes two sub-slab, concrete-lined vaults, one on the west side and one in the middle of the interior of Building 90. A metal vat was installed in the western vault prior to 1966 and removed in 1995. This vat was used for cleaning ordnance materials inside Building 90 with chlorinated liquid solvents, such as PCE and TCE. In 1995, after removal of the former solvent vat, a metal plate was welded over the concrete vault, and PCE and TCE solvents were replaced with a citrus-based cleaner system located on top of the metal plate. Uses of the second vault, located within the middle of the interior of Building 90, are not known. It was backfilled and capped with concrete at an unknown date. Building 90 continues to be used for weapons cleaning and maintenance. AOC-65 also includes the area extending outside Building 90 along the associated building drain lines and ditches. Initially, AOC-65 was limited to the confines of the former solvent vault housed within Building 90; however, investigations (**Soil Gas Survey Technical Report**, Parsons ES, August 2001) suggested that the AOC-65 boundaries should be expanded to include affected areas. Background information regarding the location, size, and known historical use of the site is also included in the Environmental Encyclopedia (**Volume 1-3, AOC-65**).

Through a records search and questioning of long-term staff involved with AOC-65, CSSA has made a substantial effort to determine the source of contamination. A potential PCE/TCE source area associated with AOC-65 is a drain line from Building 90. The drain line is currently tied in to the building storm gutter system. Floor cleanings and wash-down wastes, such as those from steam cleaning, are potentially the cause of contamination observed near the drain line outfall located to the west of Building 90. The potential COCs are: VOC, semivolatile organic compounds (SVOC), total petroleum hydrocarbons (TPH), polychlorinated biphenyls (PCB), and metals.

3.3.2 AOC-65 Characterization Activities

<u>*Soil Gas Survey Results*</u>

A soil gas survey, performed in January and February 2001, revealed a PCE plume in the soils beneath and to the south and west of Building 90. The highest PCE concentrations were recorded in the vicinity of the former metal vault. A smaller TCE plume near the same area in Building 90 was also defined. In 2001, 14 borings were advanced in and around Building 90. Four of those borings were completed as five monitoring wells. Groundwater samples were collected from borings and monitoring wells, as available.

A total of 203 samples were collected around the exterior of Building 90. Sampling depths ranged from 0.5 to 4.5 ft with depth determined by refusal. Compounds detected outside Building 90 included *trans*-1,2-DCE, *cis*-1,2-DCE, TCE, and PCE. TCE concentrations ranged from 0.04 to 8.56 micrograms per liter (µg/L). PCE was detected in 67 samples at concentrations ranging from 0.08 to 1590 µg/L. The highest readings measured outside Building 90 correlate with the highest PCE levels measured inside the building near the former southern solvent vat. Identification of the PCE plume extending to the NE and SE of Building 90 suggests that PCE is in the fill material underlying the entire building, and that PCE has likely spread from the building into underlying soil, rock, and groundwater.

A total of 40 samples were collected inside Building 90. Soil gas samples were collected at depths of 1.0 to 2.5 ft with the depth of sampling determined by refusal. TCE and PCE were both detected inside the building. The sampling grid concentrated around the former metal solvent vault, the metal tank areas, and associated drainage lines. TCE was detected in five samples at concentrations ranging from 0.14 to 0.44 µg/L.

Confirming the conclusion that PCE is present in soil gas underlying the entire building, PCE was detected in every sample at concentrations ranging from 1.77 to 24,820 µg/L with maximum results concentrated around sample locations near the former metal solvent tank in the southern portion of the building. The highest levels of PCE inside matches the locations of contaminants in the plume area identified outside Building 90, particularly in the outside grid points closest to the building near the southern solvent vat location. PCE results measured near the inactive northern solvent vat location suggest that the potential for releases from this area were unlikely and that the fill material underlying this portion of the building contains similar levels of PCE as other non-impacted areas of the building.

An additional 77 samples were collected south of Building 90. Sampling depths ranged from 1 to 4 ft, with depth determined by refusal. No target VOCs were detected in this portion of the site.

The most significant finding of the soil gas survey was the detection of a PCE contaminant plume underlying Building 90 and extending primarily to the west and SW from the building. The detection of TCE and *cis*-1,2-DCE and *trans*-1,2-DCE at significantly lower levels than PCE suggest that some natural degradation of the PCE had already begun near the southern solvent vat, which has been identified as the most likely source area for the VOC contamination. PCE levels exceeded 24,000 µg/L inside the building near the former solvent vat, decreased to 1,590 µg/L approximately 25 ft from the building, and were not detected above 5 µg/L in any of the grid points located more than 50 ft from the building. Based on this result, it appears the lateral extent of the PCE plume in the soil gas is generally confined to the immediate vicinity of Building 90.

<u>Soil/Bedrock Investigation</u>

Investigations at the site began in 2000 when soil samples were collected underneath the former solvent vat area in Building 90, and a soil boring was advanced 15 ft down gradient of the building drain line terminus extending from Building 90. Surface samples collected beneath the former vat indicated the presence of PCE ranging from 1.74-3.74 mg/kg beneath the concrete slab.

In 2001, 14 borings were advanced in and around Building 90. Four of those borings were completed as monitoring wells. Groundwater samples were collected from borings and monitoring wells, as available. Soils in the area where the drainage line from Building 90 meets the drainage ditch and where borings were advanced contain the highest soil COC concentrations from the samples collected in this field effort. PCE, TCE, TPH-DRO (diesel-range organics), TPH-GRO (gasoline-range organics), Arochlor, and several metals (chromium, copper, zinc, lead, and cadmium) in the soils significantly exceeded soil Risk Reduction Standard 1 (RRS1) concentrations. However, in the bedrock sample (21.0 to 21.5 ft), lead, barium, chromium, and nickel only slightly exceeded background, suggesting that COCs are limited to the soil.

Other borings around AOC-65 contain considerably lower concentrations of the COCs than those encountered in the drainage line soil samples. Therefore, the lateral extent of PCE and the other COCs may be limited to the portion of the drain line, and the vertical extent appears to be limited to the near surface.

The presence of PCE in the subsurface, initially identified by the soil-gas survey, is confirmed and further defined by the surface, subsurface, and groundwater samples collected at AOC-65 and under Building 90. PCE is reported in excess of reporting limits (RLs) for soils under the former solvent vat area inside Building 90, along the drain line that runs from the former vat area to the drainage ditch, and in the soils south of the drainage line. These borings are within the limits of the PCE plume delineated by the soil gas survey.

The analyses of samples collected from bedrock generally reveal that VOCs are found only in soils above bedrock. The noted exception is adjacent to the former vat, where PCE was detected in limestone at 0.0499 mg/kg at 8.5 ft. This boring is located immediately outside of Building 90 adjacent to the area that contained the vat. This is the same area that recorded the highest concentrations of PCE in the soil gas plume.

Groundwater samples collected from both inside and outside the soil-gas survey plume contained PCE. Groundwater samples from MW-2A, located outside the soil gas survey plume and screened 9-19 ft in the bedrock, have contained PCE at levels ranging from 950-3,400 µg/L after a rainfall events, suggesting that PCE migration from near surface source areas into groundwater is a likely cause of the continued presence of VOCs in deeper groundwater samples collected at CSSA.

<u>*Geophysical Surveys*</u>

Geophysical investigations were performed to identify subsurface features such as fractures, faults, and karst dissolution that may be controlling the migration of contaminants. Identification of these features was used to direct installation of PZs and an SVE system near Building 90. The geophysical methods utilized at AOC-65 include electrical resistivity, microgravity, very low frequency (VLF), EM, shear-wave seismic reflection, induced polarization (IP), and spontaneous potential (SP). These methods were selected based on their ability to detect changes in physical properties associated with fractures, faults, and karst features. The surveys were implemented in a phased approach with the results of one phase providing direction for subsequent phases.

Of the methods utilized, electrical resistivity and seismic reflection provided the best results. The SP and VLF methods proved to be ineffective due to site conditions and distance from source signals. Microgravity did not identify significant features at the site and, based on subsequent drilling activities, it is believed the karst features present are too small to be detected using this method. The IP method did not produce useful results; however; some equipment problems during the surveys complicated the evaluation of this method.

Results of the resistivity surveys identified several anomalies in the area; however, subsurface conditions in the area complicated interpretation of the resistivity data and limited effectiveness of the method. Several anomalies detected were believed to be the result of faults present in the area.

Results of the high-resolution seismic survey identified several fault locations in the area. Several reflecting events on the seismic sections were correlated to known geologic contacts: Glen Rose/BS, BS/CC, and the CC/Hammett Shale. In addition several normal faults were interpreted at the depth of these horizons, based on offsets in the mapped horizons.

3.3.3 AOC-65 Interim Measures

IMs were implemented during 2002 to abate and reduce the amount of VOC contamination emanating from AOC-65. These activities included identification and removal of near-surface contamination and installation of two SVE systems. The investigative portion of the work focused on characterizing geologic conditions of the upper 150 ft of bedrock and included installation of six PZs, seven vapor extraction wells (VEW), seven vapor monitoring points (VMP) outside Building 90, and 12 VEWs inside the building. Drilling activities also included drilling 12 soil borings to characterize the extent of impacted soils west of the building and two 150-foot deep angle coreholes to gain further knowledge of geologic conditions west of the building.

Source Area Vapor Extraction System

From April 19-21, 2002, Parsons installed 12 VEWs inside Building 90 as sub-slab ventilation wells. Between April 26 and April 29, 2002, the 12 sub-slab ventilation wells were manifolded for eventual hookup to the SVE blower system located on the west dock outside Building 90. Initial soil gas screening data were obtained from VEWs installed inside Building 90 on December 3, 2002. A second round of soil gas screening and pressure response readings were taken on December 4, 2002, shortly after the SVE system was started. This was done to determine if there was any influence or response in the sub-slab VEWs. After these initial readings were taken, the sub-slab blower system inside Building 90 was started and soil gas changes were monitored over the initial hours following system startup. The air emission results from the sub-slab system indicated that the SVE system was operating within limits of the standard air exemption.

Exterior Soil Vapor Extraction System

On May 13, 2002 a subsurface investigation was performed at AOC-65 in conjunction with the SVE treatability study conducted to evaluate effectiveness of the SVE at reducing the volatile contaminants present in the subsurface materials at the site. Rock coring and borehole geophysical surveys were conducted to assist in characterizing subsurface conditions. Upon completion of coring and logging activities, seven VEWs, seven VMPs, and six PZs were installed in the boreholes. Borehole geophysical surveys were completed at some locations to aid in characterization of geologic conditions. In addition, two exploratory angle borings were completed to intercept fractures and faults in the area.

Selection of the locations for the VEWs, VMPs, and PZs were determined based on results of the geophysical surveys, primarily the electrical resistivity imaging data. Drilling locations were selected to intercept anomalies believed to represent potential fracture and fault locations identified in the geophysical data. The seven VEWs were piped and manifolded into a blower system (blowers, moister separator, vapor phase carbon treatment unit, and electrical controls) to extract soil gas from the subsurface.

Results of the rock coring and borehole geophysical surveys were used to characterize geology in the AOC-65 area. Based on drilling and borehole information, it was determined that approximately 30-40 ft of UGR Limestone material is present in the area. The UGR deposits consist primarily of limestone and marl layers with one distinct marl layer exhibiting dissolution features resulting from removal of anhydrite/gypsum material from the layer. The LGR Limestone underlies the UGR material and consists of a sequence of limestone deposits that include fossiliferous and vuggy zones of relatively high permeability at a depth of approximately 105 to 110 ft.

Geologic correlations from the core records and geophysical logs indicate at least three faults in the AOC-65 area between wells CS-MW06-CC to the north of Bldg 90 and CS-MW08-LGR to the south. The faults are believed to be normal faults associated with the BFZ with the upthrown block on the northern side of the fault. One fault, located north of Building 90, has an estimated 5-foot offset. A second, smaller fault was intersected during drilling at location AOC65-PZ05-LGR and exhibits an approximate 2-3 foot offset. Additionally, an approximate 15-foot offset was present between locations AOC65-PZ05-LGR and CS-MW08-LGR indicating that at least one fault is present between these two locations.

AOC-65 Soil Removal and Construction Upgrades

The IM activities also included removal of near-surface contamination identified during RCRA Facility Investigation (RFI) activities on the west side of Building 90. The objective was to remove the source area contamination associated with the former drain line and storm water conveyance within the AOC. Specific activities included defining the source area with several of shallow borings, excavation and removal of contaminated soils, and engineering controls to minimize the amount of precipitation recharge that infiltrates within the source zone.

Drilling outside Building 90 (maximum depth of 4 ft) to delineate the extent of shallow contamination was initiated May 6, 2002. Results of the boring program defined a small area associated with the drain line to be contaminated in addition to near-surface soils within the stormwater conveyance. These impacted soils were removed to mitigate the total contaminant mass available for transport from the source zone.

Approximately 1,000 tons (600 CY) of impacted soil were excavated from along a drain line and drainage ditch west of Building 90. Soil samples were collected from the excavation for verification analysis to document concentrations remaining in the soils. The excavation in the parking lot was backfilled with gravel and re-surfaced with asphalt. The drainage ditch north and west of the building was rebuilt with a concrete liner to prevent water from infiltrating he suspected source area. In addition, roof gutters along the west side of the building were reconfigured to divert water away from the building and the source area.

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SECTION 4
HYDROGEOLOGIC CONCEPTUAL SITE MODEL DEVELOPMENT

4.1 BASIS OF MODEL

4.1.1 Data Input Types

The HCSM is a compilation of both quantitative and qualitative data types that are evaluated and integrated into a physical description that represents the known environmental conditions. For this report, the HCSM will be described as a function of geologic, hydrologic, meteorological conditions observed at CSSA. These controlling factors contribute greatly to the fate and transport of contaminants within the subsurface.

Because of the varying sources of data types and usability within the model, criteria were established which defined when and how a particular data set were implemented. For instance, a lithologic coring log that had been surveyed to a georeferenced datum is considered quantitative data. However, a lithologic log from a drilling report is considered qualitative since the borehole description was based upon visual inspection of the drilling mud at less then approximate depths by non-geologist personnel. Another example of qualitative data would be the obtaining of a water level measurement below top of casing (quantitative), however the measuring point has never been georeferenced (x, y, and z) thus rendering the data as qualitative with respect to a datum. The following paragraphs describe the types of data used to develop the model, and notes when data inputs were qualitative or quantitative.

<u>Geologic Inputs</u>

The basic framework of the HCSM is dictated chiefly by the geologic character of the site. Geologic inputs include physical characteristics such as soils, lithology, mineralogy, permeability, and porosity. Other contributing factors also include geomorphology (*e.g.;* landforms, recharge areas, etc.) and structural effects (*e.g.;* faulting, karst development, etc.). Ultimately, it is the geological environment that dictates the occurrence of aquifers, the rate of meteoric and surface water infiltration, and the nature of groundwater and contaminant movement through the subsurface.

Section 2.2 described the environmental setting at CSSA with respect to general geology and stratigraphy. The soils at CSSA have been mapped by the NRCS, and are described in Section 2.2.1. While the soil units at CSSA are normally very thin, most SWMUs and AOCs are land disposal units within the soil profile. However, for the hydrologic HCSM, the soil profile is so thin in comparison to the geologic units, it is believed to have little bearing on the fate and transport of contaminants.

The surface geology was mapped by the USGS in 2003, and the report is considered the definitive work in the study area. Earlier mapping performed by Parsons in 1996 is mostly corroborated by the USGS effort. For the purpose of this report, the map presented in Figure 4.1 will be considered the upper bounding (top) surface of the HCSM. In the same effort by the USGS, the major structural controls were also identified and mapped on Figure 4.1. The location and orientation of the faults will define the major geologic blocks present at the facility.

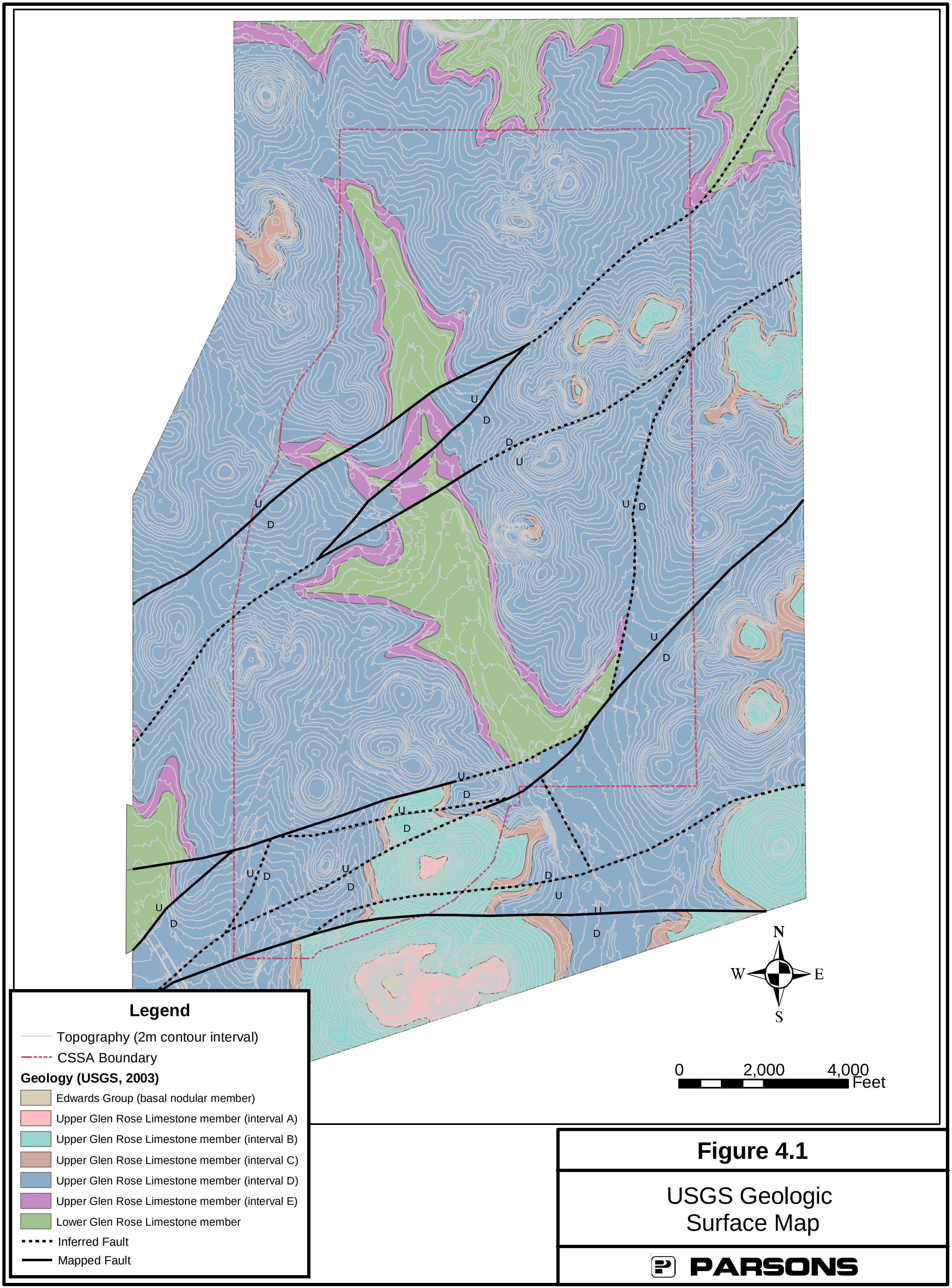

Figure 4.1

USGS Geologic
Surface Map

PARSONS

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It should be noted that the faults indicated on Figure 4.1 represent fault zones with many breaks of small displacement, rather than a single displacement of many tens of ft. While Parsons has been able to identify a multitude of fault planes over very localized areas (*e.g.,* AOC-65), their localized individual occurrences are not identified in the regional HCSM.

The primary method for defining the subsurface geology is from well logs. In 1999, as many as 140 wells were tentatively identified to exist within 1-mile of the CSSA facility. For the most part, these off-post wells are privately-owned domestic wells, or public wells located at commercial or municipal properties. Through 2007, the number of wells has increased along with the growing population in the Boerne vicinity. For most of these wells, subsurface data are incomplete, inconsistent, or non-existent. For these reasons the geologic subsurface data usability for most of the privately or publicly-held wells is considered low and are therefore excluded from this HCSM. Exceptions to this rule include those offsite wells from which geophysical data has been collected by CSSA, the EAA, or municipality contractors to Fair Oaks Ranch. The availability of geophysical logs from such locations allow for accurate correlations to be extended from CSSA to those outlying areas.

Since 1996, CSSA has performed several subsurface investigations that have dramatically refined the knowledge of the Middle Trinity aquifer near the post. Through April 2007, 37 new monitoring wells that penetrate to the LGR water bearing unit of the Middle Trinity aquifer or beyond have been installed at CSSA. Most of these well locations have been continuously cored, and all have been geophysically logged and land surveyed. These monitoring wells have been drilled in such a manner that their data are considered quantitative, and it forms the major premise for which the HCSM is based. In addition, most of the existing active or inactive water wells on-post have been evaluated, geophysically logged, and georeferenced by a land surveyor. The geophysical data allows for accurate correlations with the monitoring wells, and thus considered as usable geologic data for the HCSM. Two existing wells (MW-1 and MW-2) were re-completed to match screened intervals on the new monitoring wells. Table 4.1 lists the geological data collected or inferred from area well logs.

Meteorological Inputs

The primary meteorological input into the HCSM is groundwater recharge via precipitation. Precipitation data has been obtained from various sources in the vicinity. The National Weather Service maintains records for many municipalities throughout the United States. The dates of record used for this HCSM include 1971 through 2000 from weather stations in Boerne, TX (#410902). CSSA also operates two weather stations on-post. The northern weather station is located next to well CS-16-LGR, and has been in service since 1998. Likewise, the southern weather station is located west of Building 90, and has been operating only since February 2003. For this HCSM, a range of quantitative precipitation values for recharge will be based upon values from the Boerne #410902 and the CS-16-LGR weather stations.

Hydrologic Inputs

The hydrologic data for the HCSM is derived from both literature values and data collected on-site through investigation. Quantitative values regarding the aquifer properties have been directly computed from data gathered during pumping tests performed at wells CS-10, CSMW16-CC, and CS-16-LGR (formerly CS-16). From these tests, ranges of aquifer yield,

Table 4.1
Summary of Geological Data from Model-Area Well Logs

Well ID		NORTHING	EASTING	GROUND ELEVATION	TOC ELEVATION	Depth to Geologic Contact (ft bgs)			
		(UTM -Meters)	(UTM -Meters)	(Feet -MSL)	(Feet -MSL)	UGR/LGR	LGR-BS	BS-CC	CC-HS
CSSA MONITORING WELLS	CS-MW1-LGR	3,286,287.934	537,050.608	1,217.40	1,219.02	0	319.5	-	-
	CS-MW1-BS	3,286,286.231	537,067.858	1,218.46	1,221.09	0	319.5	379.5	-
	CS-MW1-CC	3,286,287.112	537,060.274	1,218.82	1,221.39	0	319.5	379.5	455
	CS-MW2-LGR	3,286,205.860	537,443.645	1,233.81	1,235.43	27	345	-	-
	CS-MW2-CC	3,286,207.172	537,454.016	1,237.73	1,240.11	27	345	406	479?
	CS-MW3-LGR	3,286,863.994	538,074.690	1,329.43	1,332.45	118	432	-	-
	CS-MW4-LGR	3,285,687.243	537,515.207	1,205.30	1,207.84	0	324	-	-
	CS-MW5-LGR	3,286,213.380	537,702.483	1,335.47	1,338.51	128	448	-	-
	CS-MW6-LGR	3,283,882.516	535,709.218	1,227.68	1,230.56	37	368	-	-
	CS-MW6-BS	3,283,877.935	535,704.412	1,228.08	1,230.82	37	368	427	-
	CS-MW6-CC	3,283,873.298	535,699.410	1,228.50	1,231.43	37	368	427	505
	CS-MW7-LGR	3,283,611.456	535,882.466	1,197.65	1,200.52	68	352	-	-
	CS-MW7-CC	3,283,593.031	535,883.400	1,197.35	1,200.01	68	352	413	489
	CS-MW8-LGR	3,283,575.328	535,693.675	1,203.95	1,206.49	53	361	-	-
	CS-MW8-CC	3,283,554.121	535,691.860	1,201.55	1,204.38	53	361	424	496
	CS-MW9-LGR	3,287,263.387	536,799.627	1,252.76	1,255.58	5	326	-	-
	CS-MW9-BS	3,287,255.143	536,802.707	1,252.28	1,254.99	5	326	385	-
	CS-MW9-CC	3,287,247.344	536,805.242	1,251.58	1,254.27	5	326	385	457
	CS-MW10-LGR	3,283,209.158	535,673.470	1,184.97	1,187.68	67	394.5	-	-
	CS-MW10-CC	3,283,185.989	535,674.679	1,185.46	1,188.20	85	394.5	455.5	528
	CS-MW11A-LGR	3,283,387.196	536,257.579	1,201.24	1,204.03	116	448	-	-
	CS-MW11B-LGR	3,283,382.350	536,253.156	1,200.88	1,203.52	116	-	-	-
	CS-MW12-LGR	3,286,057.765	536,451.946	1,256.40	1,259.07	34	358	-	-
	CS-MW12-BS	3,286,049.657	536,451.242	1,255.44	1,258.37	34	358	417	-
	CS-MW12-CC	3,286,041.508	536,450.706	1,254.73	1,257.31	34	358	417	494
	CS-MW16-CC	3,286,844.086	537,277.448	1,241.97	1,244.51	19	325	384	468
	CS-MW17-LGR	3,285,314.293	538,177.981	1,254.01	1,257.01	66	393	-	-
	CS-MW18-LGR	3,284,664.459	536,037.378	1,280.62	1,283.61	85	413.5	-	-
	CS-MW19-LGR	3,285,425.697	536,650.954	1,252.71	1,255.53	40	365	-	-
	CS-MW20-LGR	3,285,210.644	537,111.877	1,206.67	1,209.42	6	331	-	-
	CS-MW21-LGR	3,284,950.017	537,618.542	1,181.90	1,184.53	NA	316	-	-
	CS-MW22-LGR	3,284,436.585	537,163.077	1,277.33	1,280.49	94	422	-	-
	CS-MW23-LGR	3,284,027.777	536,199.409	1,255.71	1,258.20	68	402	-	-
	CS-MW24-LGR	3,286,837.705	536,797.414	1,250.81	1,253.90	16	328	-	-
	CS-MW25-LGR	3,287,052.589	537,652.534	1,290.31	1,293.01	74	385	-	-
	CS-MWH-LGR	3,288,741.135	536,634.309	1,316.01	1,319.19	27	365	-	-
WATER WELLS	CS-1	3,284,051.974	537,981.325	1,166.73	1,169.27	NA	NA	489	570
	CS-2	3,286,508.539	536,734.986	1,234.40	1,237.59	4	330	-	-
	CS-3	3,286,559.841	536,766.642	1,236.87	1,240.17	NA	NA	NA	NA
	CS-4	3,286,561.387	536,924.813	1,225.66	1,229.28	NA	NA	NA	NA
	CS-9	3,285,042.323	535,877.879	1,324.05	1,325.31	NA	442	502	-
	CS-10	3,285,222.523	535,990.386	1,329.59	1,331.51	NA	445	505	-
	CS-11	3,285,382.682	535,824.765	1,330.91	1,332.49	122	448	506	-
	CS-16-LGR	3,286,841.192	537,285.897	1,241.59	1,244.60	19	325	-	-
	CS-D	3,286,839.895	537,147.068	1,233.31	1,236.03	-	-	-	-
	CS-G	3,288,139.147	537,134.055	1,325.13	1,328.14	55	-	-	-
	CS-I	3,288,359.354	538,556.568	1,312.94	1,315.20	52	368	NA	NA
AOC-65 WELLS	AOC65-VMP1	3,283,761.410	535,701.190	1,217.10	NA	36	-	-	-
	AOC65-VMP2	3,283,710.900	535,702.240	1,217.40	NA	37	-	-	-
	AOC65-VMP3	3,283,701.630	535,684.630	1,216.00	NA	36.5	-	-	-
	AOC65-VMP4A	3,283,720.850	535,689.160	1,216.80	NA	36.5	-	-	-
	AOC65-VMP5	3,283,726.260	535,732.420	1,216.80	NA	36.5	-	-	-
	AOC65-VMP6	3,283,683.200	535,685.820	1,214.50	NA	38	-	-	-
	AOC65-VMP7	3,283,811.030	535,672.380	1,228.30	NA	37	-	-	-
	AOC65-PZ1	3,283,735.988	535,671.094	1,222.10	1,224.11	40	-	-	-
	AOC65-PZ2	3,283,607.762	535,671.114	1,209.20	1,211.28	35	-	-	-
	AOC65-PZ3	3,283,834.013	535,671.764	1,232.27	1,234.39	36.5	-	-	-
	AOC65-PZ4	3,283,838.547	535,671.928	1,232.37	1,234.46	36.5	-	-	-
	AOC65-PZ5	3,283,603.005	535,671.032	1,208.86	1,210.97	35	-	-	-
	AOC65-PZ6	3,283,740.738	535,671.118	1,222.52	1,224.60	40	-	-	-

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Table 4.1
Summary of Geological Data from Model-Area Well Logs

Well ID		NORTHING	EASTING	GROUND ELEVATION	TOC ELEVATION	Depth to Geologic Contact (ft bgs)			
		(UTM -Meters)	(UTM -Meters)	(Feet -MSL)	(Feet -MSL)	UGR/LGR	LGR-BS	BS-CC	CC-HS
WESTBAY WELLS	CS-WB01	3,283,552.968	535,712.781	1,203.97	1,206.00	55	NA	NA	NA
	CS-WB02	3,283,619.881	535,693.987	1,218.55	1,220.42	43	NA	NA	NA
	CS-WB03	3,283,706.512	535,687.504	1,217.20	1,219.08	35	NA	NA	NA
	CS-WB04	3,283,519.471	535,402.031	1,221.82	1,223.09	48	377	440	510
	CS-WB05	3,286,787.53	537,323.36	1,240.19	1,242.93	17	334	393.5	469
	CS-WB06	3,286,580.07	537,304.50	1,232.31	1,235.20	17	330	-	-
	CS-WB07	3,286,696.33	537,283.75	1,233.15	1,235.13	13	330	-	-
	CS-WB08	3,286,689.26	537,397.17	1,251.86	1,253.26	35	347	-	-
OFFSITE WELLS	FO-1	3,290,813	536,398	1,263	NA	NA	200	240	330
	FO-2	3,288,969	536,053	1,351	NA	70	380	442	514
	FO-3	3,288,955	535,433	1,437	NA	138	458	526	608
	FO-4	3,288,924	535,406	1,435	NA	NA	NA	525	NA
	FO-5	3,287,693	535,625	1,323	NA	NA	NA	454	NA
	FO-6	3,288,277	535,300	1,445	NA	NA	NA	555	NA
	FO-7	3,288,321	536,387	1,314	NA	NA	NA	423	NA
	FO-8	3,287,613	536,356	1,323	NA	NA	NA	447	NA
	FO-9	3,289,554	536,383	1,316	NA	NA	NA	477	NA
	FO-10	3,290,977	536,411	1,282	NA	NA	NA	339	NA
	FO-11	3,288,105	534,089	1,395	NA	NA	NA	425	NA
	FO-12	3,290,287	536,405	1,254	NA	NA	NA	328	NA
	FO-13	3,287,260	534,954	1,424	NA	NA	NA	560	NA
	FO-14	3,290,072	536,393	1,272	NA	NA	NA	347	NA
	FO-15	3,287,561	534,361	1,440	NA	NA	NA	571	NA
	FO-16	3,287,310	533,788	1,315	NA	NA	NA	453	NA
	FO-17	3,284,721	534,438	1,220	NA	NA	320	383	NA
	FO-18	3,290,172	535,600	1,264	NA	NA	NA	309	NA
	FO-19	3,291,218	536,459	1,262	NA	NA	NA	325	NA
	FO-20	3,289,244	536,379	1,327	NA	NA	NA	416	NA
	FO-21	3,288,864	536,384	1,310	NA	NA	NA	404	NA
	FO-22	3,287,277	536,124	1,304	NA	NA	NA	428	NA
	FO-23	3,289,015	535,164	1,373	NA	NA	NA	470	NA
	FO-24	3,288,463	535,595	1,370	NA	NA	NA	NA	NA
	FO-25	3,286,933	533,847	1,271	NA	NA	NA	428	NA
	FO-26	3,286,829	533,859	1,302	NA	NA	NA	439	NA
	FO-27	3,287,013	534,633	1,378	NA	NA	NA	511	NA
	FO-28	3,286,275	534,743	1,299	NA	NA	NA	450	NA
	FO-29	3,291,350	536,340	1,277	NA	NA	NA	239	NA
	FO-30	3,290,904	536,096	1,262	NA	NA	NA	324	NA
	FO-31	3,290,831	536,223	1,258	NA	NA	NA	315	NA
	FO-32	3,288,987	534,984	1,431	NA	NA	NA	474	NA
	FO-J1	3,284,810	535,480	1,268	NA	NA	NA	448	NA
	JW-8	3,284,954	535,466	1,270	NA	70	396	458	534
	I10-2	3,283,404	535,115	1,165	NA	0	315	384	459
	LS-7	3,283,140.991	535,627.419	1,179.39	1,181.73	63	388	-	-
	OFR-2	3,284,063	535,047	1,200	NA	0	-	-	-
	RFR-10	3,283,530.660	535,354.186	1,226.36	1,228.16	53	369	433	-

UTM = Universal Transverse Mercator

TOC = Top of casing

NA = Not Available/Not Interpretable

- = Strata not penetrated

This format is consistent with the format used by the CSSA GIS/database.

x,y (UTM-meters: NAD 1983-Zone 14), z (feet MSL-NGVD 1929) transmissivity, and storativity have been estimated. Drill-stem packer tests have also been performed at discrete locations within the aquifer to provide qualitative estimations regarding the aquifer hydraulic conductivity. These tests were particularly useful in demonstrating the inherent heterogeneity of the aquifer matrix.

Aquifer water levels have been obtained on a quarterly basis since September 1999 from the wells located on-post. These quantitative measurements are used to estimate the horizontal and vertical flow of groundwater throughout the aquifer. Horizontal flow rate and direction are determined by standard gradient calculations. The vertical flow component is empirically-derived by evaluating hydraulic head differences within well clusters through the use of flow nets. For the report, typical data sets that represent seasonal fluctuations have been selected to represent the groundwater flow regime.

The process of groundwater recharge has not been studied at CSSA, but multiple studies regarding regional aquifer recharge and discharge have been performed over the Middle Trinity aquifer. Much of this work has been utilized in the TWDB publication, *"Groundwater Availability of the Trinity aquifer, Hill Country Area, Texas: Numerical Simulations through 2050."* The assumption and values calculated by the TWDB numerical model will be implemented in the CSSA HCSM until such time more site-specific values are generated.

Contaminant Concentration and Distribution Inputs

On-post groundwater sampling has been performed since 1992, and on a routine quarterly schedule since September 1999. Beginning December 1999, off-site monitoring began at both private and publicly-owned wells. Following the detection of chlorinated solvents at off-post locations, a well installation program was initiated in November 2000. Since that time, 37 new monitoring wells within the Middle Trinity aquifer have been installed on-post. Through 2007, a total of 40 off-post locations, both public and private, have also been sampled for VOC contamination.

In May 2005, CSSA pursued a Long-Term Monitoring Optimization (LTMO) evaluation to streamline the basewide groundwater sampling program (see the CSSA Environmental Encyclopedia (**Volume 5-1.1, Three-tiered LTMA Evaluation**). By this process, a total of 139 sampling points at CSSA were evaluated using qualitative hydrogeologic information, temporal statistical techniques, and spatial statistics to evaluate the overall benefit to the groundwater program. As each tier of the evaluation was performed, monitoring points that provide relatively greater amounts of information regarding the occurrence and distribution of COCs in groundwater were identified, and were distinguished from those monitoring points that provide relatively lesser amounts of information. The results of the evaluations were combined to generate a refined monitoring program that could potentially provide information sufficient to address the primary objectives of monitoring, at reduced cost. Monitoring wells not retained in the refined monitoring network could be removed from the monitoring program with relatively little loss of information.

For the on-post and off-post wells, the LTMO results indicated that a refined monitoring program consisting of the same 88 wells sampled less frequently (33 wells sampled biennially, 28 sampled annually, 16 sampled annually, and 7 sampled quarterly) would be adequate to address the two primary objectives of monitoring:

1. Evaluate long-term temporal trends in contaminant concentrations at one or more points within or outside of the remediation zone, as a means of monitoring the performance of the remedial measure (*temporal objective*); and
2. Evaluate the extent to which contaminant migration is occurring, particularly if a potential exposure point for a susceptible receptor exists (*spatial objective*).

The LTMO approach was reviewed and approved by the TCEQ and EPA, and was initiated in December 2005. This refined on and off-post monitoring network resulted in an average of 104.5 (49.5 on-post and 55 off-post) well-sampling events per year, compared to 242 (120 on-post and 122 off-post) well-sampling events per year under the pre-December 2005 monitoring program. Implementing these recommendations for optimizing the monitoring program at CSSA reduced the number of on- and off-post well-sampling events per year by approximately 57 percent and the Westbay multi-port sampling events per year by approximately 88 percent.

For the HCSM, only the most recent data has been included in constructing contaminant concentration and distribution representations. Prior to the year 2001, the data set was much smaller. However, historical maximum concentrations and aerial distribution will be discussed. The chemistry data used from the groundwater sampling events is quantitative due to the rigorous quality assurance/quality control (QA/QC) and data validation procedures currently in place with the AFCEE and CSSA Quality Assurance Program Plans (QAPPs). Some screening data obtained during drilling (discrete interval groundwater sampling) is also used to delineate vertical distribution within the aquifer. While these data has not been validated, its usability is considered high because the laboratory used the same procedures to analyze the samples.

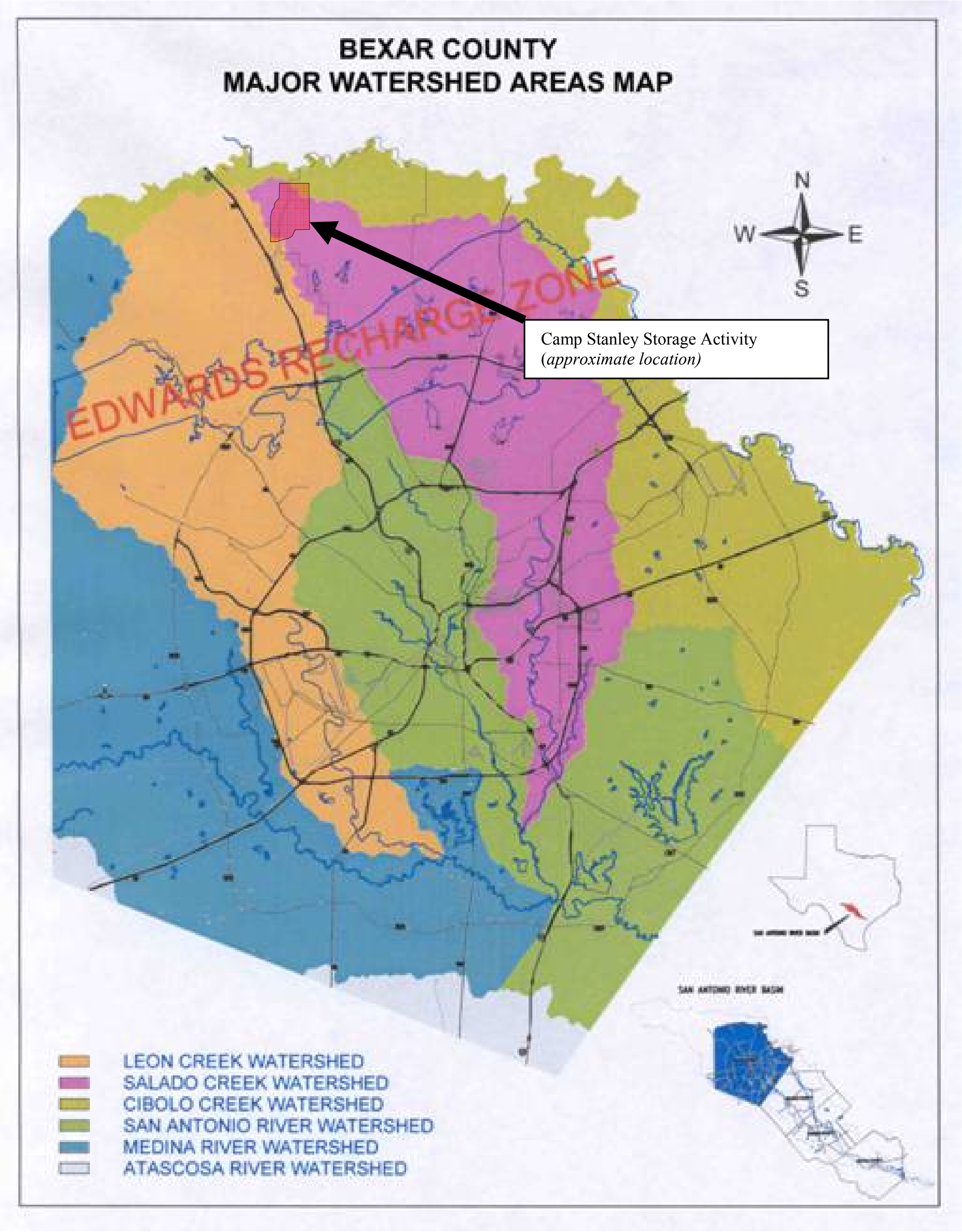
4.1.2 Watershed Identification

A major step in preparing a HCSM is to define the extents and boundaries of the study area. Many factors come into play in this definition; namely the amount and distribution of data. In calculating hydrologic budget, the overwhelming factor is normally defining the extent of the watershed. This is also important since many aquifer characteristics in terms of recharge and discharge are implicitly related to the local watershed. In addition to the watershed effects, the limits of the model also consider the lateral extent of VOC contamination. Therefore, the model will be defined by the maximum extent of contamination within a mapped subunit of a watershed.

At CSSA, three major watersheds are intersected by the property boundary. The most dominant is the Salado Creek watershed, which drains approximately 75 percent of the CSSA property from the central and eastern portions of the facility. Plume 1 is found almost exclusively within the Salado Creek watershed. Likewise, Plume 2 is located exclusively within the Leon Creek watershed to the SW. The Leon Creek watershed receives flow from approximately 11 percent of the base. Finally, 14 percent of the NE quadrant flows towards the north within the Cibolo Creek watershed. At this time, groundwater contamination is not known or suspected within this watershed at CSSA.

A regional watershed map is presented in Figure 4.2. This figure shows all of the watersheds near CSSA. The Salado and Leon Creek drainages trend towards the SE, while the Cibolo Creek watershed drains toward the east.

Figure 4.2 Watersheds of the San Antonio River Basin



Camp Stanley Storage Activity
(*approximate location)*

4.1.3 Defining the Limits of the Study Area

For the purposes of this report, the model coverage extends beyond the CSSA property boundary and areas of known off-post contamination. Figure 4.3 illustrates the HCSM limits as dictated by the previous parameters. To the NW, the HCSM is bounded by the headwaters of the Salado Creek drainage, the Cibolo Creek watershed bounds the model to the north and NE. Again, to the south, SE, and east, the HCSM is bounded by the watersheds of Salado Creek tributaries that extend well into Camp Bullis. Finally, portions of the Leon Creek watershed define the southwestern and western extent of the model in areas of known offsite contamination.

4.1.4 Regional Groundwater Movement

According to the TWDB (Report 353, September 2000), water levels in the aquifers generally follow topography with higher water-level elevations coinciding with higher land-surface elevations and lower water-level elevations coinciding with lower land-surface elevations. Their report cites that water levels in this area are a subdued representation of surface topography due to recharge in the uplands and discharge in the lowlands. Water-level maps indicate that water levels are influenced by the location of rivers and springs.

Water flows from higher water-level elevations toward lower water-level elevations. Water-level maps show that regional groundwater flow is from the NW toward the SE except where there is local flow to streams and springs and where the flow is from the SW to the NE in Comal and Travis counties. Water level maps also show that groundwater in the Upper and Middle Trinity aquifers (Figures 4.4 and 4.5) flows out of the study area to the SE in the direction of the Edwards BFZ Aquifer.

Over the past twenty years, water levels have generally declined in the Middle Trinity aquifer in Kerr, Kendall, Bandera, and Bexar Counties and risen, at least locally, in central Gillespie County.

4.2 DEFINITION OF HYDROSTRATIGRAPHIC UNITS

As previously mentioned, the geologic framework is critical to the hydrologic regime. An accurate description of the geologic factors is important to understand how and where groundwater and/or contamination are likely to occur. As described in Section 4.1.1, the geologic framework of the model is composed of surface geologic mapping along with subsurface investigations through drilling or geophysics. The results of these studies have resulted in the combined stratigraphic model presented in Figure 4.6.

The uppermost surface of the HCSM consists of the topographic landforms and the outcropping geologic units. Figure 4.1 illustrates the upper bounding unit of the HCSM as mapped by the USGS in the summer of 2003. As shown in the figure, the UGR member crops out over more than 89 percent of the CSSA facility.

The LGR outcrops are limited to the streambed and floodplains along Salado Creek and its tributaries within the central and northern portions of the facility. The LGR outcrop accounts for nearly 11 percent of the exposed rock at CSSA. However, since the overlying UGR member is relatively thin, it usually occurs within 50 ft of land surface, depending on elevation of the location.

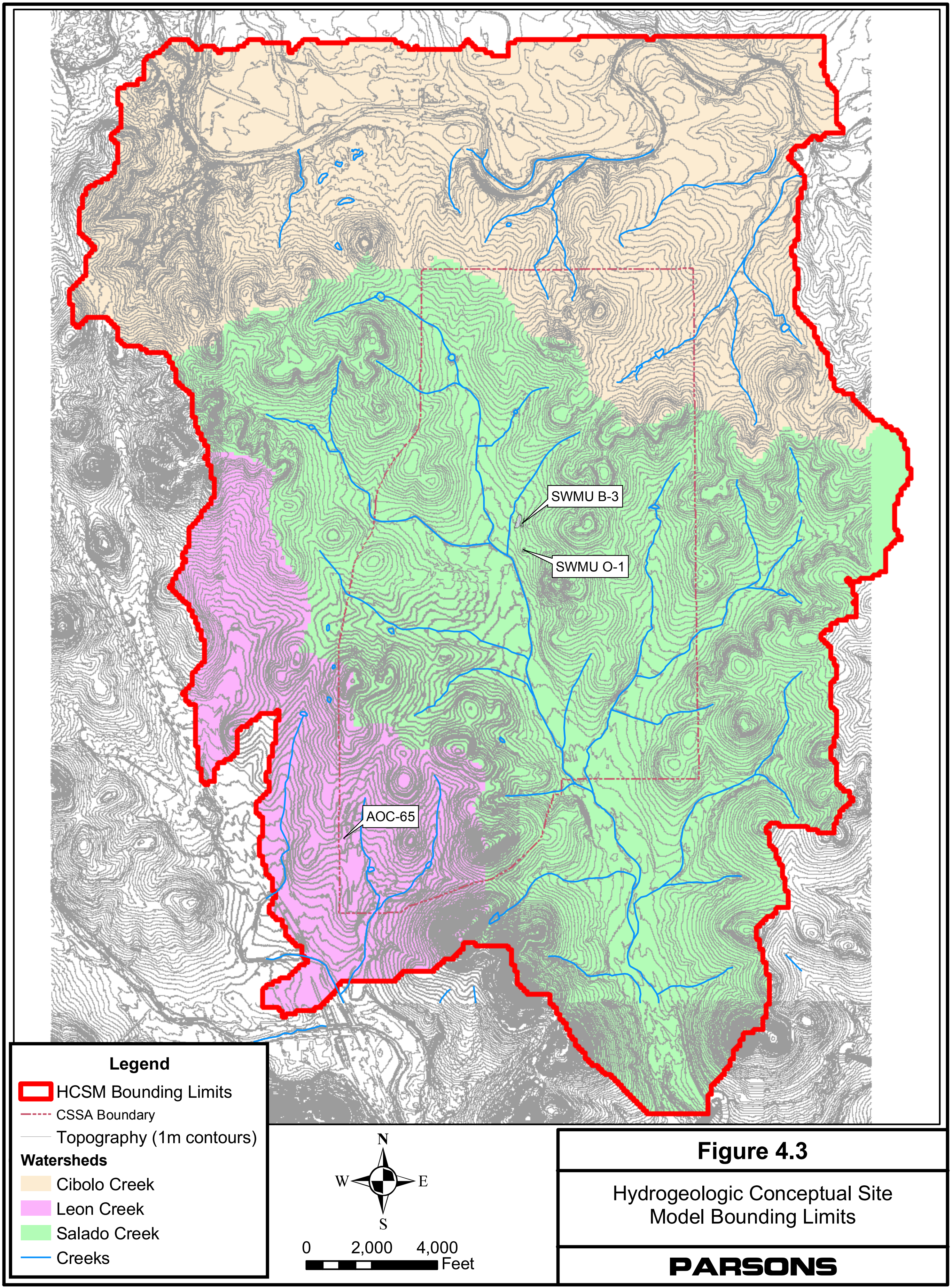


Figure 4.3

Hydrogeologic Conceptual Site Model Bounding Limits

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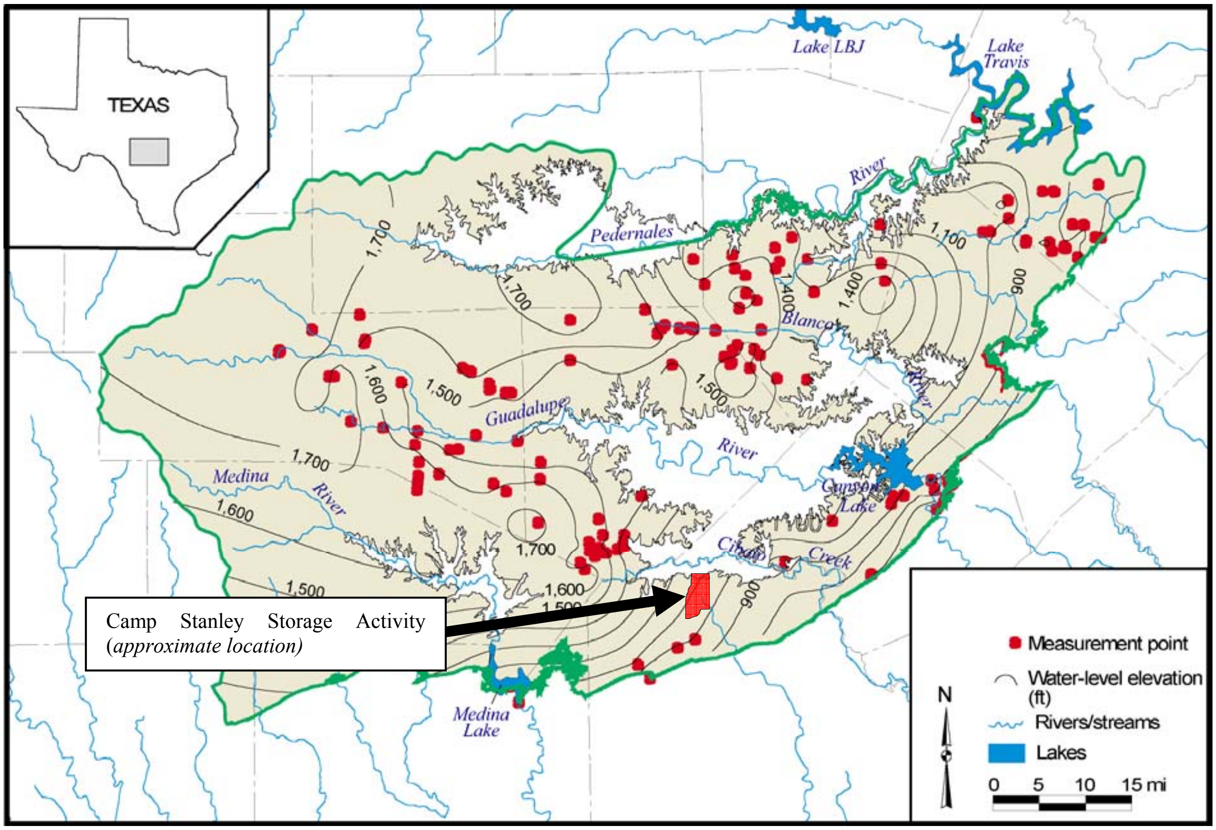
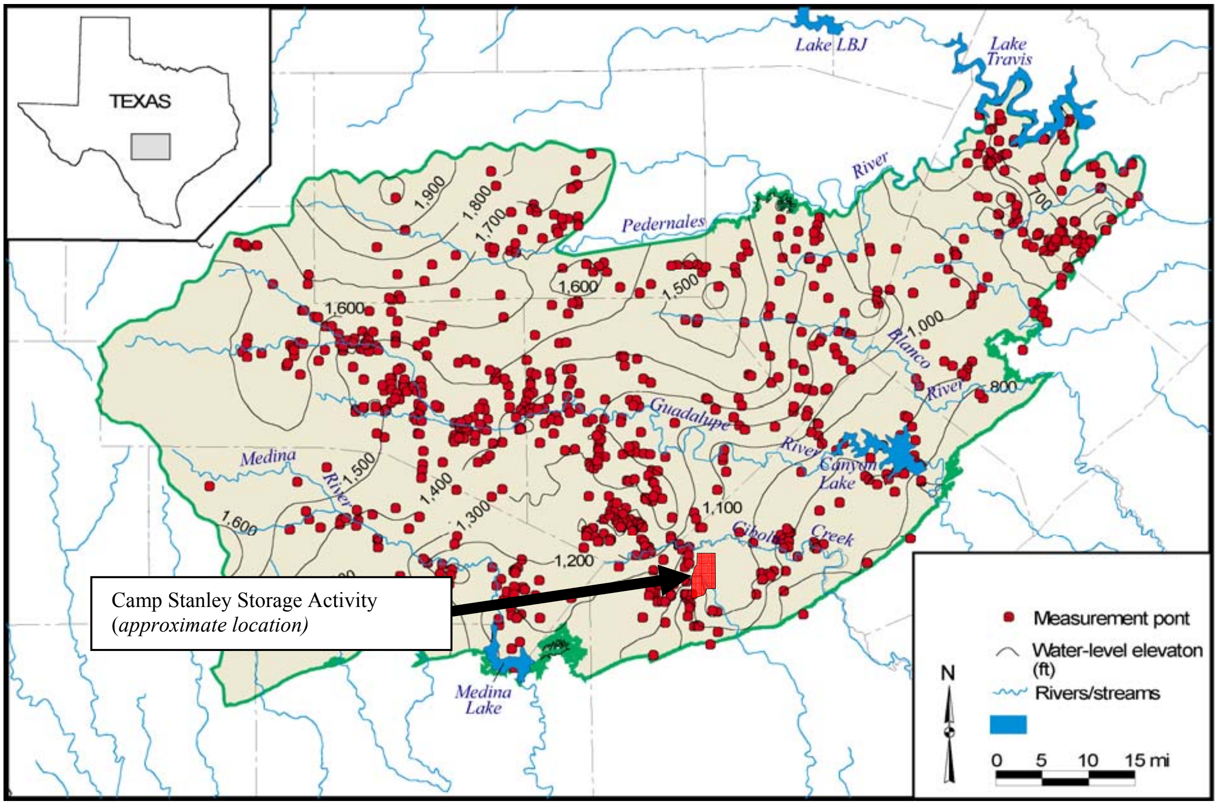
Figure 4.4 Water-level Elevations in the Upper Trinity Aquifer (includes water-level measurements from 1965 to 1985)



Camp Stanley Storage Activity (*approximate location)*

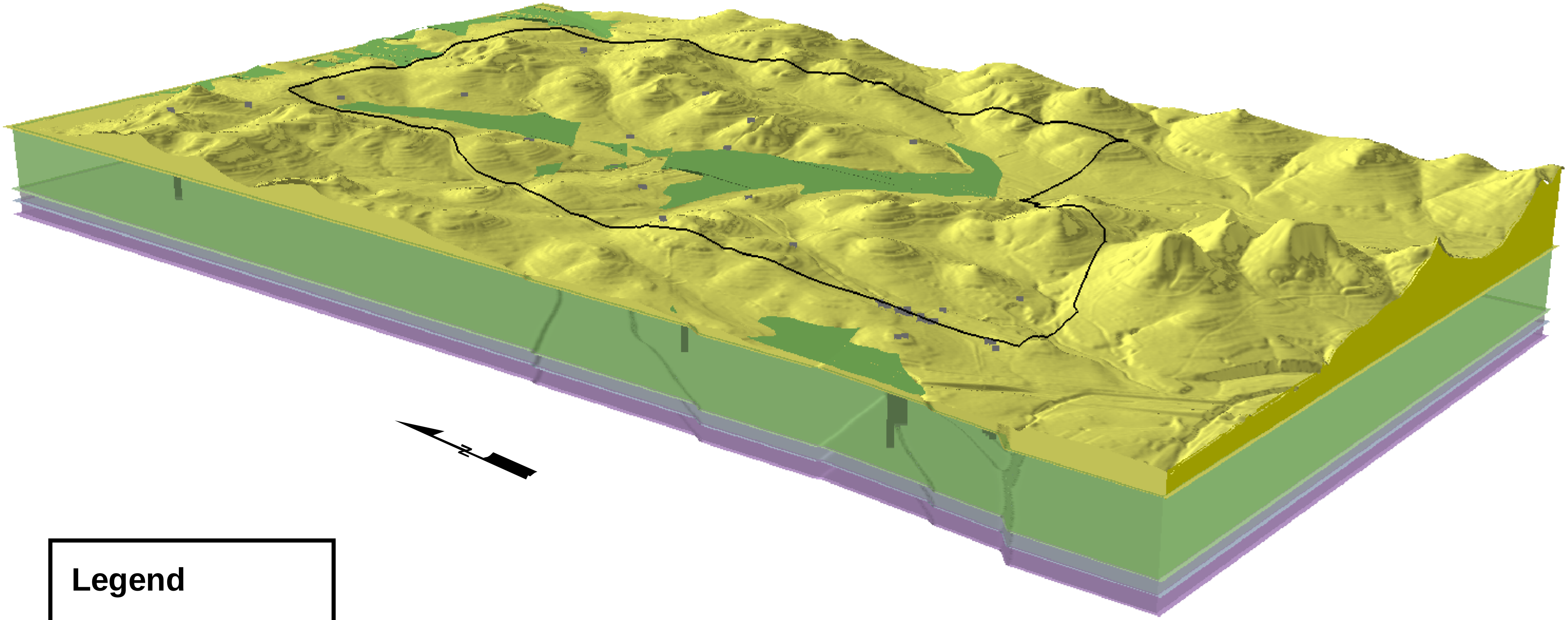
(modified after TWDB Report 353, September 2000)

Figure 4.5 Water-level Elevations in the Middle Trinity Aquifer (includes water-level measurements from 1965 to 1985)



Camp Stanley Storage Activity
(*approximate location)*

(modified after TWDB Report 353, September 2000)



Legend

Stratigraphy

🟨 Upper Glen Rose

🟩 Lower Glen Rose

🟦 Bexar Shale

🟪 Cow Creek

Vertical Exaggeration: 5X

Figure 4.6

Combined Stratigraphic
Model of CSSA

PARSONS

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The carbonate-rock classification system of Dunham (1962) was used for the lithologic descriptions made by both Parsons and the USGS during their independent field efforts. Classification of limestone and dolostone is based on rock texture and includes (from coarse- to fine-textured) grainstone, packstone, wackestone, and mudstone. In addition, the USGS implemented the sedimentary carbonate classification system of Choquette and Pray (1970) to characterize porosity type. Choquette and Pray classified carbonate-rock porosity as either “fabric selective” or “not fabric selective.” Porosity that reflects the depositional or (usually early) diagenetic elements of a sedimentary rock and tends to form along specific lithostratigraphic horizons is termed “fabric selective.” Fabric selective porosity includes interparticle, intraparticle, intercrystalline, moldic, and fenestral. Porosity that results (usually later) from structural or solutional processes within or across lithostratigraphic horizons is termed “not fabric selective.” “Not fabric selective” porosity includes vugs, channel fractures, and caverns. Breccia porosity is a subcategory of interparticle porosity that can be either fabric selective or not fabric selective. Both types of porosity can evolve into appreciable permeability, depending on rock type and conditions over geologic time.

4.2.1 Upper Glen Rose (Upper Trinity aquifer, Layer 1)

At CSSA, the exposed rock unit over most of the facility is the UGR. Work by others in the area indicates that the full thickness of the UGR member is approximately 450 ft thick. However, much of this thickness has been significantly, if not completely, eroded away from CSSA. The thickest sequence of UGR exists in the southern portion of the post at Schasse Hill, where there is as much as 400 ft of UGR Limestone. The full thickness of the UGR is present just south of the post at Hidden Springs Estates, which is capped by the basal section of the Edwards Group. Figure 4.7 shows the exposed surface of the UGR Limestone and the locations where the full thickness of the UGR exists.

Through April 2007, the environmental investigations performed at CSSA have been conducted in the portions of the post where the UGR thickness ranges from 0-128 ft, with an average thickness of nearly 50 ft. Figure 4.8 interpolates the base of the UGR based upon drilling data.

The following hydrostratigraphic description is based upon work performed by the USGS, in which the UGR member has been informally divided into five mappable units within Camp Bullis and CSSA. For this report, the UGR Limestone (has been subdivided into five intervals (UGR[A-E]), as described below from youngest to oldest. Exposures of units UGR(A, B, and C) are limited to the very highest elevations within the post, with unit A only being present atop Schasse Hill at the southern edge of CSSA. The lower two units, UGR(D and E), comprise over 83 percent of the outcrop at CSSA.

Interval UGR(A) (after USGS, 2003)

Interval UGR(A) is an approximately 120-ft-thick interval composed of alternating and interfingering medium-bedded mudstone to packstone, with evaporites occurring locally. Interval UGR(A) has been referred to as the “cavernous zone” (GVA, 2000) because of an abundance of caves in the interval. GVA has mapped the occurrence of caves throughout the Glen Rose Limestone in south-central Texas and has graphically demonstrated the increase in abundance of caves in this interval (relative to Interval UGR[B]). Well-developed “not fabric

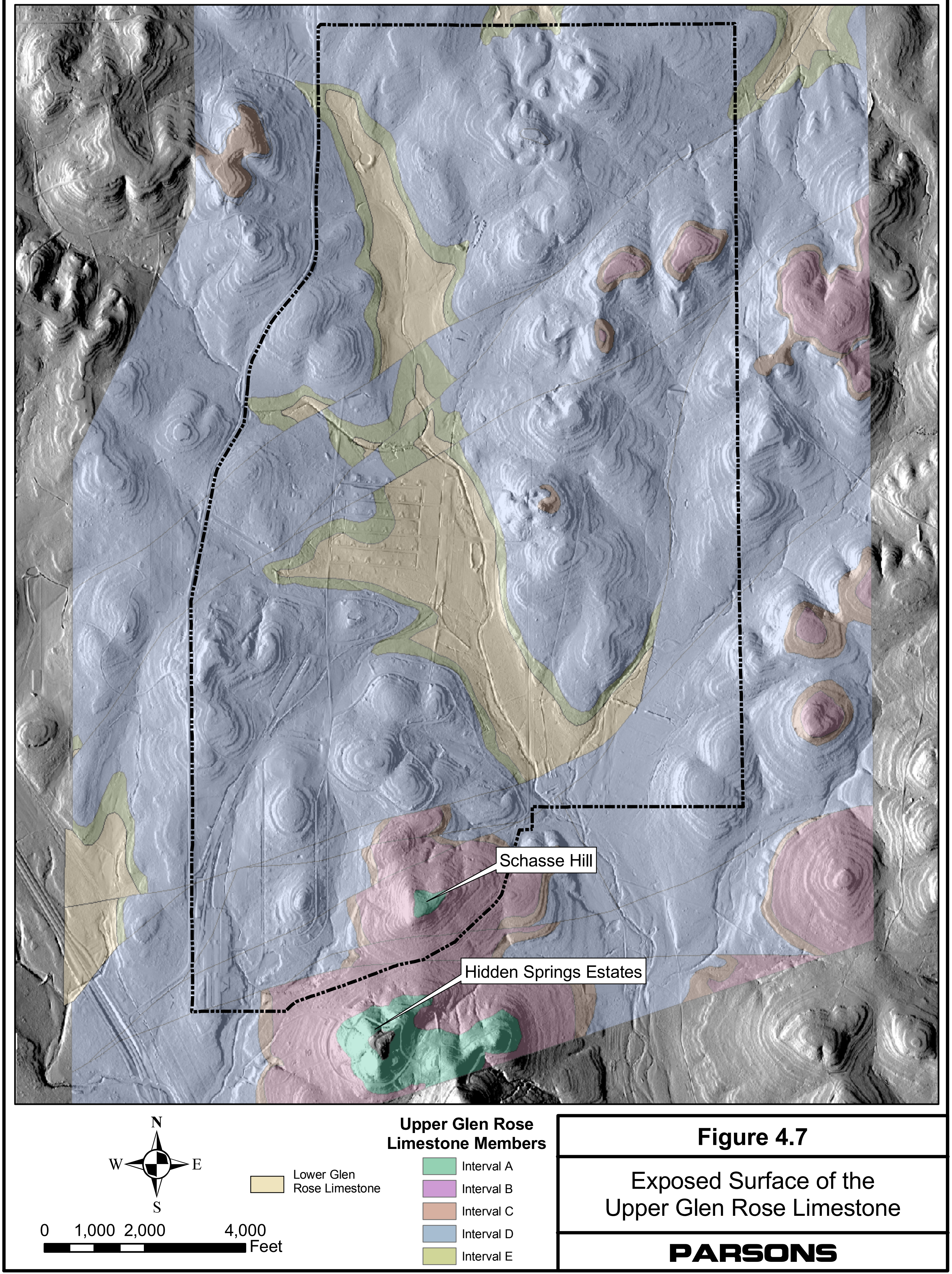

Figure 4.7

Exposed Surface of the Upper Glen Rose Limestone

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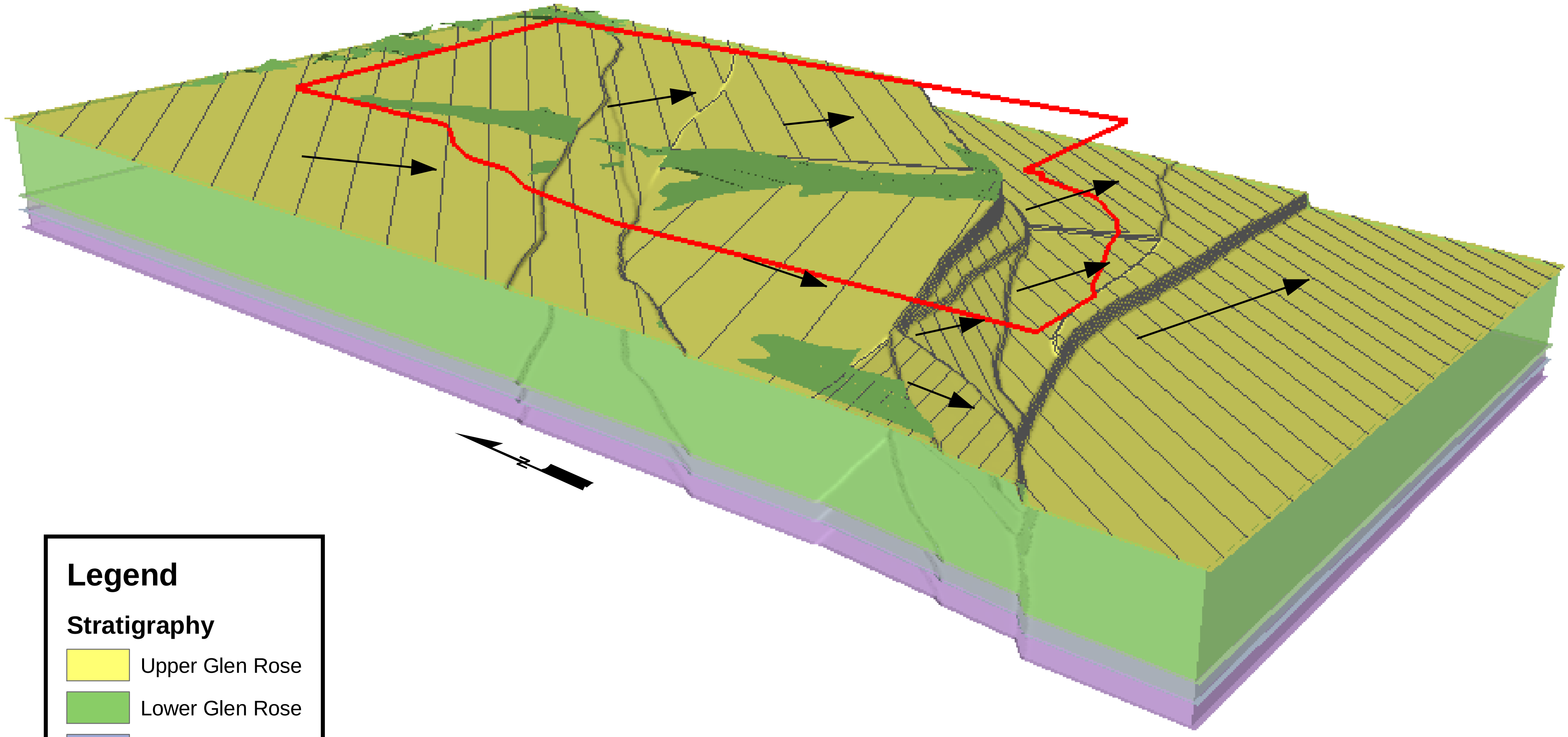

Figure 4.8

Base of Upper Glen Rose Limestone

Legend

Stratigraphy

🟨 Upper Glen Rose

🟩 Lower Glen Rose

🟦 Bexar Shale

🟪 Cow Creek

Vertical Exaggeration: 5X

CSSA Boundary

Average Dip Direction of Fault Block

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selective" fracture, channel, and cavern porosity is associated with cave development in the interval. This porosity has become interconnected over geologic time and provides avenues for water to enter and move in the subsurface. Locally, the conformable contact between the overlying Edwards Group and the Glen Rose Limestone has relatively large cavern porosity and permeability, which decreases with depth. The interval is relatively devoid of fossils; the few fossils present are mainly *Protocardia texana* (Conrad) and *Tylostoma sp*.

Interval UGR(A) only crops out atop Schasse Hill within the confines of CSSA (0.1 percent coverage), and 1.2 percent of the HCSM area. No waste management activities are known to have occurred upon the limited outcrop area. Groundwater occurring within Interval UGR(A) is laterally discontinuous and likely free of contamination. Recharge to the zone is through direct precipitation only, and much of that water is believed to be lost to seeps along the base of the outcrop. This unit has not been addressed through any environmental investigation, with the possible exception of the Background Soils Study (Parsons, 2002) conducted to establish natural concentrations of inorganic elements at CSSA.

Interval UGR(B) (after USGS, 2003)

Interval UGR(B) is a 120- to 150-ft-thick interval similar to Interval UGR(A) but with appreciably less cave development and thus less permeability than the overlying interval. Overall, intervals A and B are indistinguishable based on lithology. As with Interval UGR(A), the interval is composed of alternating and interfingering medium-bedded mudstone to packstone, with localized evaporites. The mudstones and marl that compose the major part of the interval have low "not fabric" porosity and appear to have little permeability. The interval has more of the properties of a confining bed than an aquifer. What distinguishes Interval B from Interval UGR(A) is the relatively greater number of caves in Interval UGR(A). The interval is relatively devoid of fossils; the few fossils present are mainly *Protocardia texana* (Conrad) and *Tylostoma sp*.

Interval UGR(B) only crops out atop some of the larger hills (Schasse, Wells, and Steele) within the confines of CSSA (4.5 percent coverage), and 8.1 percent of the HCSM area. No waste management activities are known to have occurred upon the limited outcrop area at CSSA. Groundwater occurring within Interval UGR(B) is laterally discontinuous and likely free of contamination. Limited recharge to the zone is through direct precipitation on the outcrop and recharge from Interval UGR(A), and much of that water is believed to be lost to seeps along the base of the outcrop. Some groundwater may leak vertically to lower strata where the outcrop is bisected by faults or fractures. This unit has not been addressed through any environmental investigation, with the possible exception of the Background Soils Study (Parsons, 2002) conducted to establish natural concentrations of inorganic elements at CSSA.

Interval UGR(C) (after USGS, 2003)

Interval UGR(C) is a solution zone that is approximately 10 to 20-ft thick. Like the underlying Interval UGR(E) at the base of the UGR, it was originally an evaporite bed. It is composed of yellow-to-white calcareous mud with some very thin mudstone layers interspersed and tends to form broad, valley-like slopes. Exposures of the unit are subdued to nonexistent due to weathering. Fossils in this interval are fewer in both diversity and abundance than those of Interval UGR(E). The primary fossils found in this interval are *Protocardia texana* (Conrad), *Tylostoma sp*., *Turritella sp., Hemiaster sp*., *Porocystis golobularis* (Giebel), and worm tubes.

Interval UGR(C) only crops out along the slopes of the larger hills (Schasse, Wells, and Steele) within the confines of CSSA (1.1 percent coverage), and 2.7 percent of the HCSM area. No waste management activities are known to have occurred upon the limited outcrop area at CSSA. Groundwater occurring within Interval UGR(C) is laterally discontinuous and likely free of contamination.

This 10-20-ft-thick dissolutioned evaporite bed, which contains boxwork (intersecting blades or plates) permeability and fabric selective collapse breccia porosity associated with solutioning, tends to intercept and channel groundwater laterally to seeps where the bed intersects land surface. Limited recharge to the zone is through direct precipitation on the outcrop and recharge from overlying intervals. Some groundwater may leak vertically to lower strata where the outcrop is bisected by faults or fractures. This unit has not been addressed through any environmental investigation, with the possible exception of the Background Soils Study (Parsons, 2002) conducted to establish natural concentrations of inorganic elements at CSSA.

Interval UGR(D) (after USGS, 2003)

Interval UGR(D) is composed of 135 to 180 ft of alternating beds of wackestone, packstone, and marl. The full thickness of this interval only coincides with the higher topographic relief at CSSA, otherwise the interval is significantly reduced over the majority of the facility. At locations drilled thus far, the thickness of Interval UGR(D) has ranged from a few ft to approximately 120 ft, with a postwide average of 40 ft. This interval contains abundant fossils and fossil fragments. The predominant fossil is the foraminifera *Orbitolina texana* (Roemer). The interval also contains *Porocystis golobularis* (Giebel), *Tapes decepta* (Hill), *Protocardia texana* (Conrad), *Loriolia sp*., *turritella sp*., *Hemiaster sp*., *Neithea sp*., and various species of Mollusca.

The interval contains two identifiable marker beds. The first marker bed is 15 to 20 ft above the Corbula bed discussed in Section 4.2.1.5 and is a thinly bedded, silty mudstone. It can be recognized in outcrop by its “platy” character (splits into thin layers or laminae). Above this mudstone marker bed is about 75 ft of alternating wackestone, packstone, and marl. Locally, near the top of these alternating beds is a rudist biostrome. This biostrome is thickly bedded in places, reaching thickness of 30-40 ft, composed mostly of *Caprinuloidea sp*. This biostrome is overlain by 10-30 ft of alternating, thin-to-medium-bedded wackestone and packstone containing abundant *Orbitolina texana* (Roemer), which is capped by the second marker bed, a 2-3-ft-thick layer of crossbedded and ripple-marked grainstone. The grainstone is very resistant to weathering and is found either in place or as float.

Because of its high mud content, the 135 to 180-ft-thick Interval D (between the two solutioned evaporite beds (Intervals UGR[C] and UGR[E] and known locally as a “fossiliferous zone”) in general has low porosity and permeability, with some local exceptions. In a few locations, some cavern porosity can be seen in outcrop along fractures. The crossbedded grainstone marker bed at the top of the interval has well-developed fabric selective moldic and “not fabric selective” vug, channel, and fracture porosity and, although thin, appears permeable. Numerous seeps issue water from the top of the interval along the contact with the overlying solutioned evaporite bed. The biostrome near the top of this interval also appears to have excellent “fabric selective” moldic and “not fabric selective” vug, fracture, and cavern porosity, which likely is interconnected.

Interval UGR(D) crops out over most of CSSA (77.5 percent coverage), and 72.6 percent of the HCSM area. Most of the developed areas at CSSA are upon the Interval UGR(D) outcrop. Likewise, most of the waste management activities that have occurred at CSSA are also within this interval. However, most of the more permeable zones near the top of the unit have been eroded from CSSA, and only occur near the top of hills where less development and waste management activities have occurred. Significant recharge to the zone is through direct precipitation on the outcrop and recharge from overlying intervals. This is the first pervasive stratum across the facility that lends itself to lateral groundwater movement without being cropped out by the intersecting land surface. A significant volume of groundwater is assumed to leak vertically to lower strata where the outcrop is bisected by faults or fractures. This unit has been investigated during RFI and groundwater investigation activities, as well as during the Background Soils Study (Parsons, 2002). Groundwater contamination is known to exist within this interval near the source areas of Plumes 1 and 2.

Interval UGR(E) (after USGS, 2003)

Interval UGR(E) is a 7- to 10-ft thick solution zone that originally was an evaporite bed, but that has subsequently been dissolved, leaving behind a calcareous mud. The Corbula bed (*Corbula martinae*) lies at the base of this interval and marks the geologic contact between the UGR and LGR Limestone. The Corbula bed is a thin to very-thin-bedded grainstone. Because of the more resistant characteristics of the grainstone relative to the calcareous mud that surrounds it, the grainstone commonly is found as float (displaced rock fragments) on the land surface. In outcrop, Interval UGR(E) appears as a yellow carbonate-rich mud that typically forms broad, gentle valley-like slopes. This interval contains abundant fossils, including numerous species of pelecypods, gastropods, shell fragments, and worm tubes. Locally, the very large and generally very rare gastropod *Nerinea romeri* (Whitney) can be found.

As with Interval UGR(C), this solutioned evaporite bed, which includes the Corbula bed at its base, appears to intercept the downward seepage of water. The interval acts as a lateral conduit for flow, as demonstrated by seeps observable at the surface in outcrop. These seeps can continue to transmit water even after long periods with no rainfall. Also like Interval UGR(C), this interval likely is characterized by boxwork permeability and fabric selective collapse breccia porosity that resulted from the dissolution of evaporites. Boxwork and collapse structures have not been observed in the study area because of the subdued (weathered) characteristics of the exposures, but they have been noted in exposures west of CSSA.

Interval UGR(E) crops out over a limited area of CSSA (6.0 percent coverage), and 5.2 percent of the HCSM area. Limited development and waste management activities have occurred within the outcrop areas. However, much of the outcrop is located adjacent to Salado Creek and its tributaries. Significant recharge to the zone is through direct precipitation on the outcrop and recharge from overlying intervals. It is also likely that surface water within the streambeds is lost to this interval as Salado Creek dissects this unit. Once water has entered this unit, a significant volume is assumed to leak vertically to lower strata where the outcrop is bisected by faults or fractures.

This unit has been investigated during RFI and groundwater investigation activities, as well as during the Background Soils Study (Parsons, 2002). Groundwater contamination is known to exist within this interval near the source areas of Plumes 1 and 2. The VEWs at B-3 and the shallow PZs (-2, -4, and -6) at AOC-65 are mostly completed within this depth interval, and groundwater samples from these wells routinely result with solvent contamination that is in excess of the main plume within the LGR. At B-3 (Plume 1), *cis*-1,2-DCE has been reported in excess of 27,000 µg/L, and nearly 3,000 µg/L of PCE. At AOC-65 (Plume 2), lesser concentrations of PCE generally ranging between 30 µg/L and 3,410 µg/L (AOC65-MW2A) are perched about the LGR.

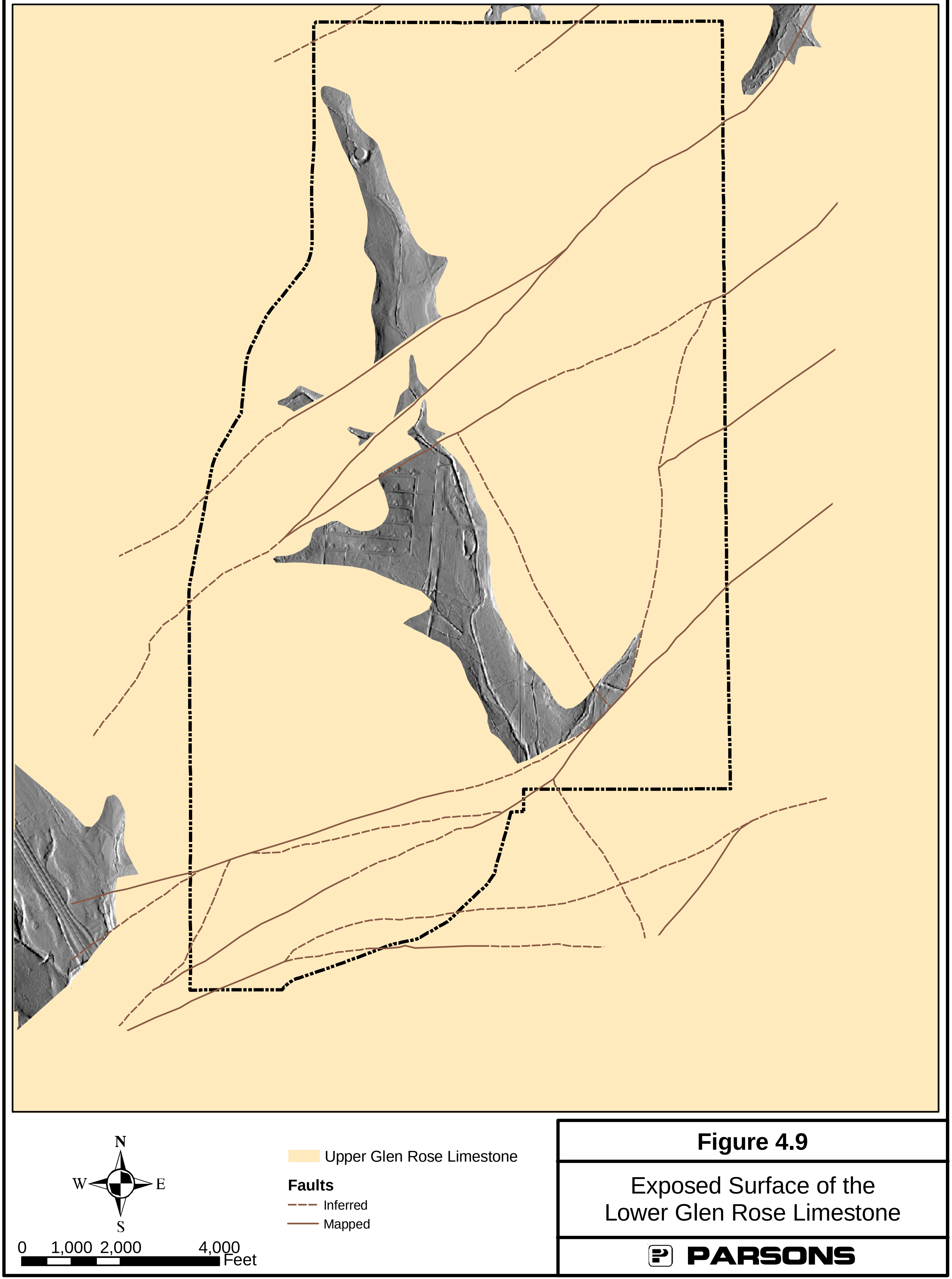
During the July 2002 floods, this zone was saturated to the point where cascading groundwater and venting air could be heard in the open boreholes of AOC65-VEW13, -VEW14, -VMP6, -VMP7, and existing well AOC65–MW2B. Otherwise, this interval is generally low-yielding and is non-responsive to except to the heaviest rain events (flood scale). However, groundwater does persist in these wells, in almost a sump-like fashion. Nearly 16 months of monitoring (March 2003 through June 2004) show that water levels are mostly unwavering in this zone. Once the 2002 flooding effect had dissipated, groundwater fluctuations within this zone at AOC-65 typically varied by only several tenths of feet. By way of comparison, the deeper PZs (-1, -3, and -5) screened at the base of LGR(B) fluctuated by more than 50 feet during the same 16-month monitoring period.

4.2.2 LGR (Middle Trinity aquifer, Layer 2)

Through April 2007, the environmental investigations performed at CSSA have been conducted in the portions of the base where the LGR thickness ranges from 284 to 338 ft, with an average thickness of nearly 320 ft. The average thickness encountered at CSSA corresponds exactly with approximate maximum thickness of the LGR published by Ashworth (1983). Variations in the thickness of the LGR appear to be attributable to areas of pronounced reef structures (thicker than average) or significant faulting (thinner than average). Figure 4.9 shows the exposed surface of the LGR Limestone. Figure 4.10 interpolates the base of the LGR based upon drilling data.

The following hydrostratigraphic description is based upon work performed by CSSA and its contractors. For this report, the LGR Limestone has been subdivided into six intervals LGR(A-F), as described below from youngest to oldest. As expected, these subunits can be quite variable over the extent of CSSA. The type locality for this division of the LGR is based upon the work conducted near AOC-65 at the southwestern corner of the post. A basewide fence diagram on the HCSM area is presented in Figure 4.11. Figure 4.12, 4.13, and 4.14 present multiple cross-sections that defines the model layers through the extent of the post. The model layers represent a generalization of rock types grouped upon lithologic and geophysical character. It is important to note that these figures are a generalization of the subsurface, and that the actual conditions can vary significantly from location to location.

Exposures of unit LGR(A) are limited to the basal portion of Salado Creek and its tributaries in the central portion of the post (10.8 percent of CSSA). The remaining older units do not crop out within the post. Additional exposure of the LGR occurs within 10.1 percent of the HCSM area, including areas north of CSSA and just SW of CSSA along the I-10 corridor.



🟨 Upper Glen Rose Limestone

Faults

--- Inferred

— Mapped

Figure 4.9

Exposed Surface of the Lower Glen Rose Limestone

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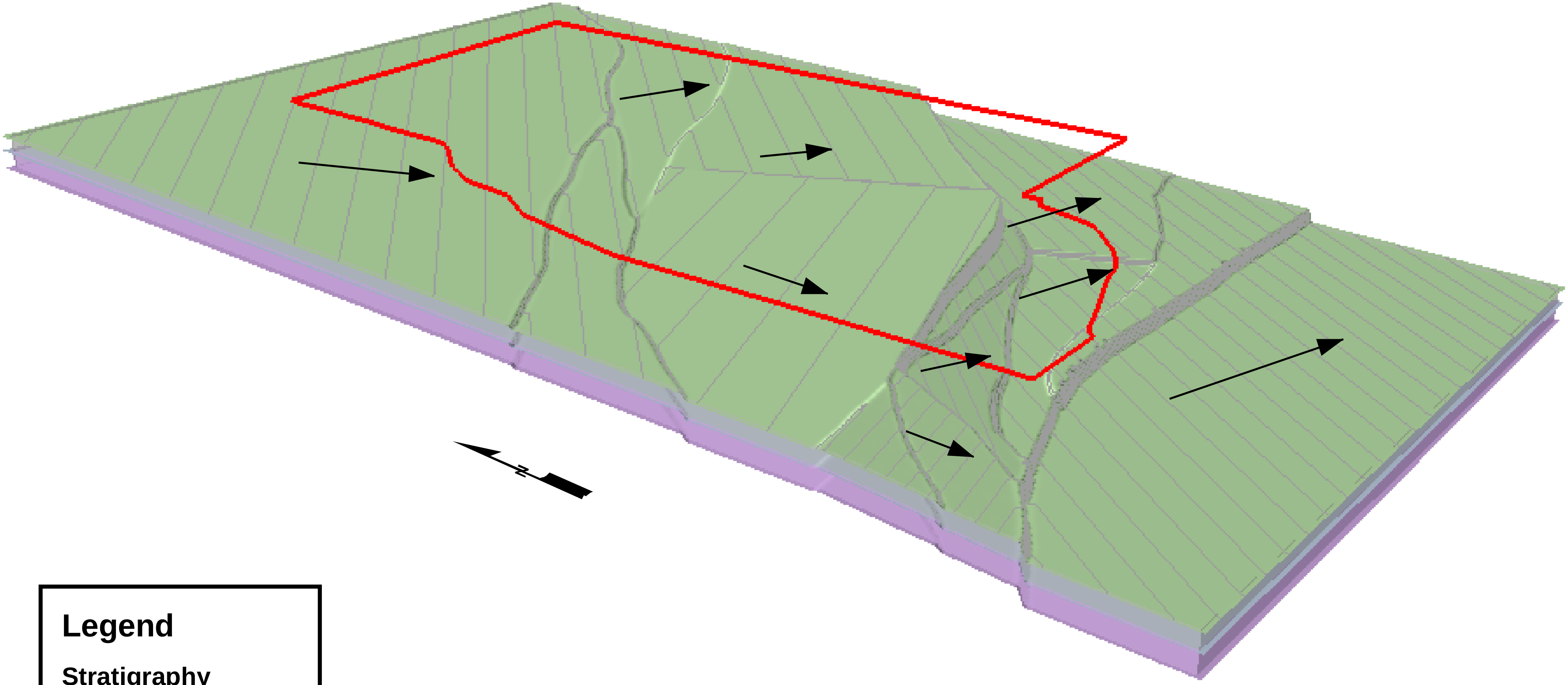

Legend

Stratigraphy

🟩 Lower Glen Rose
🟦 Bexar Shale
🟪 Cow Creek

Vertical Exaggeration: 5X

— **CSSA Boundary**

→ **Average Dip Direction of Fault Block**

Figure 4.10

Base of Lower Glen Rose Limestone

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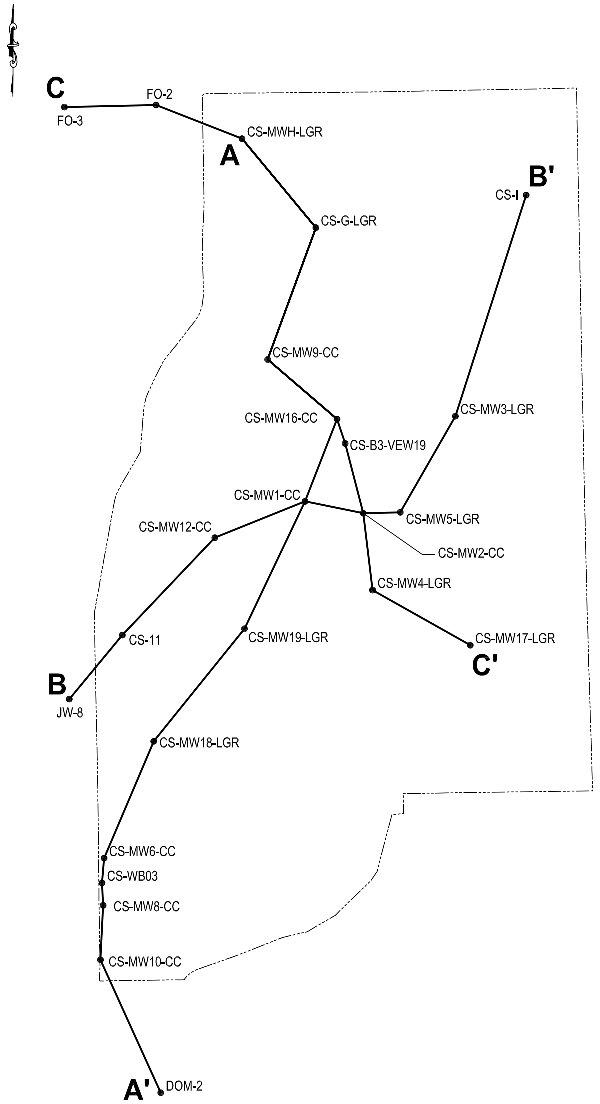
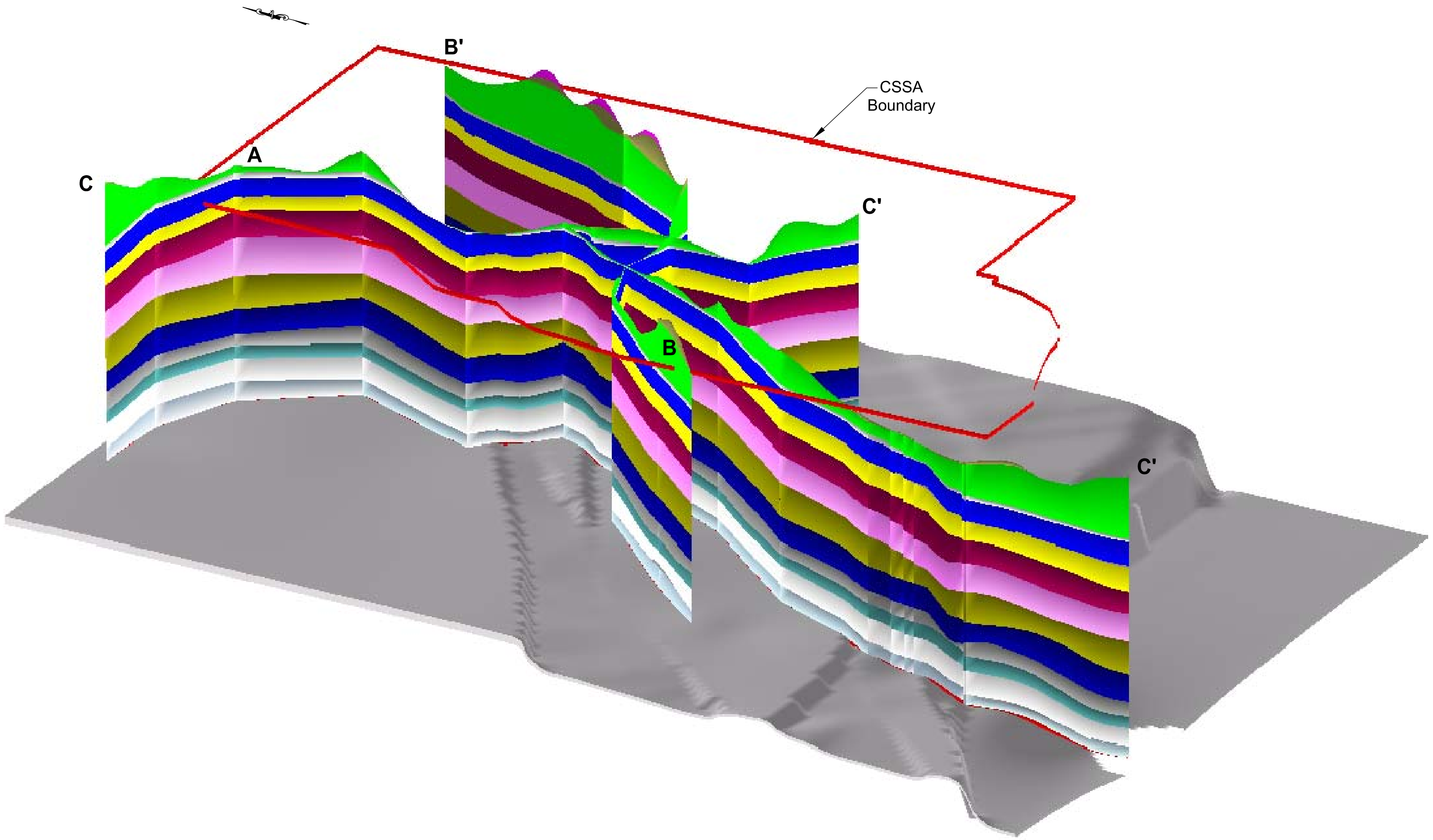


Cross Section Location



Oblique View (above from Southwest)

Stratigraphy

- UGR-A
- UGR-B
- UGR-C
- UGR-D
- UGR-E
- LGR-A
- LGR-B
- LGR-C
- LGR-D
- LGR-E
- LGR-F
- BS-A
- BS-B
- CC-A
- CC-B
- HS

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Figure 4.11

Geologic Fence Diagram for CSSA

Camp Stanley Storage Activity, Texas

PARSONS

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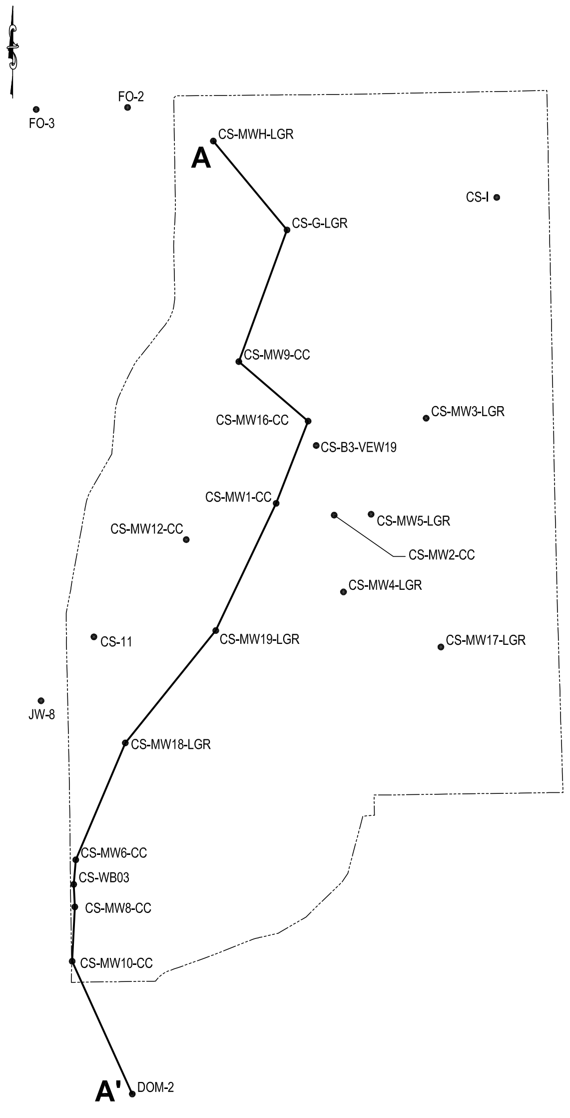
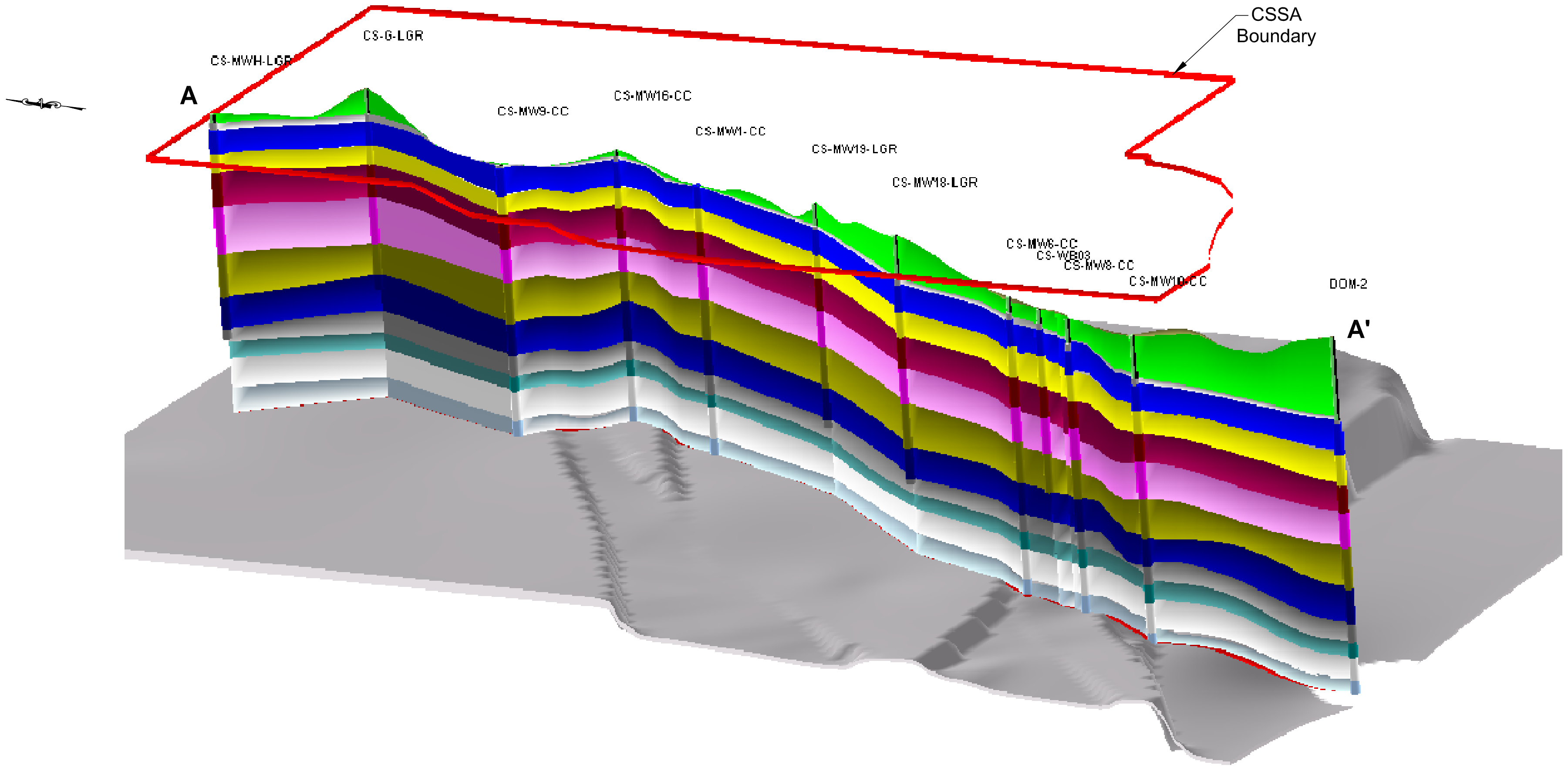
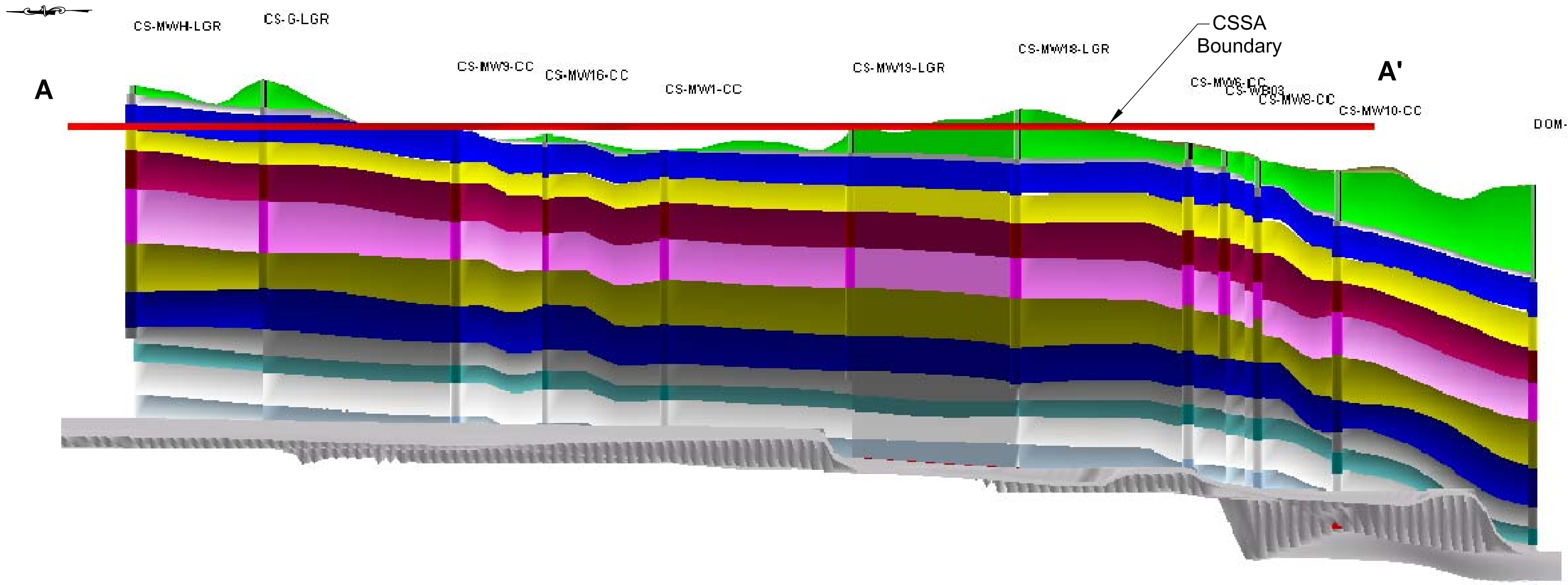


Cross Section Location



Oblique View (above from Southwest)



Western View

Stratigraphy
- 🟥 UGR-A
- 🟪 UGR-B
- 🟫 UGR-C
- 🟩 UGR-D
- ⬜ UGR-E
- 🟦 LGR-A
- 🟨 LGR-B
- 🟥 LGR-C
- 🟪 LGR-D
- 🟫 LGR-E
- 🟦 LGR-F
- ⬛ BS-A
- 🟩 BS-B
- ⬜ CC-A
- 🟦 CC-B
- 🟥 HS

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Figure 4.12

Geologic Cross Section A-A'
(North-South)

Camp Stanley Storage Activity, Texas

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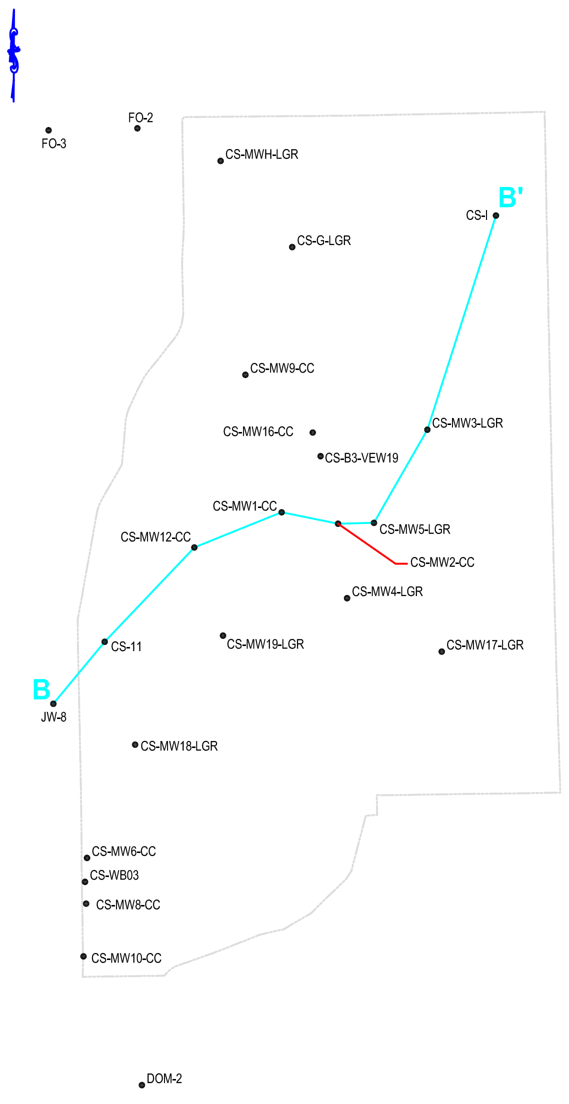
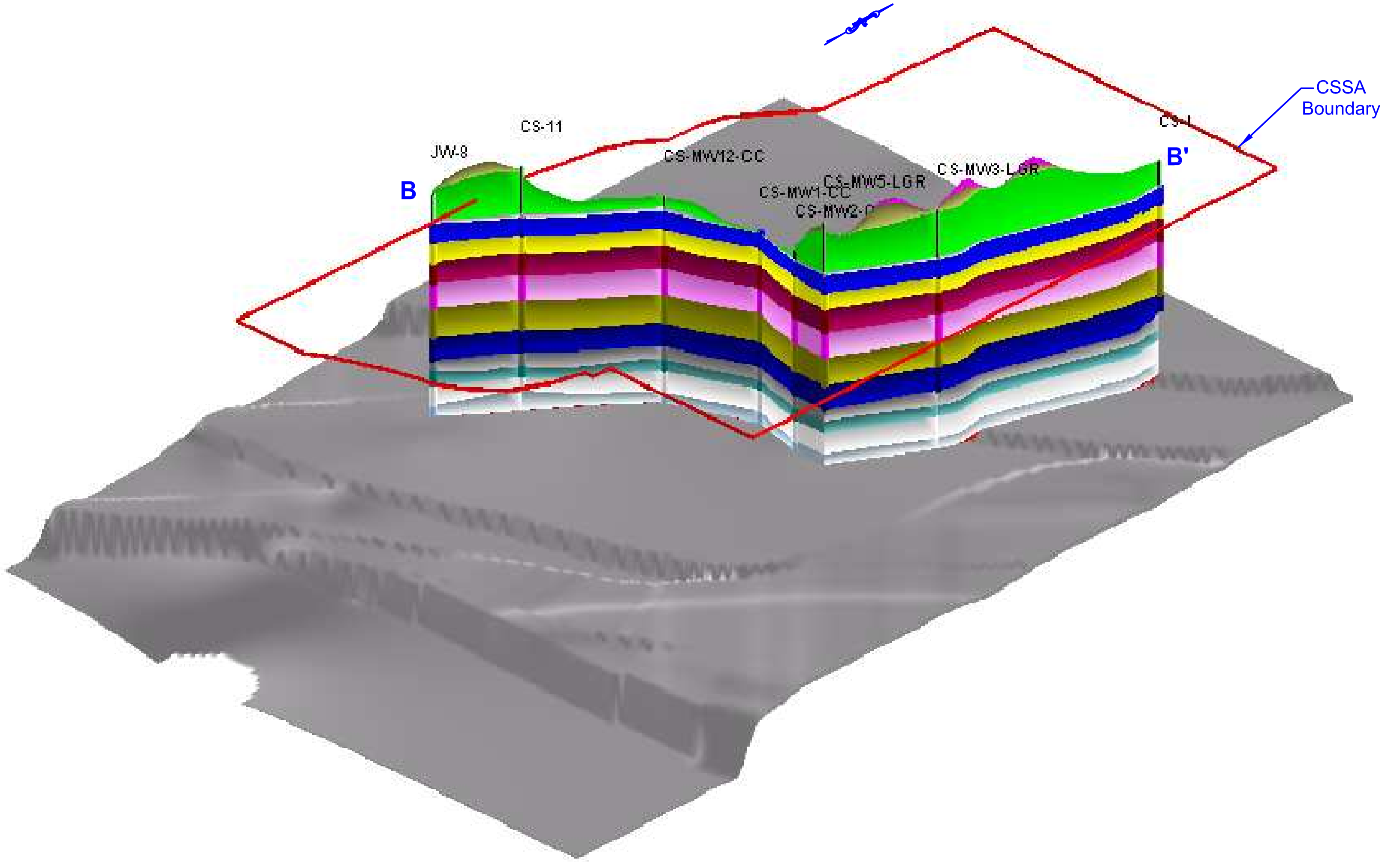
740911 CSSA-CSMAA.DWG



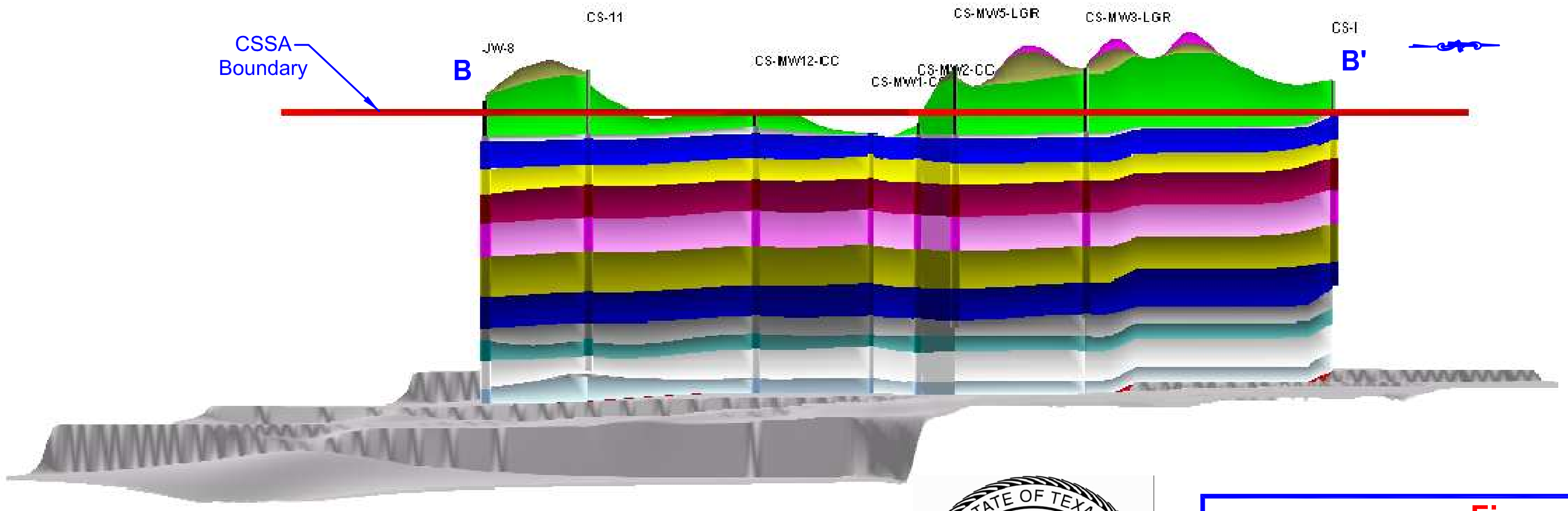
Cross Section Location



Oblique View (above from Southeast)

Stratigraphy

- 🟥 UGR-A
- 🟪 UGR-B
- 🟫 UGR-C
- 🟩 UGR-D
- ⬜ UGR-E
- 🟦 LGR-A
- 🟨 LGR-B
- 🟥 LGR-C
- 🟪 LGR-D
- 🟫 LGR-E
- 🟦 LGR-F
- ⬜ BS-A
- 🟩 BS-B
- ⬜ CC-A
- 🟦 CC-B
- 🟥 HS



Southeastern View

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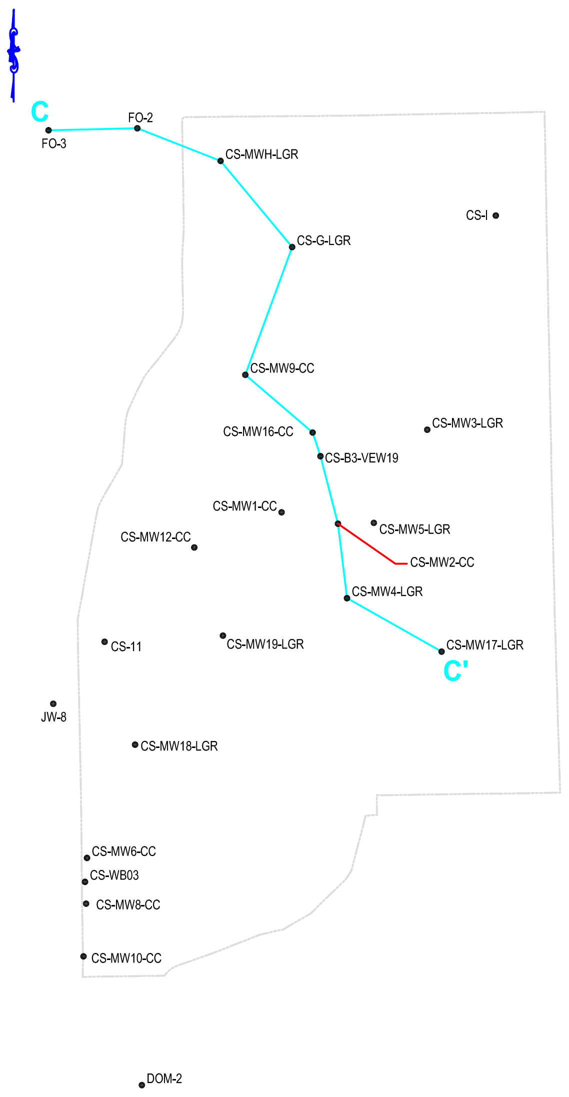
Figure 4.13

Geologic Cross Section B-B'
(Southwest-Northeast)

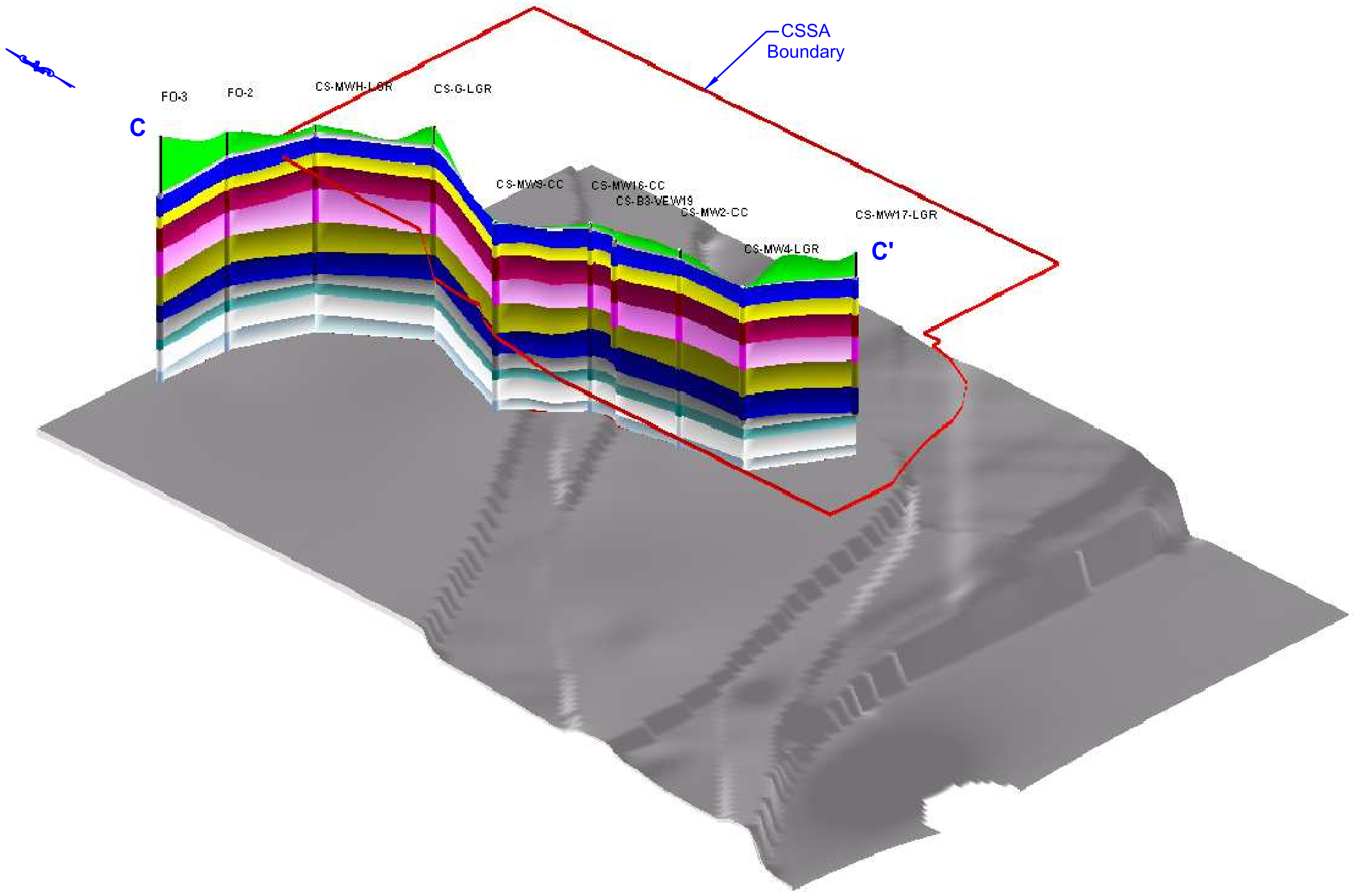
Camp Stanley Storage Activity, Texas

PARSONS

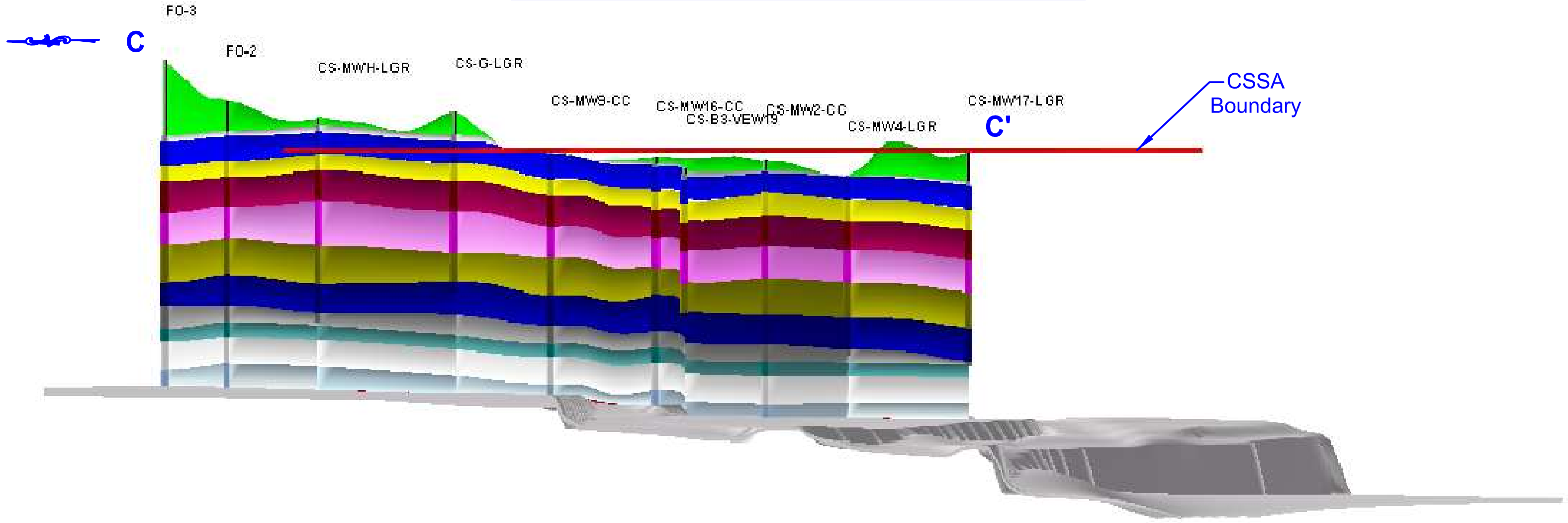
740911 CSSA-CSMBB.DWG



Cross Section Location



Oblique View (above from Southwest)



Southwestern View

Stratigraphy

🟥 UGR-A
🟪 UGR-B
🟫 UGR-C
🟩 UGR-D
⬜ UGR-E
🟦 LGR-A
🟨 LGR-B
🟥 LGR-C
🟪 LGR-D
🟫 LGR-E
🟦 LGR-F
⬜ BS-A
🟩 BS-B
⬜ CC-A
🟦 CC-B
🟥 HS

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GEOLOGY
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Figure 4.14

Geologic Cross Section C-C'
(Northwest-Southeast)

Camp Stanley Storage Activity, Texas

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740911 CSSA-CSMDD.DWG

Interval LGR(A)

For the purposes of this model, Interval LGR(A) is defined as the uppermost 50-foot sequence of LGR deposits throughout the HCSM area. The unit is characterized by alternating layers of pale yellow mudstone, wackestones, and packstones. Over much of the model area, the upper 20 ft of the unit is a grain-supported limestone (packstone) that includes a distinct foram hash near the top of the interval just below the UGR/LGR contact. The remaining basal 30 ft of Interval LGR(A) consists of thin-to-medium-bedded mudstones and wackestones. The entire interval appears to have low porosity and permeability with only “not fabric selective” fracture porosity evident and no known cavern development.

Interval LGR(B)

The top of Interval LGR(B) ranges between 30 to 50 ft beneath the UGR/LGR contact, and the interval is between 30 and 50 ft thick. The interval is characterized as a whitish fossiliferous packstone and grainstone that is evident both in lithologic and geophysical logs. A foram hash is located within the grainstones near the top of the interval. The porosity of the interval can be quite high due to the vugs associated with the moldic porosity (fabric selective). Within many boreholes, a distinct 15-ft-thick layer of mudstones is interbedded within the grainstones. Borehole logs indicate that the unit is thinnest towards the north, and generally thickens to the south.

The water-bearing capacity of this zone has been investigated somewhat during the RL83 drilling initiative, and the Task Order (TO) 58 recharge study carried out at AOC-65. During much of the year, the main aquifer level is well below the elevation of this interval. During these times, groundwater will tend to perch within this zone. A drill-stem injection packer test conducted at the CS-MW9 cluster in November 2000 resulted with the most permeable interval tested to date within the entire thickness of the LGR. However, this is an isolated occurrence, and LGR(B) is generally a lower permeability than LGR(F).

Interval LGR(B) is also the deeper of the two zones chosen to monitor for the TO58 recharge study at AOC-65. During the July 2002 floods, this zone was saturated to the point where groundwater could be heard rushing through the open borehole of AOC65-PZ3. Since the flood waters have receded, the zone has been a low-yielding perched interval. However, since the well has been completed with screen and casing, it periodically vents a noticeable amount of air.

It is likely that this interval can quickly transmit water during elevated aquifer conditions. The basal grainstone of this interval appears to be associated with the reef-building events that occurred at locations of wells CS-MWH-LGR and CS-G to the north and the CS-MW11 cluster to the south. Interpretations of the logs indicate the lower grainstone lithology is stratigraphically equivalent to the top layers of those respective reefs that occur within Intervals LGR(C) and LGR(D). According to the USGS, field observations indicate that the largest porosity and permeability in the LGR is developed in the rudist bioherms below the top of the unit. This rudist zone contains well-developed “fabric selective” moldic porosity and “not fabric selective” fracture and cavern porosity. Large sinkholes and other solution features have formed in this zone.

Interval LGR(C)

Over much of CSSA, a 60-70-foot thick sequence of thin and medium-bedded mudstones exists below the more permeable grain-supported limestones of Interval LGR(B). The mudstones are described as alternating layers of tannish-brown and greenish-gray bioturbated muds with a low percentage allochemical constituents (e.g., fossils). The rock is competent and highly styolitic (susceptible to diagenetic pressure solutioning). The competency of the interval makes it easier to identify structural features such as slickensides and fracturing that have occurred throughout the unit. Based on the drilling results, this zone is not considered to be a significant groundwater producer except where significant fracturing may have occurred. The unit served as "marker" bed during the stratigraphic correlation of the AOC-65 groundwater study (TO58). The "fabric selective" porosity is considered low because of its fine-grained nature and lack of moldic porosity. The "not fabric selective" porosity is also probably characterized as low except where faulting or fracturing may have allowed for minimal karstic development.

According to the USGS, downward migration of water appears to be hampered by dense mudstone underlying the rudist zone; the mudstone is the lowermost exposed (along Cibolo Creek) rock of the LGR. The only porosity evident in this mudstone appears to be fracture porosity, some of which has been solutionally enlarged. The low porosity/permeability of this mudstone is demonstrated in the bed of Cibolo Creek where unconnected waterholes contain water even during drought conditions.

Interval LGR(C) also includes some significant reef structures to the north and south. The largest reef encountered to date is located beneath the North Pasture at well locations CS-MWH-LGR and CS-G. Beginning approximately 60 ft below the UGR/LGR contact, a rudistid reef with a thickness of 115 ft has been identified. The reef is characterized as very porous (fabric selective) grainstone composed of fossil casts and molds of corals, rudistids, and bivalves. The reef has a unique geophysical signature in which the gamma count is very low in comparison to the surrounding rock. In this locality, the reef extends from the lower portion of Interval LGR(B), to the upper portion of Interval LGR(D). The eastern and western extent of this reef has not been defined to date.

Interval LGR(D)

Below the mudstones of Interval LGR(C) is a 65-70-foot thick unit of rock that is characterized by a unique resistivity signature with respect to the overlying and underlying rocks. The change generally represents two resistive packstone layers divided by a less resistive mudstone. The upper and lower packstone layers tend to be approximately 25 ft thick, and are described as interbedded fossiliferous wackestones and packstones that are pale yellow to white in color. The middle layer is more characteristic of a bioturbated mudstone that is tan in color.

The upper packstone layer appears to thicken to the north, where it appears to form the basal portion of the Interval LGR(C) reef complex at wells CS-MWH-LGR and CS-G. Towards the south near Building 90, the upper packstone unit may be as thin as 10 ft thick, with the middle mudstone layer increasing in thickness accordingly. The top of the lower packstone bed is characterized by a unique geophysical marker (which has been referred to as the "scissor tail" by the on-site geologists). This resistivity feature represents a short sequence of packstone/mudstone/packstone that is more or less uniformly present over most of CSSA.

Overall, the water-bearing capacity of this interval is low to moderate, but it can vary greatly within short distances. The localized vugs associated with moldic porosity (fabric selective) can store and transmit limited amounts of groundwater. "Not fabric selective" porosity in the form of fractures has also been observed to yield low quantities of groundwater in this unit.

Interval LGR(E)

Interval LGR(E) is a 50-60-foot layer of tan and light brown wackestones with intermittent thin fossiliferous layers and grain-supported rock. The unit is fairly unremarkable, except for the presence of a notable vuggy packstone layer located at the base of the interval. This lower packstone unit ranges in thickness between 6 and 10 ft, and is separated from the underlying Interval LGR(F) by 10 ft of mudstones. At this time, it is uncertain how pervasive this interbedded packstone bed is throughout CSSA, but it has served as a key marker bed near Building 90.

The predominant mudstone/wackestone matrix that is mostly free of fabric selective porosity is not a pervasive permeable unit. With the exception of the vuggy packstone along its basal boundary, most groundwater movement through this unit is limited to "not fabric selective" features such as fractures. However, discrete interval packer testing has demonstrated that low to moderate groundwater production is possible from the fabric selective moldic porosity in the basal packstone unit.

Interval LGR(F)

Interval LGR(F) comprises the main groundwater production zone within the LGR throughout CSSA. Interval LGR(F) is comprised of a 45-55-foot reefal complex whose lateral extent appears to extend beneath the entire confines of CSSA. The occurrence of this reef has been well documented within boreholes drilled at CSSA and neighboring areas. The interval is described as a white to tan, very fossiliferous packstone/grainstone with high fabric selective moldic porosity. The interval is characterized by its relatively low gamma response and high resistivity response. The vuggy porosity left as a result of fossil dissolution has resulted in voids that range from several millimeters to 5 centimeters in size. The fossil assemblage is vast, including caprinids (rudists), corals, bivalves, and gastropods. In some locations, the basal 15 ft of the interval has a pronounced increase in mud content, and a color change to pale brown.

The primary permeability of this unit is moldic (fabric selective) porosity. Extensive testing through packer tests and discrete interval groundwater sampling indicate that the interval is capable of yielding groundwater in excess of 75 gpm. Where not fabric selective porosity exists in the form of developed fractures, karst, or small caverns, groundwater production can easily exceed 150 to 300 gpm. For the monitoring well program, this interval has been the focus of the investigations where typically the basal 25 ft of the aquifer is monitored for the occurrence of contamination.

4.2.3 Bexar Shale Aquitard (Layer 3)

Through August 2003, the environmental investigations performed at CSSA have been conducted in the portions of the base where the BS thickness ranges from 58-63 ft, with an average thickness of nearly 60 ft. Variations in the thickness of the BS appear to be attributable to depositional variation (thicker than average) or significant faulting (thinner than average).

The BS facies of the Hensell Sand is not exposed to the surface at CSSA. Figure 4.15 interpolates the base of the BS based upon drilling data.

The following hydrostratigraphic description is based upon work performed by CSSA and its contractors. For this report, the BS has been subdivided into two intervals, BS(A-B), as described below from youngest to oldest. As expected, these subunits can be quite variable over the extent of CSSA. Figures 4.11 through 4.14 present cross-sections through the extent of the post that defines the model layers. The model layers represent a generalization of rock types grouped upon lithologic and geophysical character. It is important to note that this figure is a generalization of the subsurface, and that the actual conditions can vary significantly from location to location.

The BS forms a relatively impermeable aquitard for the overlying LGR water bearing zones. Significant vertical water movement in the BS is anticipated to be through fractures and faults only. CSSA currently has 4 monitoring wells completed in the BS.

Interval BS(A)

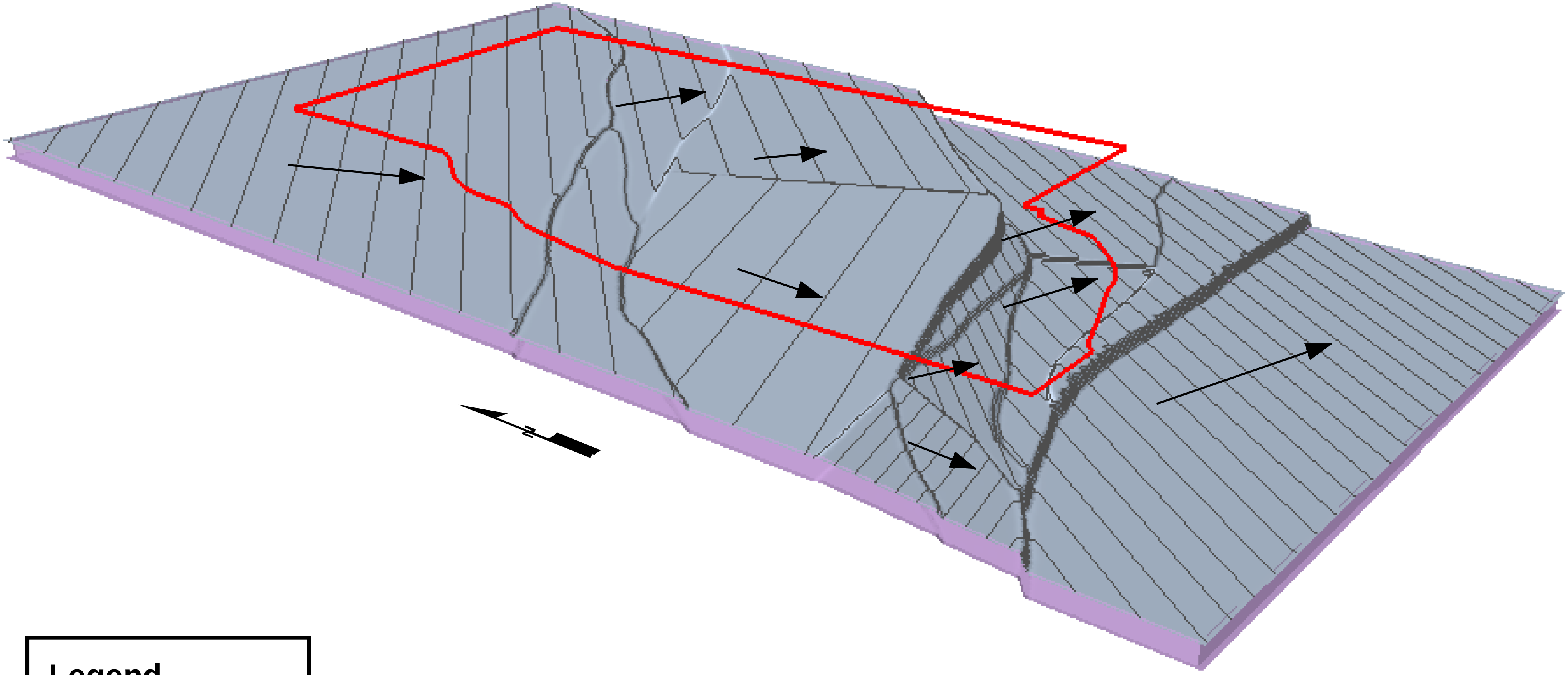
For the purposes of this model, Interval BS(A) is defined as the uppermost 25-30-foot sequence of BS deposits throughout the HCSM area. The unit is characterized by alternating layers of pale yellow mudstone, wackestones, and packstones. Over much of the model area, the upper 25 ft of the unit is a dolomitic wackestone that is dark gray in color. In terms of texture, this "dirty limestone" is very similar to the mudstones of interval LGR(E), including the presence of fossils and limited moldic porosity. The gamma count is high in comparison to LGR(F), and the resistivity of the entire layer is very low. The BS(A) interval appears to have low porosity and permeability with only not fabric selective fracture porosity evident and no known cavern development.

Interval BS(B)

The basal 30 ft of the BS is more characteristic of the shale lithology with increasing mud content and a laminated fissile bedding structure. Beneath much of CSSA, the top of interval BS(B) is denoted by a large increase in gamma counts, which peaks and quickly declines. An approximately 10-15-ft-thick oyster bioherm also appears to be predominant at the top of BS(B). The basal 20 ft of the BS consists of a platy, fissile mudstone that has an olive gray appearance. At this depth the unit is more characteristic of a shale bed that has few allochems, and a very low porosity. The BS(B) interval appears to have low porosity and permeability with only not fabric selective fracture porosity evident and no known cavern development.

4.2.4 Cow Creek Limestone (Middle Trinity aquifer, Layer 4)

At CSSA, the CC Limestone is not exposed at the surface. The CC Limestone is only known to crop out along isolated locations of the Guadalupe River Valley and Pedernales River to the NE of the facility. Through August 2003, the environmental investigations performed at CSSA have been conducted at locations where the CC Limestone thickness ranges from 72 to 84 ft, with an average thickness of nearly 76 ft.



Legend

Stratigraphy

▨ Bexar Shale

▨ Cow Creek

Vertical Exaggeration: 5X

— **CSSA Boundary**

→ **Average Dip Direction of Fault Block**

Figure 4.15

Base of the Bexar Shale

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The following hydrostratigraphic description is based upon work performed by CSSA and its contractors. For this report, the CC has been subdivided into two intervals, CC(A-B), as described below from youngest to oldest. As expected, these subunits can be quite variable over the extent of CSSA. Figures 4.11 through 4.14 present cross-sections through the extent of the post that defines the model layers. The model layers represent a generalization of rock types grouped upon lithologic and geophysical character. It is important to note that this figure is a generalization of the subsurface, and that the actual conditions can vary significantly from location to location.

Interval CC(A)

For the purposes of this model, Interval CC(A) is defined as the uppermost 50-55-foot sequence of CC deposits throughout the HCSM area. The unit is characterized by alternating layers of white and light gray packstones and grainstones. The occurrence of the CC Limestone is easily identified by its geophysical signature relative to the BS. The large decrease in gamma count indicates the reduction in the amount of mudstone, and the sharp increase in overall resistivity supports the lithologic change which is capable of increased groundwater storage. The fossil assemblages appear to form in lenticular bioherms that are different from the reef-building events evident in the LGR. Discontinuous layers of biostromes include masses of gastropods, bivalves, and occasionally corals.

Portions of this interval can be quite permeable from either moldic (fabric selective) porosity or not fabric porosity in the form of dissolutioned vugs, voids, or fractures. Moderate to large amounts of groundwater can be expected to be produced from this interval. Communication with the geophysical contractor (GeoCam) indicates that dissolutioning and cavern development within the upper 30 ft of this interval occurs within the Texas Hill Country. This zone has been identified as an interval of interest with respect to groundwater monitoring at CSSA.

Interval CC(B)

The basal 20 ft of the CC Limestone represents a conformable transition with the underlying Hammett Shale. The grainstones and packstones of unit CC(A) grade into a soft olive gray silty mudstone. Being that the contact is transitional, there are numerous interbeddings between soft shaley members and more competent limestone rock, with bedding units ranging from a few inches to several ft in thickness. The increase of shale content is reflected in the geophysical surveys with an increasing gamma count and a decreasing resistivity. At this depth the unit is more characteristic of shale rather than a limestone. The contact with the underlying Hammett Shale is interpretive due to the transitional nature of the contact. For this report, the contact has been defined typically as the greatest gamma peak below the base of the BS.

The CC(B) interval appears to have low porosity and permeability with only not fabric selective fracture porosity evident and no known cavern development. Drill-stem packer testing and discrete interval groundwater sampling indicate that unit CC(B) yields only small quantities of groundwater.

4.2.5 Hammett Shale Aquitard (Layer 5)

Through August 2003, upper contact of the Hammett Shale has been penetrated during drilling at nine monitoring well locations. Since the Hammett Shale is considered an aquitard between the Middle and Lower Trinity aquifers, this unit has not been investigated. Data regarding the upper portion of the Hammett Shale is reported here as a result of the CC Limestone investigations.

According to Ashworth (1983), the Hammett Shale is expected to be approximately 80 ft in thickness, and is described as a dark blue to gray, fossiliferous, calcareous and dolomitic shale with thinly interbedded layers of limestone and sand. During the Camp Stanley investigations, the unit was rarely penetrated more than 15 ft, and only to accommodate geophysical tools. The CSSA investigations indicate that the top of the unit is a soft, shaley mudstone that is slightly dolomitic. Thin beds of alternating olive gray shale and light gray fossiliferous limestones appear to be the dominant feature of the member. The water-bearing capacity of the Hammett Shale is low and any secondary porosity would be limited to not fabric selective features such as fracture development. Historically, the Hammett Shale is a difficult member to drill because of its propensity to quickly slough and cave in during or shortly after drilling operations. Any water development from the Lower Trinity aquifer below necessitates the use of surface casing to hold back the Hammett Shale from eventual collapse.

4.3 MATRIX AND STRUCTURAL EFFECTS

4.3.1 Stratigraphy

Stratigraphy plays a major role in the storage and transmission of groundwater. With respect to carbonate aquifers, the underlying assumptions are that well-developed karst features and wide fracture apertures store and transmit the greatest quantities of groundwater. However, where not fabric selective features are absent, groundwater availability becomes dominated by stratigraphic properties. Extensive drilling at CSSA has demonstrated that most of the groundwater production occurs from the reef zones associated with intervals LGR(F) and CC(A). The significance of the reef zones (biostromes) is their inherent capacity to store large quantities of water due to significant permeability related to moldic (fabric selective) porosity. Other productive zones may originate from younger-aged reefs within LGR(C), especially within the vicinity of wells CS-MWH-LGR, CS-G, and the CS-MW11 cluster. Undoubtedly, more of these permeable reef structures exist in the vicinity, but are as of yet undiscovered. The upper reefs of unit LGR(C) are probably prolific in yield, but are more sensitive to seasonal precipitation. Some of these zones have been drilled during periods of drought where that storage capacity has been drained by a declining water table.

Drilling data suggests that the UGR units UGR(D) and UGR(E) yield very little water, except at times when significant precipitation has occurred. Groundwater occurrence within unit D is probably laterally discontinuous and heavily dependent upon significant recharge and localized bioherms or fracture systems. Numerous RFI borings ranging in depths between 10 and 35 ft bgs has demonstrated that very little to no groundwater is readily available from the immediate near surface. Shallow groundwater wells installed to depths of 40 ft and less have shown that groundwater may, or may not accumulate within the borehole. However, the occurrence of shallow groundwater can be significant, such that the greatest concentration of PCE detected (3,400 µg/L) at CSSA was reported from a well (AOC65-MW2A) that is only 19 ft in depth. The well barely yields water, but what groundwater is present has been impacted by ordnance maintenance operations. The role of the evaporite zone UGR(E) and the upper portions of LGR(A) have also been studied as part of a different project (TO58). Three shallow wells (AOC65-PZ02, -PZ04, -PZ06) have been installed within this unit to assess its recharge properties. With the exception of the July 2002 flooding, this zone has shown very little fluctuation in water levels, suggesting they act only as sumps and are essentially dry since installation.

Work performed under the TO58 delivery order also investigated occurrence of groundwater within the upper portions of the LGR Limestone, specifically interval LGR(B). Three wells (AOC65-PZ01, -PZ03, -PZ05) drilled near AOC-65 are used to assess the recharge potential to unit LGR(B). With the exception of the July 2002 flooding event, these wells have shown slight response to a limited amount of precipitation. Drill-stem testing at AOC-65 has shown that the matrix-dominated flow is quite low, usually less than 2 gpm. The AOC-65 PZs thus far have indicated that less than 10 ft of water may perch within this zone over much of the year, and that well recovery may last as much as 24 hours.

Unit LGR(F) is by far the most permeable and pervasive unit of the LGR. Here the stratigraphy is dominated by moldic porosity which can yield large quantities of groundwater. Drilling activities within this portion of the aquifer has yielded more than 200 gpm of fluids during drilling operations. From a stratigraphy standpoint, it is clear that this interval is the major year-round contributor of groundwater. Only the perched reefal zones of LGR(C) may rival this production, and then only during periods of elevated water tables. From a storage standpoint, LGR(F) holds and transmits more groundwater than is contained in units LGR(A) through (E) combined by almost one order of magnitude. As a result, elevated concentrations of contaminants within the upper units of the LGR are essentially reduced to very low concentrations because of the dilution mechanism.

In contrast to the porosity of LGR(F), the matrix of the BS units is relatively impermeable. Field observations while drilling has demonstrated that the predominantly mudstone lithology of the BS yields very little to no formation water during air rotary drilling. The upper portion of BS(A) may yield more groundwater than the rest of the formation because of its inherent proximity to LGR(F), and because the upper portion of this interval can possess a limited amount of fabric selective moldic porosity. The lower portion of the BS, especially BS(B), tends to be more shaley without any secondary porosity features.

As would be expected, the bulk of matrix-type groundwater in the CC is associated with the packstones and grainstones of the CC(A) interval. Drilling fluid production from this interval confirms its capacity to yield water, and core samples have shown layers of carbonate sand that have an above-average carbonate matrix porosity. The moldic porosity of biostromes within this layer also contributes significantly to its ability to store and transmit groundwater. The lower portion of the CC is a transitional contact with the Hammett Shale below. The gradational interbedding of limestone and shale reduces the capacity of the unit to store and transmit groundwater. Well above the inferred geologic contact of the CC and the Hammett Shale, the groundwater production capacity of CC(B) has reduced to virtually nothing because of the fine-grained matrix effect.

Until August 2003, only small portions of the Middle Trinity aquifer were discretely monitored by conventional well installations. A new approach to monitor more of the aquifer was implemented using multi-level completion technology by Westbay Instruments. Westbay multi-level wells (CS-WB01, CS-WB02, CS-WB03, and CS-WB04) have been installed to monitor the Middle Trinity aquifer in the AOC-65 vicinity. An additional set of West multi-level wells (CS-WB05, CS-WB06, CS-WB07, and CS-WB08) were installed at SWMU B-3 in August 2005. Specific data regarding the multi-level wells is described in detail in Section 4.4.2.4, the following generalizations can be stated:

- When fabric selective matrix flow is the dominant permeability feature, groundwater yield from LGR zones A through E is low, with no more than several gpm available from any one zone. This data are supported by RL83 drill-stem packer data and indicates that as many as 50 percent of the zones tested yield little no groundwater in the upper 260 ft of the LGR postwide. Hydrophysical testing performed in association with the Westbay installations confirmed this premise that groundwater-producing intervals usually produced less than 0.25 gpm under a pumping condition. The hydrophysical data also indicated 85 percent of the total groundwater production from the LGR at CS-WB04 originates from the LGR(F) interval.
- Contaminant concentrations in groundwater zones LGR(A-E) can be orders of magnitude higher than concentrations reported in adjacent wells completed within interval LGR(F), which are typically less than 1 µg/L in the Plume 2 vicinity. Concentrations of PCE in excess of 750 µg/L have been reported for LGR(E) during packer samples collected at CS-WB03, while nearby MW8-LGR has reported a maximum concentration of 1.10 µg/L within zone LGR(F).
- Groundwater head potentials obtained from the multi-level wells indicate a downward component of groundwater flow under normal conditions. Tentative data suggests that groundwater can perch along the base of LGR(A) some 30 ft above groundwater that is present in LGR(B). Groundwater is present throughout zones LGR(B) to the upper zone of LGR(D) with downward vertical component of over 30 ft within 120 ft of vertical stratigraphy. All of this groundwater appears to be perched above the hydraulic head of the main aquifer body by approximately another 30 ft. Horizontal flow with a small downward vertical component prevails within the lower portion of LGR(D), LGR(E), and LGR(F).
- Multi-level well CS-WB04 is completed through all members of the Middle Trinity aquifer. Data from this location mimics the LGR findings of the previous paragraph. For the data set gathered thus far, the BS has shown an upward gradient relative to the LGR by as much as 10 ft of hydraulic head. This would indicate the BS is serving as a confining unit to the LGR Limestone. However, additional data from quarterly events show that the BS hydraulic head relative to the LGR is variable, and can also indicate downward vertical flow at times. The CC Limestone essentially shows horizontal flow, and exists at a hydraulic head that is as much as two ft below the LGR, and 12 ft below the BS.

4.3.2 Porosity and Karst

For the LGR aquifer, the terms of "regional" and "local" have been used by Hammond (1984) and others to describe components of groundwater flow. According to Hammond, groundwater movement occurring through pore spaces associated with fabric selective permeability is described as "regional", and is typified by slow moving, laminar flow groundwater. "Localized" groundwater systems consisted of those smaller portions of the aquifer that were dominated by voids of secondary not fabric porosity, and are characterized by turbulent and rapid groundwater movement. GVA (2002) suggested the use of “diffuse” and “conduit” flows as defined by White (1969). While diffuse flow describes the same characteristics of the “regional”, and is defined by having a slow and subdued hydrograph and geochemical response to recharge. Likewise, conduit exhibits the properties of “localized” flow and exhibits rapid hydrograph and geochemical responses to recharge. GVA’s report cites Worthington et al. (2000) who demonstrated that while only 0.05 to 2.8 percent of groundwater in karst aquifers is stored within conduits, 94 to 99.7 percent of the water that moves through karst aquifers over time moves through conduits.

Veni (1997) made some basic regional observations of the permeability structure of the LGR, such as that honeycombed units are particularly effective cave formers, calcarenites are generally good cave forming units, marly and nodular limestone units are typical moderate to poor cave formers, and caves predominantly form along fractures rather than bedding planes. Additionally, Veni et al (1998, 2000) found that most cave entrances occur from 35-50 ft below the UGR/LGR contact, which corresponds to the model layer LGR(A) put forth in this HCSM. On a regional scale, the uppermost cave passage development was noted to occur 80-115 ft below the UGR/LGR contact (upper portion of model layer LGR[C]) in the Cibolo Creek area north of CSSA. Regionally, a lower level of passage development can also occur 130-150 ft below the UGR/LGR contact (middle portion of model layer LGR[C] equivalent).

There is evidence of karst development along some of the streams on post. Estavelles, vertical karst conduits, are present in the Salado Creek streambed at several locations in the northern portion of the inner cantonment. These karst features provide a direct pathway for stream flow to recharge the LGR and can contribute to the rapid recharge response observed in the on-post wells.

Thus far, CSSA drilling activities have been mostly focused on the contamination plume of the main aquifer body. Only a handful of wells near AOC-65 monitor the lower portion of interval UGR(D) and UGR(E). The remainder of the environmental wells monitors the “regional”, or diffuse portions of the Middle Trinity aquifer. The LGR wells almost exclusively monitor the basal biostrome above the BS. The BS wells typically monitor the middle portion of a relatively impermeable unit, and the CC wells monitor groundwater within the upper portion of the member. Over the course of drilling 47 environmental wells, only a handful of notable large karst or fracture features were encountered. These features were most notable due to either the loss of fluid circulation, slight drops in the drill stem, or significant increases in groundwater production.

4.3.3 Faults/Fractures

According to Veni (2002), fractures are the primary structural features known to affect conduit development and associated groundwater flow in Bexar County. This aspect of conduit development has been studied by Veni at CSSA and nearby locations, most notably at Camp Bullis to the east. The data has suggested that the 60˚-99˚ range of fracturing are typically the most permeable, reflecting the influence from the Balcones fault trend. The Phase One Hydrogeologic Investigation (Veni, 2002) performed at CSSA demonstrated that fractures that developed into karst features showed a strong preference for the 140˚-159˚ range. These karst-developed fractures within both the UGR (ten locations) and LGR (two locations) usually trend approximately at 145˚, and are more or less perpendicular in orientation to the Balcones fault trend. Veni states that the perpendicular orientation of the fracture trend was probably key in the location and orientation of Salado Creek at CSSA.

The effect of fracturing has long been considered as a primary controlling feature dictating the direction and path of groundwater and contaminant migration. While the true nature of structural breaches in the rock are not completely understood, some assumptions can be made. First of all, fractures within an exceptionally fine-grained matrix (e.g., mudstones and wackestones) will likely create a more permeable avenue for migration than the actual rock matrix itself. This aspect is important to the distribution and migration of both recharging groundwater and contaminant migration. A well-developed fracture system can distribute fluids both along vertical and horizontal axes in an erratic pattern. In the vadose zone, gravity will be the driving force such that the primary direction of migration will tend to be downward. Within the phreatic zone, the advective forces of moving groundwater will impart a much larger horizontal component of movement. Depending on the aperture of the fracture, the opening may either be enlarged by karstic dissolution or reduced (or even closed) by mineralization or clay infilling.

Fracturing is often the primary response to structural faulting, but can be associated with weathering, temperature, and mass unloading. As shown on the USGS Geologic Map (Figure 4.1), at least 11 regional fault zones that trend with the Balcones Escarpment (NE-SW) have been identified or are inferred to transect the CSSA property. The USGS report on the *Geologic Framework and Hydrogeologic Characteristics of the Glen Rose Limestone at Camp Stanley Storage Activity, Bexar County, Texas* (Clark, 2003) indicates that most fault displacements are 20 ft or less. The fault zones inferred on the geologic map may actually represent a system of closely-spaced faults, each of which has a minor displacement occurring over a relatively small area, yet having a total displacement of many tens of ft. This hypothesis has been validated by the drilling effort, especially where there has been a high concentration of investigative borings. A high degree of faulting has appeared to have occurred at the southern portion of facility. This “shatter zone” is reflected in the geologic map as evidenced with the area with the greatest amount of displacement across the facility.

In the end, faulting can greatly alter the hydrogeologic regime by juxtaposing less permeable rocks against more permeable water-bearing rock. The amount of displacement along a fault plane can be critical to its overall influence on the hydrogeology. Fault planes with minimal displacement, ranging from inches to 10 ft, probably do not have a large impact on regional groundwater flow patterns at CSSA. Unless the fault plane has been enlarged or brecciated, groundwater will most likely flow across the structural feature with little to no impedance. Only the thinnest of water-bearing beds (less than 10 ft thick) may result in a barrier condition in which water cannot cross the plane. That groundwater would ultimately be redirected in the direction of decreasing head parallel to the fault, or downward along the fault plane or underlying rocks at a significantly reduced flow rate. A series of closely spaced faults with minimal displacement will have the net effect of conducting groundwater deeper over a relatively short distance. Drastic changes in groundwater gradient represented on a potentiometric map can represent the impact that stepwise faulting may have on a groundwater system. The net effect may result with inconsistent water levels in wells completed within the same strata in different fault blocks. This has been observed in the PZ wells around AOC-65, particularly between PZ-1 and PZ-5.

At CSSA, structural displacements of 10 ft or more can begin to have significant effect on groundwater flow and direction. Once more than 50 percent of a permeable groundwater strata has been occluded by less permeable juxtaposed strata, a "barrier" fault condition has been created. By its very nature, a barrier fault will impede movement across the fault and redirect groundwater flow to those areas with a lower head, whether that direction is horizontal or vertical. These large-throw faults also have the ability to cause co-mingling or cross-contamination of individual confined water-bearing units that otherwise normally have little to no interaction. A single fault with a large displacement can ultimately be responsible for juxtaposing an upper contaminated interval with a lower, non-impacted interval. In the CSSA area, because there are no known faults with over 65 ft of displacement, the LGR is not thought to have direct communication with the CC Limestone.

4.4 GROUNDWATER FLOW

Groundwater elevation data are collected at CSSA as part of the groundwater monitoring program. Groundwater elevation measurements are collected from CSSA's on-post wells during each quarterly sampling event. Additional groundwater elevation data are collected on a weekly or monthly schedule. These groundwater elevations were measured with an electric water level indicator (e-line). A groundwater elevation for off-post well FO-20 is also obtained from Fair Oaks Water Utilities to correspond with the quarterly sampling event. In general, the construction of each wellhead at the remaining off-post wells does not allow an e-line water level indicator to be used. The exception is off-post well RFR-10, which has been retrofitted with an e-line drop tube.

To assist in evaluating the influence of precipitation upon groundwater elevations, a meteorological station and a downhole water level transducer were installed at well CS-16 in August 1995. A more sophisticated transducer was installed in January 1999. The transducer was removed briefly while CS-16 was upgraded to CS-16-LGR in June 2002. Since then, sixteen other transducers have been in various wells throughout the Middle Trinity aquifer below CSSA. Transducers collect groundwater elevation data on a programmable schedule, usually set for every three hours.

The average change in quarterly groundwater elevations compared to the previous quarterly event is calculated and compared to the amount of precipitation recorded at the CSSA CS-16-LGR weather station. An overall summary of changes in the groundwater elevation, precipitation, and the approximate groundwater gradient flow direction is given in Table 4.2. This table presents data collected since September 1999. Groundwater levels collected prior to September 1999 could not be compared among the three formations present at CSSA because the wells completed before that date were not distinct among the three formations. It is important to note that the number of monitoring wells used for these statistics increased from 14 to 37 wells between June 2001 and June 2007.

Table 4.2 Comparison of CS-16-LGR Weather Station Precipitation and Average Overall Groundwater Elevation Change

Report Period (Date of quarter end)	Total Quarterly Precipitation (inches)	Average Groundwater Elevation Change* (ft)	CS-16-LGR Groundwater Elevation Change* (ft)	Average GW Elevation in each Formation (ft MSL)			Approx. Gradient (ft/ft)	Approx. Gradient Flow Direction
				LGR	BS	CC		
Sep-99	7.52	-188.4	-136.82	979.80	--	--	0.007	SW
Dec-99	2.84	-4.9	-8.13	973.10	--	--	0.004	SW
Mar-00	3.58	-9.3	-1.28	970.94	--	--	0.009	South-SE
Jun-00	11.1	11.77	0.29	976.27	--	--	0.006	SE
Sep-00	1.96	-6.34	-13.28	967.03	--	--	0.006	SE
Dec-00	14.48	122.99	142.19	1118.59	--	--	0.005	South-SE
Mar-01	10.13	53.19	48.07	1157.20	--	--	0.0125	SE
Jun-01	6.58	-47.5	-48.04	1104.00	1106.85	1093.89	0.007	SE
Sep-01	14.73	23.96	13.44	1140.55	1098.18	1095.75	0.0067	SE
Dec-01	10.16	15.46	28.21	1149.68	1131.36	1125.63	0.0092	SE
Mar-02	2.25	-70.97	-74.03	1077.91	1064.46	1059.27	0.0086	SE
Jun-02	4.46	-48.29	-53.41	1030.51	1022.51	994.02	0.0137	South-SE
Sep-02	30.98	104.5	113.27	1130.87	1129.21	1098.34	0.017	South-SE
Dec-02	12.91	19.48	33.89	1143.98	1148.26	1133.11	0.0061	South-SE
Mar-03	6.22	-8.47	-10.11	1135.18	1140.52	1122.95	0.012	South-SE
Jun-03	4.67	-41.08	-37.1	1097.87	1095.36	1069.02	0.0022	South-SW
Sep-03	8.05	-52.85	-52.21	1046.77	1060.39	1025.61	0.0045	South-SE
Dec-03	2.79	-32.85	-38.68	1011.38	1029.39	1002.07	0.018	South-SW
Mar-04	6.35	29.23	35.15	1046.61	1030.75	1020.50	0.016	South-SE
Jun-04	12.95	71.91	84.31	1121.80	1101.85	1074.56	0.0012	South-SW
Sep-04	14.3	-8.05	-19.31	1106.43	1110.17	1074.96	0.003	South-SE
Dec-04	21.04	63.07	74.82	1173.98	1159.46	1135.16	0.004	South-SE
Mar-05	7.38	-6.47	-7.67	1168.46	1151.60	1127.58	0.00436	South-SE
Jun-05	NA	-45.93	-53.66	1119.19	1125.27	1082.40	0.0041	South-SE
Sep-05	NA	-61.24	-62.95	1054.88	1077.87	1033.65	0.0068	South-SW
Dec-05	NA	-57.9	-63.86	994.23	1023.45	980.25	0.0054	South-SW
Mar-06	2.52	-24.81	-7.16	974.10	990.23	948.80	0.0084	South-SW
Jun-06	7.65	-9.46	-3.57	966.16	983.47	933.59	0.0104	South-SW
Sep-06	3.42	-6.66	-1.42	961.07	979.78	922.34	0.0099	South
Dec-06	4.68	2.48	0.75	958.87	979.73	933.37	0.0099	South
Mar-07	9.86	14.53	-0.11	969.87	992.53	958.06	0.00474	South
Jun-07	11.96	176.6	185.13	1162.17	1119.36	1128.32	0.0016	SE
Sep-07	29.4	15.56	5.46	1168.77	1168.14	1154.47	0.0019	South
Dec-07	1.95	-70.45	-76.43	1095.68	1101.19	1088.93	0.0052	South-SE

1 Data derived from CSSA Quarterly Groundwater Reports
*Change since previous quarter

Generally, the depths-to-water at CSSA range from approximately 50-280 ft bgs, dependent upon the land surface elevation. During periods of heavy precipitation, water levels have reached as high as 45 ft bgs (following the October 1998 flood event). During drought conditions groundwater elevations have been as deep as 375 ft (June 2000).

4.4.1 Potentiometric Maps

The potentiometric maps representing measurements collected from December 2002 through December 2007 are included in Appendix A. For this HCSM, these recent monitoring events have been chosen since they represent the time period with the greatest amount of data collection points. By June 2004, the cluster well monitoring network had been installed. The well installation monitoring program allows each portion of the Middle Trinity aquifer to be monitored individually. Prior to June 2001, most groundwater data was obtained from open hole completions, which penetrated one or more members of the Middle Trinity aquifer. The most recent data gives the best look of the individual geologic members, which make up the hydrogeologic regime. Additional information on potentiometric maps for previous quarterly monitoring events is included in previously submitted Quarterly Groundwater Reports (**Volume 5, Environmental Encyclopedia**).

Upper Glen Rose

Basewide, there is very little data available regarding the UGR groundwater elevation. Many RFI borings have been drilled into the UGR and monitored for the accumulation of groundwater. Thus far, no freely yielding groundwater unit has been encountered within the UGR postwide. Past experience has shown that most 30-foot borings will eventually accumulate small quantities of water if allowed to stay open long enough. During the early 1990's, a series of shallow wells were drilled around former underground storage tank (UST) sites at CSSA. Those wells were poor producers, and were subsequently plugged and abandoned as specific site closures were granted by the TCEQ.

Currently, most of the UGR data generated comes from a series of shallow wells drilled in a tightly spaced vicinity of AOC-65. General conclusions indicate that UGR groundwater in that vicinity is sporadic and discordant. These conclusions are derived from shallow monitoring wells and vapor extraction wells (less than 35 ft bgs) that have been drilled around Building 90, and include both MWs and VEWs. Significant work performed around AOC-65 has demonstrated that the UGR groundwater, when present, is variable over short distances. Some wells remain dry, while nearby wells at equivalent depths will accumulate a measurable amount of groundwater, on the order of several feet.

Periodic monitoring indicates that the UGR wells are slow to yield and recharge with groundwater. There has been suspicion that water accumulation within very shallow (less than 12 feet) VEWs around Building 90 is derived water from utility leaks. At the same location, slightly deeper wells in the UGR will react to significant precipitation, and recharge can quickly add a measurable amount of water that is eventually lost back to the formation. Overall, the groundwater accumulation in these wells is slight, and are very slow to recover when bailed dry. However, the greatest contaminant concentration found at CSSA exists within a 19-foot nested well located just west of Building 90. At this time there is inconclusive data to construct accurate potentiometric surface maps for the UGR.

LGR

Historical water level data at CSSA shows that typical groundwater flow gradient is towards the south, with directional variations ranging from the SW to the SE, depending on the level of recharge. During extended periods of drought, the flow direction reflects a greater westerly component of flow. The potentiometric maps (representing 21 monitoring events) were generated using Surfer™ v7.0, and are presented in Appendix A. These potentiometric maps use elevations measured from fully penetrating wells open to the basal portion of the LGR. Recent work from the Westbay multi-port wells and AOC-65 piezometers has demonstrated that LGR wells that are not fully penetrating usually have an elevated hydraulic head relative to the fully penetrating wells. This effect is associated perched water-bearing strata above the highly permeable LGR(F) zone, and contributes to the overall downward gradient within the LGR. Using this criteria, wells that are not fully penetrating to the LGR(F) zone are not considered during the potentiometric mapping (CS-4, CS-D, CS-G, CS-MW11B-LGR, and all AOC-65 VEWs and PZs).

In addition, multiple public supply wells (CS-1, CS-9, CS-10, CS-11, FO-20, and RFR-10) are considered within the LGR potentiometric maps. While these wells a fully penetrating and open to the Middle Trinity aquifer (LGR, BS, and CC), the resultant water level of the open borehole best reflects the expected hydraulic head of the LGR. However, it can be expected that the water level between a LGR well and a borehole open to the entire Middle Trinity aquifer will be somewhat discordant. During much of the year, an overall downward gradient from the LGR to the CC is evident at CS-WB04 and CS-WB05. It is logical in an open borehole that LGR groundwater is lost to the CC strata, and resultant water level within the borehole would be similarly depressed. However at this time, for this HCSM it has been deemed that the open borehole style of fully penetrating wells into the Middle Trinity aquifer are best represented with the LGR both from a hydraulic and contaminant distribution perspective.

The potentiometric surface maps, as well as those from previous monitoring events, indicate highly varying flow directions in the LGR. From December 2002 through December 2007, the overall direction of groundwater flow is predominately to the south-SE. Groundwater flow in this unit is apparently influenced by groundwater mounding in the vicinity of well CS-MW4-LGR. Groundwater appears to move in several directions from this groundwater mound, which may be the result of well CS-MW4-LGR intersecting a significant recharge feature. The proximity of CS-MW4-LGR to Salado Creek is possibly the cause of a consistently higher potentiometric surface near this well. It is possible that this feature is over-stated during the gridding process; however, this mounding effect remains as one of the most notable features of the groundwater surface.

During the drought between March 2005 and March 2007, groundwater levels in LGR plummeted by an average of 210 feet from their pre-drought elevations. During the peak of the drought in September and December 2006, the mounding effect noted at CS-MW4-LGR was muted by the distressed aquifer levels (Figures A-46 and A-49). Upon its rebound, the mounding effect near Salado Creek resumed. The addition of wells CS-MW20-LGR, CS-MW21-LGR, and CS-MW22-LGR in Spring 2007 have helped define the groundwater mounding to the south and southeast.

Common elements to each map in addition to the CS-MW4-LGR mounding include southeasterly flow in the southern portion of the post, and easterly flow in the North and East Pastures. The removal of well CS-G from the gridding process negates mounding effect is present at well CS-G that disrupts the normal southerly and easterly components of the North Pasture. This well is not fully penetrating to LGR(F) and therefore is not considered within this map.

Bexar Shale

Currently, groundwater head information is limited to four data points (CS-MW1-BS, CS-MW6-BS, CS-MW9-BS, and CS-MW12-BS). At best, the BS groundwater maps should be considered qualitative. The BS appears to have very limited groundwater that is likely associated with fracturing. Fractured bedrock such as this often results in discordant water levels between neighboring points. The appropriateness of preparing potentiometric surface maps for the BS is debatable, but these maps have been generated for completeness. Potentiometric maps for the Bexar Shale are presented in Appendix A.

Figure A-2 shows how the only three available data points for December 2002 form a line from the MW9 cluster to the MW6 cluster. In March 2003, the BS water levels did not vary by more than 11 ft postwide, with flow radiating from the highpoint at CS-MW12-BS. In comparison, the June and September 2003 data set shows a strong northward gradient from CS-MW6-BS towards CS-MW9-BS, with nearly 50 ft in head loss between the extremes. An interesting observation is the amount of declining head between the two events increases dramatically in the northernmost wells. Only a 7-foot head loss was measured at CS-MW6-BS, versus the 65-foot differences at CS-MW12-BS and CS-MW9-BS. Over the same time period, only 35 to 40-foot declines were observed in the LGR wells. The interaction of the BS with other hydrologic units is addressed further in Section 4.5.2.

By September 2005, the beginning stages of a significant drought had started, and aquifer water levels were on the decline. As the 2005-2006 drought progressed, the potentiometric surface maps between December 2005 and March 2007 (Appendix A) indicate potentiometic depression that occurs in the vicinity of well CS-MW12-BS. It is speculated that as the drought conditions persisted, the affect of long-term water production from wells CS-9 and CS-10 to the southwest became evident in the BS. In this instance, as the LGR became more depleted and groundwater production relied more on the CC portion of the aquifer, a strong downward vertical gradient was created. Invariably, the small quantity of groundwater in the BS responded to the downward gradient in the vicinity of the production wells. It is not known if this phenomenon represents any significant structural feature that may facilitate vertical leakage. By June 2007, the significant precipitation received during that year recharged the aquifer, and the phenomenon ceased to persist.

Cow Creek

As with the BS, the postwide monitoring of the CC groundwater is limited due to the small number of wells completed only in the CC. Potentiometric maps for the CC are presented in Appendix A. Four of the nine CC wells are concentrated in the vicinity of AOC-65. The lack of temporal data makes definite conclusions impossible, but the earlier monitoring periods (December 2002 and March 2003) indicate flow northward from Plume 1 (Inner Cantonment) towards the North Pasture, and southerly flow near AOC-65 in the SW corner. Subsequent quarterly events included an expanded monitoring network. Data from these later events suggest a strong westerly component of groundwater flow. Presumably, this groundwater flow pattern has been induced by groundwater pumping at CSSA, Fair Oaks, and other residential consumers to the west. It is also possible that this directional shift is a response to the drought conditions that affected the region for most of 2003, or a combination of the two factors.

Beginning March 2004, a long-term pilot study was undertaken at well CS-MW16-CC. At this location, CC groundwater was extracted at an average rate of 12 gpm and treated and released through a permitted outfall. Between March 2004 and September 2005, the affects of the CC pumping action have been evident in nearby wells CS-MW1-CC and CS-MW2-CC. During this time period, the CC groundwater gradient in the central portion of CSSA was dramatically affected by the CS-MW16-CC pumping test such that gradient reversal towards the pumping well occurred. Transducer data has indicated nearly a 7-foot drawdown in wells nearly 2000 feet away (CS-MW1-CC and CS-MW2-CC) in direct response to the start of pumping. The fact that CC well can invoke such a drawdown at that distance within the CC is compelling evidence that the BS is a competent confining unit in this vicinity. However, overall easterly gradient indicated during this timeframe is likely overstated during the gridding process because sparse data set. It is quite possible that strong westerly and southerly components still existed during this timeframe, but the sparse well data cannot confirm this conclusion.

The CS-MW16-CC pilot study was concluded about the same time that a prolonged, 18-month drought was beginning in Central Texas. Initially when well CS-MW16-CC pumping ceased, a westerly component of flow resumed in the CC aquifer. Between September 2005 and June 2006, the westerly flow is dominated by a radial pattern emanating from well CS-MW2-CC, which is topographically higher than the other CC wells. However, as the drought progressed and aquifer levels declined, a southerly CC groundwater gradient emerged beginning September 2006, and persisted through March 2007. Even though the drought essentially ended in the beginning of 2007, the rebounding effects of active precipitation season of 2007 did not manifest itself in the CC aquifer until sometime after March 2007.

4.4.2 Aquifer Interaction

The Middle Trinity aquifer is a dynamic system that is continually balancing the interacting forces of recharge, discharge, and gravity. Two significant considerations are the immediate effect of recharge upon the system, and how the connectivity of the water-bearing units (LGR and CC) are impacted by the presence of the BS. Seasonal variations can be monitored through the use of monitoring equipment and wells to help quantify the flux of groundwater moving through the system.

Response to Precipitation

The groundwater levels in the wells at CSSA have been monitored periodically since 1992; precipitation has been measured on post since October of 1998. For the period of record in which both precipitation and water levels have been recorded it is possible to examine, at least qualitatively, the response of the water levels to rainfall events. It is important to note that rainfall was recorded daily, but water levels were measured much less frequently. Generally the water levels were measured quarterly with additional monitoring after severe rainfall events, notably during the fall of 1998 and the late summer of 2002. The sampling effort was not identical at each well, so some wells have more data than others.

Figures 4.16 through 4.19 show the water levels for the wells on CSSA and daily precipitation. The wells are grouped according to the formation in which they are screened, with the open-borehole wells grouped together. For the open-borehole wells, the general pattern of water level over time is fairly consistent between wells, although there are some apparent deviations, likely due to differences in sampling effort. As an example, the water level in CS-9 does not immediately appear to have responded to the large rainfall event in October of 1998. However, the well was not sampled after the rainfall event until September of 1999. The water level in most of the other open-borehole wells did respond dramatically to the October 1998 rainfall, rising rapidly to a peak in mid-November and declining by mid-December. By September of 1999 the water levels in most of the wells had returned to elevations similar to their pre-October 1998 levels. Since CS-9 behaves like the other open-borehole wells for most of the period of record, it is likely that the water level in CS-9 also responded dramatically to the October 1998 rainfall, but this was not identified due to a lack of monitoring.

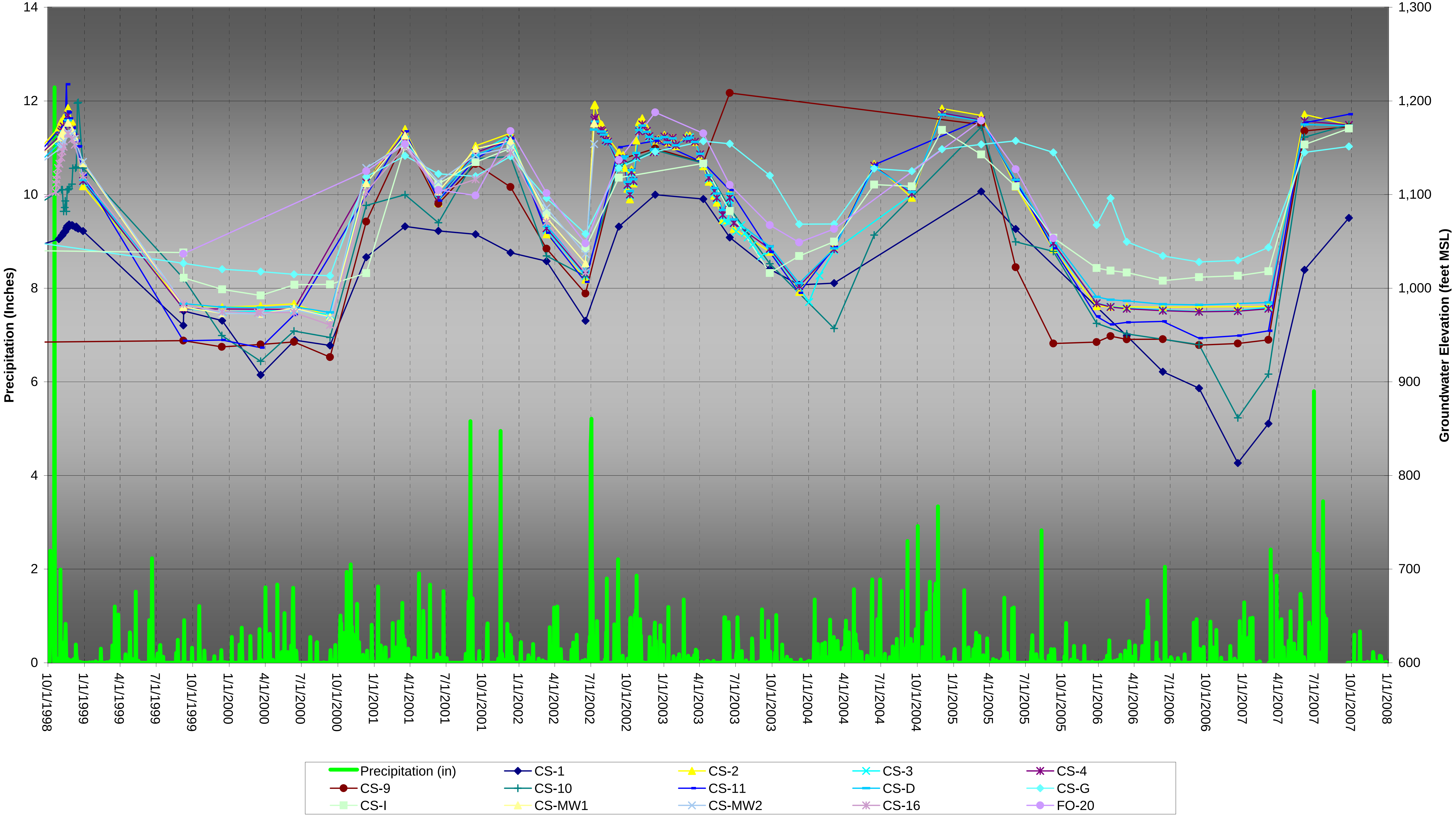
Figure 4.20 averages the record of water levels by geologic unit. With the exception of prolonged drought cycles, the general trend over the period of record is that the potentiometric head in a given unit generally corresponds to the order of the geologic strata. While there are temporal variations, the LGR is typically higher than the BS, which in turn has a higher head than the CC. However, because this graph does not differentiate between the spatial relationship between the wells (upgradient versus downgradient groundwater elevations), and therefore caution must be used when interpreting the figure since the data can easily skewed by position relative to the overall hydraulic gradient.

There are variations in the amplitude of the groundwater level fluctuations between wells. At one extreme, the water level in CS-11 has a range, from minimum recorded value to maximum recorded value, of 295 ft for the period of record, while at the other end of the spectrum CS-G has a range of only 149 ft. Both wells respond similarly to large rainfall events, in terms of their lag time, but their magnitude of response is somewhat different. However, one noticeable difference between the two wells is that CS-G lags in response to drought cycles. However, this may be partially attributable to being hydraulically upgradient of all the CSSA water production activities.

The response of the wells screened in the LGR Formation is similar, with the water level rising quickly after large rainfall events and dropping nearly as quickly (Figure 4.17). There is good agreement between wells, although occasional differences between the shapes of the water level curves do occur, but this is likely due to differences in sample frequency and not due to differences in recharge.

The water levels in the wells completed in the BS (Figure 4.18) and CC (Figure 4.19) behave similarly and are discussed together. There is significantly less data for the BS and CC wells than for the LGR or open-borehole wells, so it is difficult to fully interpret. Water levels were first recorded in June of 2001 and were measured quarterly thereafter until the summer of 2002, when sampling was increased in response to severe weather. In 2001, the water levels in the BS and CC wells were fairly constant, despite the fact that there were two large storm events in August and November (5.15 and 4.95 inches, respectively). It is possible that any fluctuations in response to the rainfall events were not recorded due to the lack of resolution provided by the

Figure 4.16
Hydrograph of Wells with Open Borehole Completions
December 1998 through September 2007



J:\743\743322 CSSA TO 08\11000 CSM Update\TO 008 HCSM\Figures&Tables\Hydrographs sorted by WL (TO8).xls

Figure 4.17
Hydrograph of Wells with Lower Glen Rose Completions
December 1998 through September 2007

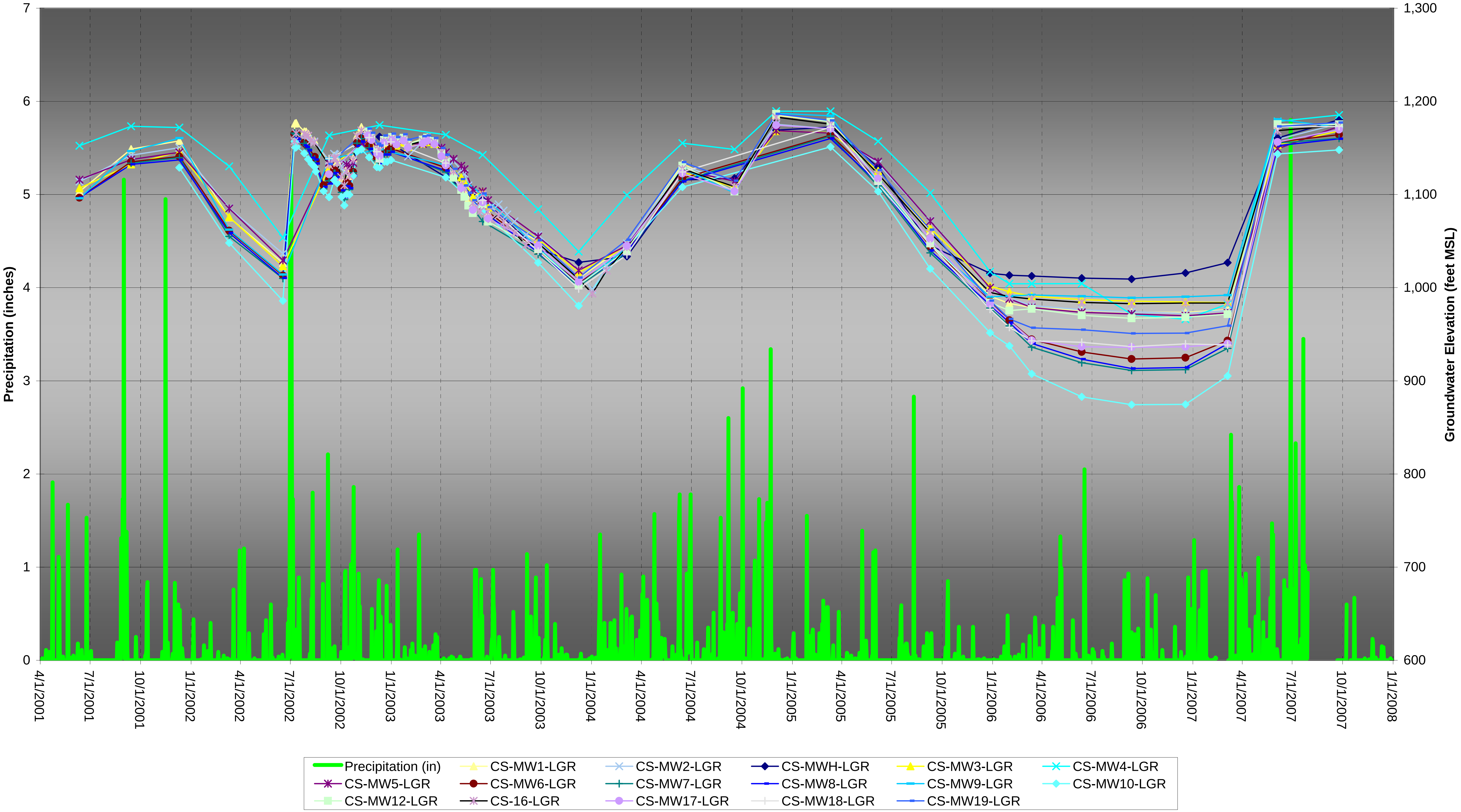


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Figure 4.18
Hydrograph of Wells with Bexar Shale Completions
December 1998 through September 2007

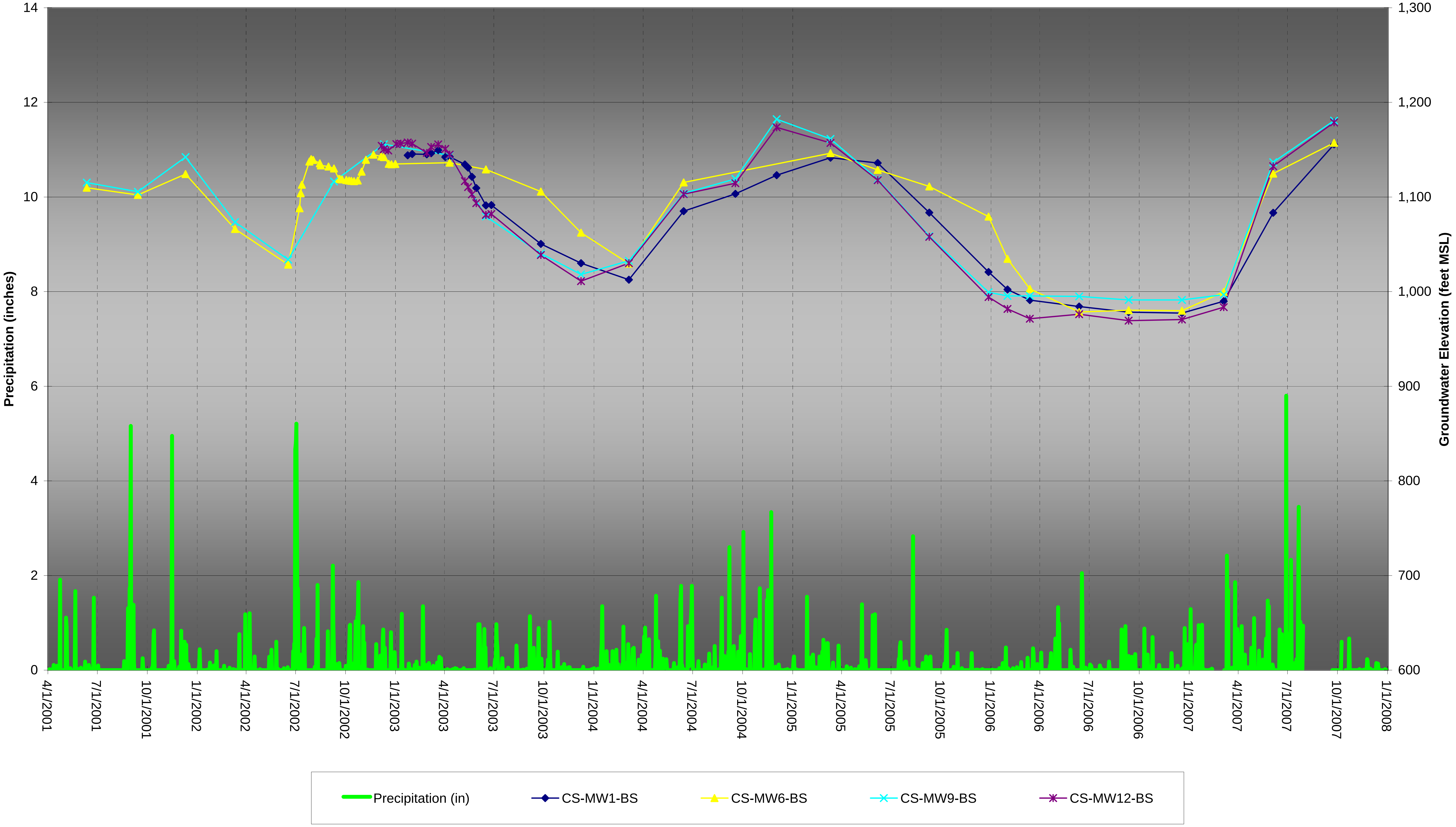

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Figure 4.19
Hydrograph of Wells with Cow Creek Completions
December 1998 through September 2007

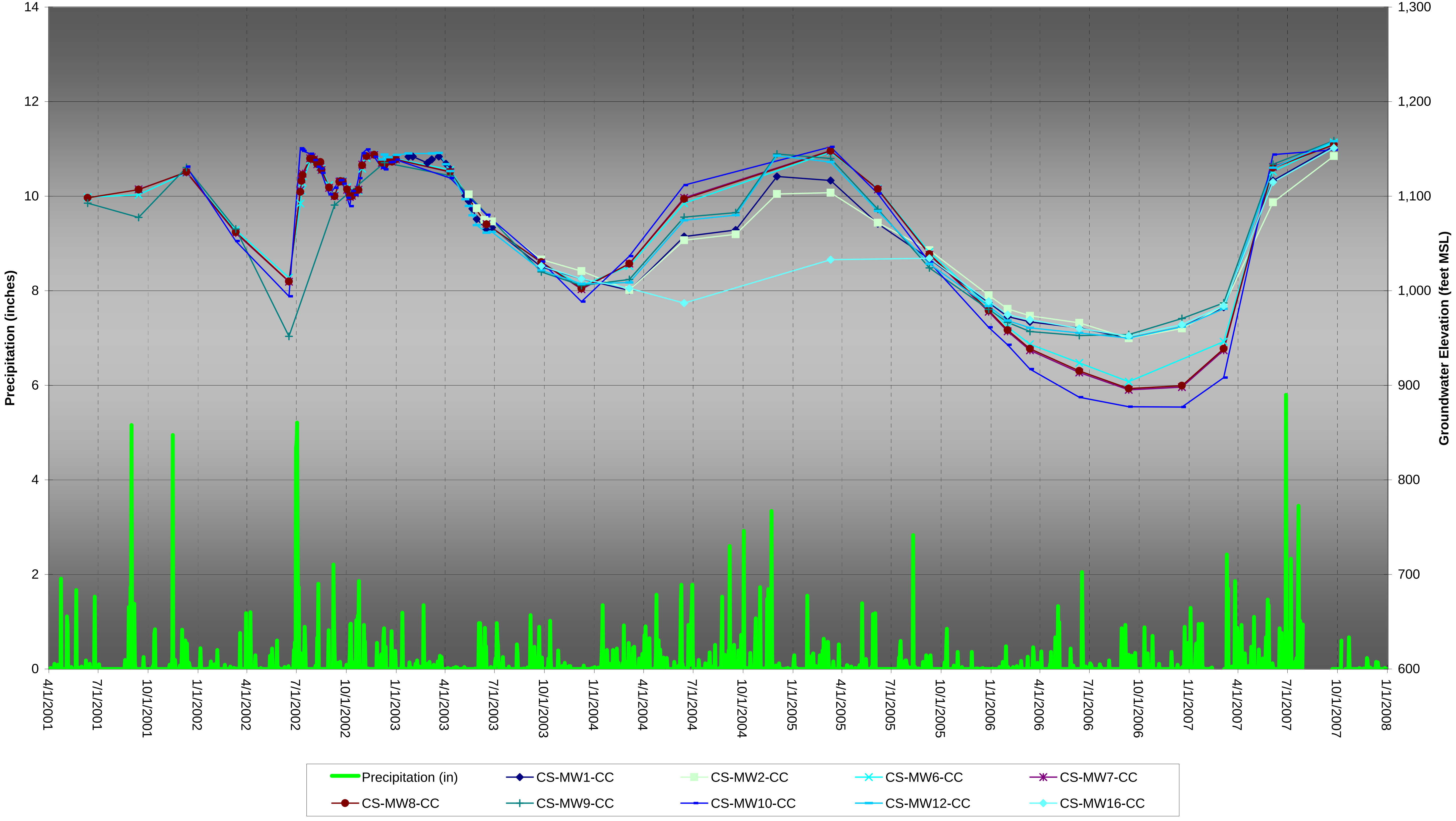

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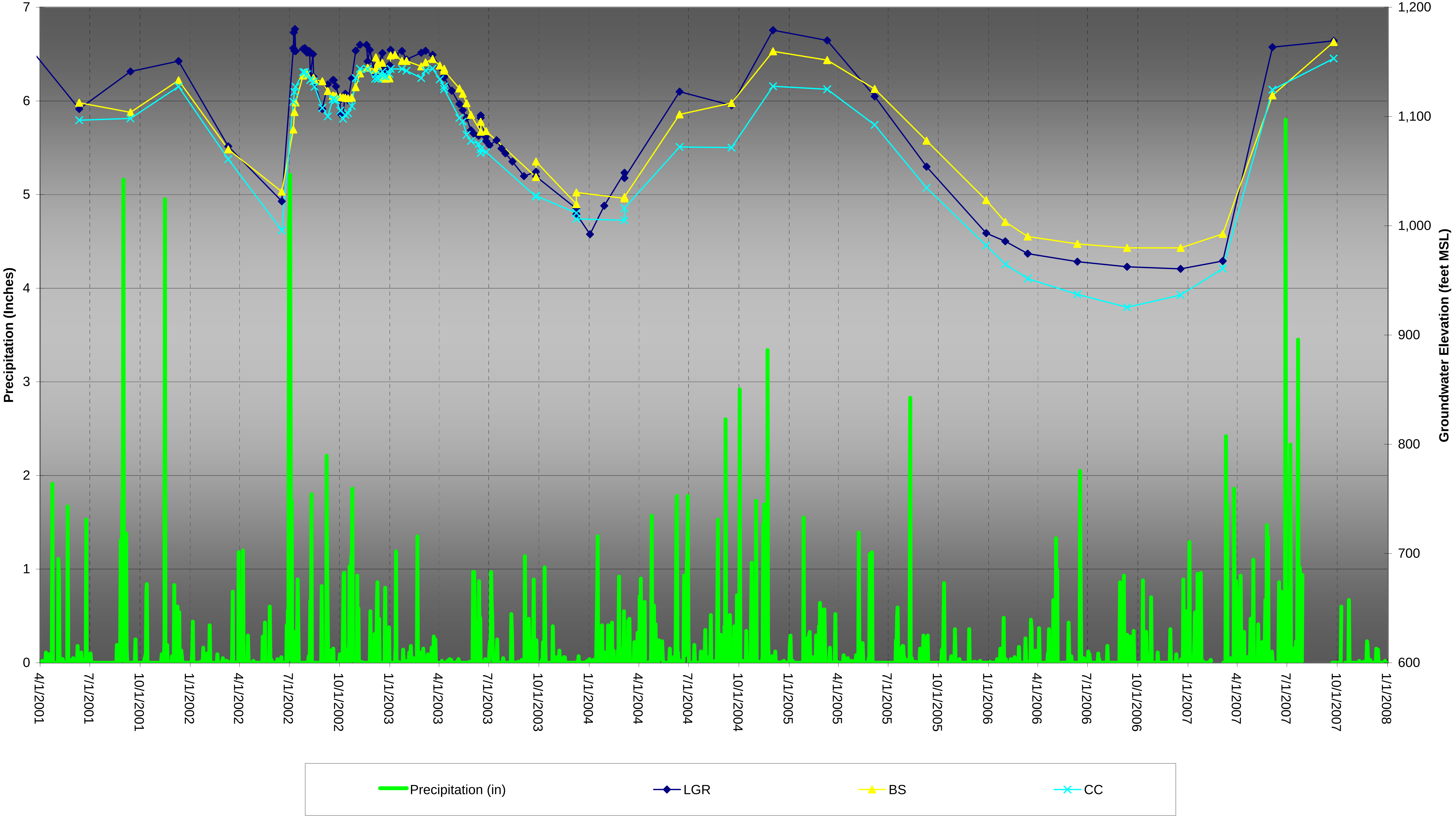
Figure 4.20
Hydrograph of Average Water Level Elevations by Geologic Unit
December 1998 through September 2007



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3-month sampling interval. It is also possible that the water levels were already quite high due to the fairly consistent rainfall during the fall of 2000 and spring of 2001, thereby damping any response to the large storm events towards the end of 2001.

For the first half of 2002, the water levels in the BS and CC wells declined steadily, reflecting the lack of rainfall. Following the heavy rainfall in July 2002, the water levels peaked over 100 ft higher than their June levels. This dramatic increase occurred rapidly with the peak water levels recorded three weeks after the storm event. For the remainder of 2002, the water levels in the CC and BS wells oscillated in response to various storm events with a lag time of approximately two weeks. The magnitude of these oscillations was not nearly as large as the magnitude of the increase between the June 2002 levels and their July peaks. In addition, the magnitude of the oscillations for wells in the BS was significantly less than for the wells in the CC Limestone.

Like the LGR, both the BS and CC responded with declining groundwater elevations during two cycles of drought between March 2003 and March 2007, and is well illustrated in Figure 4.20. It is noteworthy to mention that a long-term pumping test was performed at well CS-MW16-CC between March 2004 and September 2005, and the depressed groundwater elevation due to extraction is reflected in Figure 4.19.

Groundwater levels in the CSSA monitoring wells, irrespective of the formation(s) in which the wells are screened, largely reflected the pattern of rainfall and drought. Water levels peaked in the fall of 1998 and declined rapidly in 1999. The groundwater levels remained depressed throughout 1999 and most of 2000, but rebounded rapidly in response to the late precipitation of 2000. Water levels remained high throughout 2001 with some minor fluctuations in response to specific precipitation events, but started to decline in 2002. Following the heavy July 2002 rainfall, groundwater levels rebounded and exhibited dampened fluctuations similar to the previous year.

On the hydrographs (Figures 4.16 through 4.20), two drought cycles are notable features that affect all portions of the Middle Trinity aquifer. The first drought cycle occurred between March 2003 and February 2004 when the area only received approximately 20 inches of rainfall during the same time period. Water levels in CSSA wells declined by 125 feet or more by the end of the drought. Nearly 51 inches or rain in 2005 ended the drought cycle and returned the aquifer to its pre-drought levels.

Beginning March 2005, Central Texas entered a 2-year drought in which less than 42 inches of precipitation was received for the same duration. In fact, less than 17 inches of precipitation was received during the first 12 months of the cycle. As the drought persisted, water levels declined by more than 200 feet in most area wells, with some wells showing more than a 275-drop in water elevation. During this cycle, groundwater elevations were lowered to the top of the main aquifer production interval LGR(F), and for a time period, the CC portion of the aquifer was the predominant source of Middle Trinity groundwater. Once again, the drought cycle was ended by more than 45 inches of precipitation in 2007.

<u>*Seasonal Variations*</u>

Probably the most tangible effect of recharge to a karstic or fractured bedrock aquifer is the large range of groundwater elevation at individual locations that can be measured over time. At

CSSA, water level information for some wells goes back as far as 1992, with quarterly measurements being steadily collected since May 1994. Since 2001, the number of monitored groundwater wells has risen dramatically. The temporal data has shown that the aquifer storage can vary drastically in a short period of time with significant weather events, and the aquifer is rarely ever under a "steady-state" condition. Typically, aquifers that exhibit very large water level responses also imply very low storage capacity. While a karstic aquifer can transmit vast quantities of groundwater quickly, their overall porosity capable of storage can be low, especially when compared to an unconsolidated sand or gravel aquifer.

Figure 4.21 is a graphical depiction of the minimum and maximum groundwater elevation recorded in each well, and the calculated geometric mean groundwater elevation. The number of data points associated with each well is included in parenthesis along the x-axis. As expected, the older wells with numerous measurements show the greatest range of fluctuation when compared to the newer wells. The CSSA water supply wells (CS-9, CS-10, and CS-11) have the greatest fluctuation of water levels, which is due to the fact that those wells continue to be used during drought periods, resulting in drawdown.

From the data set used to create Figure 4.21, long-term monitoring has shown that the greatest fluctuation of groundwater has occurred at CS-11 (pumping well) with a net change over 295 ft. The average fluctuation of water levels was approximately 227 ft when the data set is weighted by well for the number of actual monitoring events. The lower water levels occur during periods of reduced precipitation (summer and winter) and/or droughts, while the higher water levels are associated with the increased fall and spring rainfall.

Figure 4.22 shows how the historical seasonal data plots within the maximum and minimum aquifer levels recorded at CSSA. An interesting aspect of this graphic is that the relative age of the well is evident by the data. Older wells with larger data sets have seasonal averages that fall well within the extreme recorded ranges. By contrast, the newer wells show seasonal extremes, which closely correspond to maximum/minimum water levels recorded (e.g., wells CS-MW20-LGR through CS-MW25-LGR). Most of the new wells have not experienced intense flooding events such as October 1998 or July 2002. The wells with long-term data prior to the RL83 drilling initiative clearly show that groundwater levels within the aquifer are at their highest during the fall season (October through December). Likewise, these same wells show that the time period with the lowest groundwater elevation normally occurs between January and March. Groundwater levels remain fairly low during the June through September season, and are slightly higher during April through June.

Beginning with the flood of October 1998, Figure 4.23 shows a hydrograph from well CS-16-LGR. This graphic illustrates the wide range of groundwater elevations that can occur within the Middle Trinity aquifer, and how the aquifer responds to significant precipitation. Between October 1998 and September 2006, the maximum recorded elevation was 1190.55 ft above mean sea level (MSL) in November 2004. This elevation occurred during an abnormally wet year when CSSA received over 50 inches of precipitation. Prior to that, the highest water table elevations have been associated with the flood events of October 1998 and July 2002, resulting in an LGR aquifer thickness over 250 ft.

Figure 4.21
Range of Groundwater Elevations in Selected Wells
1992-2007
Camp Stanley Storage Activity - Boerne, TX

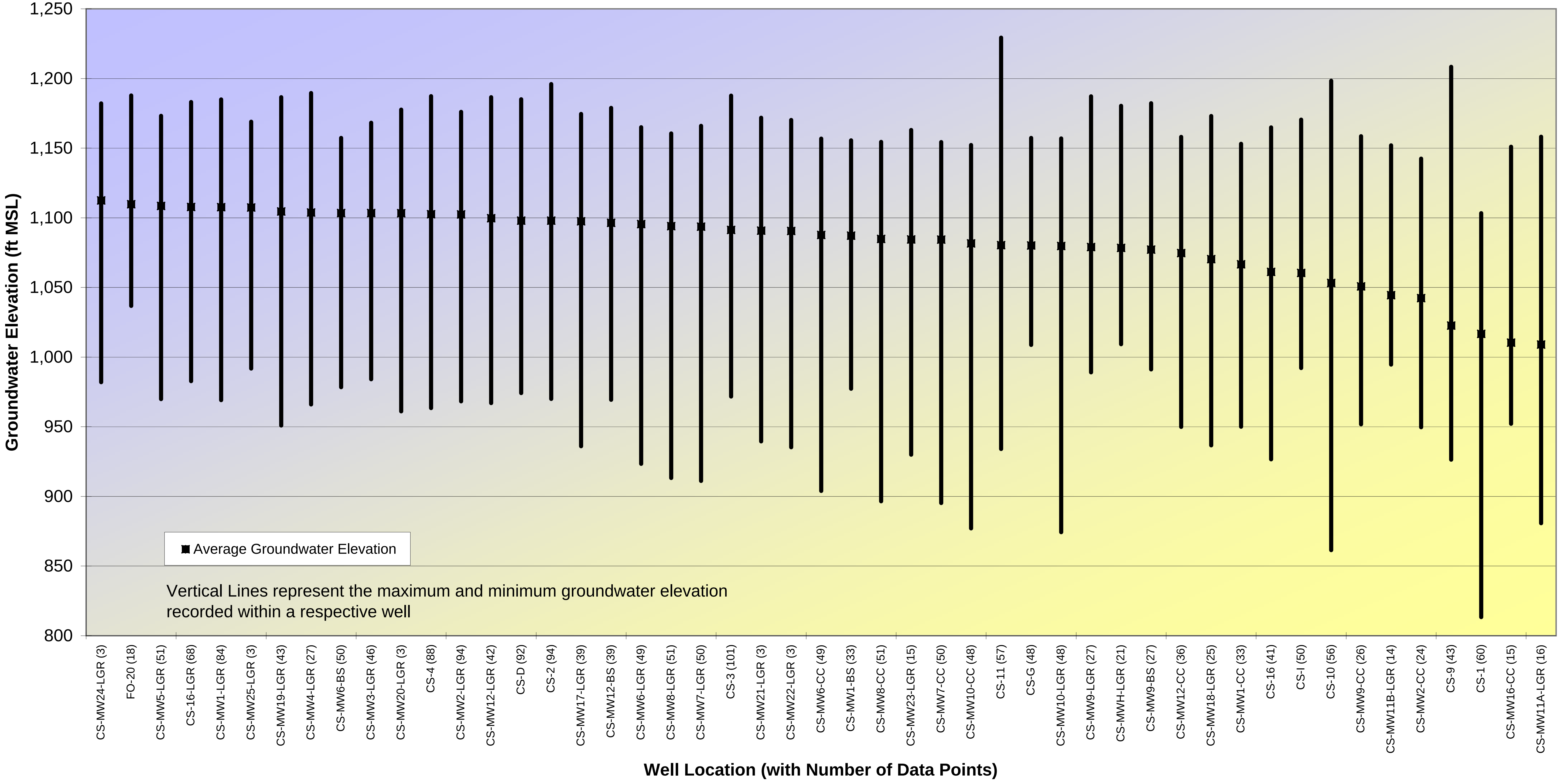

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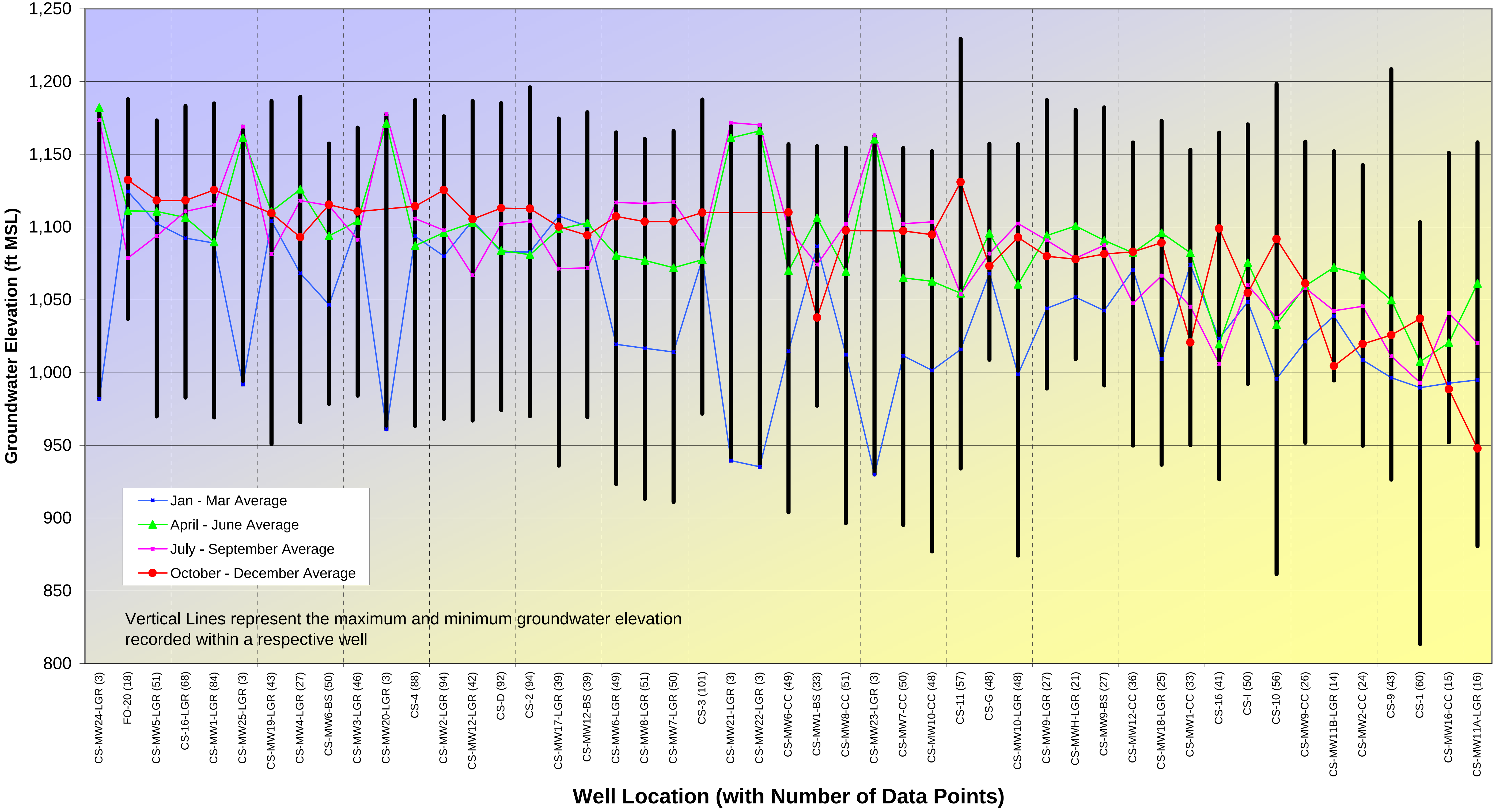
Figure 4.22
Seasonal Groundwater Fluctuations in Selected Wells
1992-2007
Camp Stanley Storage Activity - Boerne, TX



Vertical Lines represent the maximum and minimum groundwater elevation recorded within a respective well

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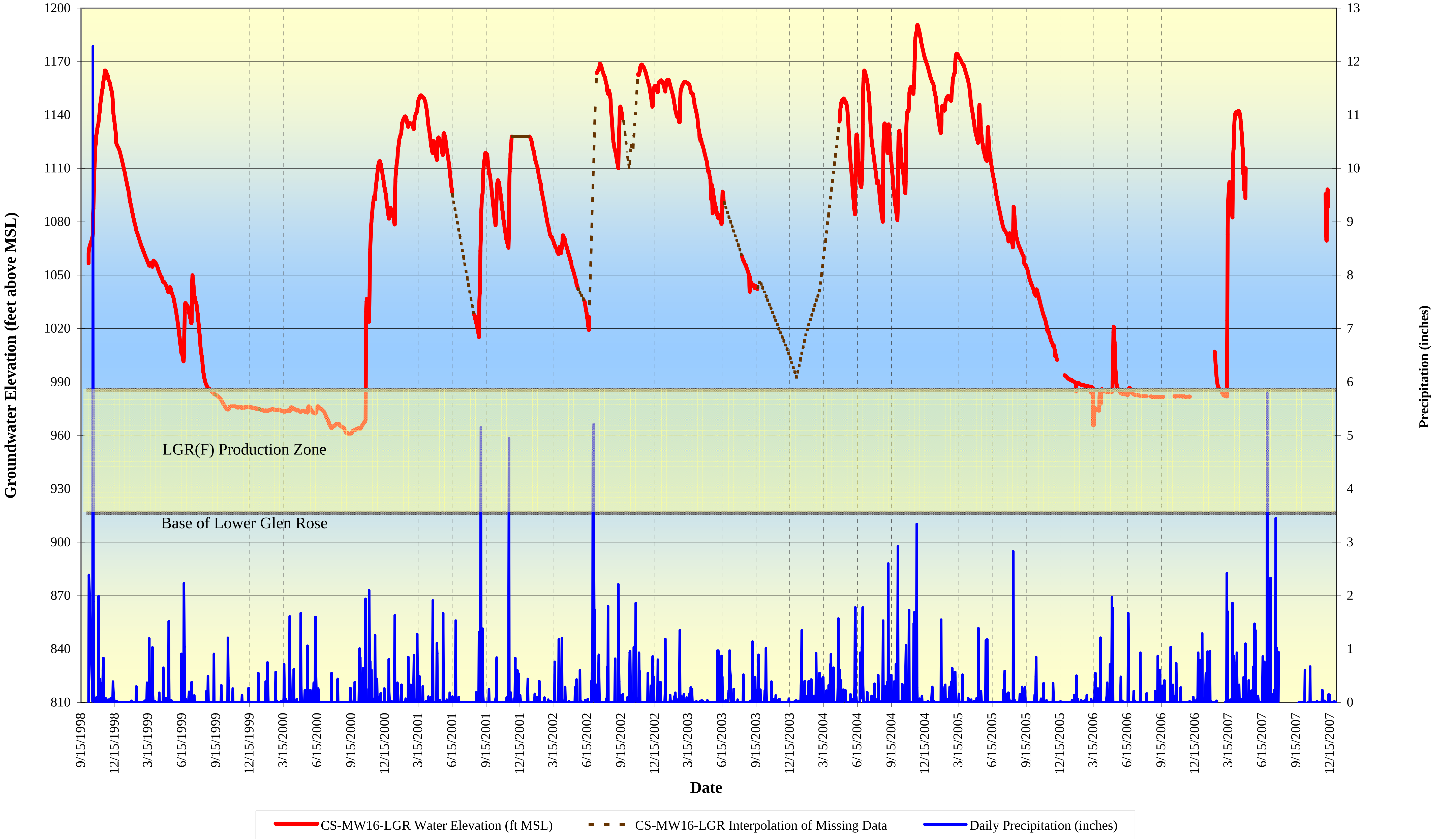
Figure 4.23
Hydrograph of Well CS-MW16-LGR and Precipitation Data



Missing data is interpolated for periods of transducer malfunction and/or removal during well construction.
Elevation of CS-MW16-LGR is 1243.4 feet MSL at top of casing.

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Likewise, the lowest recorded groundwater elevation occurred during the drought of 2000, at an elevation of 960.59 ft above MSL. During this timeframe, the approximate LGR aquifer thickness was less than 45 ft. Shallower LGR wells such as CS-D and CS-4 are susceptible to going dry (or very close) during these drought periods.

Well Cluster Data

Since November 2000, nine well clusters have been installed to discretely monitor individual members of the Middle Trinity aquifer in select locations. Each well cluster may consist of a well pair that monitors both the LGR and CC (four locations), or a well triplet that additionally monitors the BS (five locations). Cluster well data are useful in assessing the interconnectivity between the formations at a given location and determining the vertical component of groundwater flow.

Basic groundwater principle suggests that a groundwater zone with a higher head (*e.g.,* elevation) will move towards a zone with a lower head. However, more often than not this direction is typically in the downward direction, due to the force of gravity. However, it is possible to have a lower confined unit under artesian pressure that will have a higher head than an overlying unit. Such a condition is favorable for retarding the downward migration of contaminants. Figure 4.24 compares well cluster data obtained on a quarterly basis between December 2002 and December 2007.

The graphics show that at an individual location, the head in the LGR well is typically greater than in the CC well. The graphics also suggest that the head in the BS is often significantly greater than in the LGR or CC wells. The amount of dissimilarity between water levels within a cluster is a good indicator to the degree of hydraulic separation between the formational units. Intervals that are well connected hydraulically will have the same or very similar groundwater elevation. Wells in the vicinity of AOC-65 (CS-MW6, MW7, MW8, and MW10 clusters) show closer water levels between the LGR and CC than wells located northward (CS-MW9 and MW12 clusters). The elevated head of the BS in comparison to the LGR and CC wells would suggest that it could act as a hydraulic barrier to the downward migration of contaminated groundwater from the LGR.

The elements of Figure 4.24 are only random snapshots in time, and are better understood through analysis of an accompanying hydrograph. As an example, Figure 4.25 is a long-term hydrograph of transducer data collected from well cluster CS-MW9 in the North Pasture. For this discussion, the year 2002 was selected because it demonstrates the aquifers response to dramatic changes. The first half of 2002 represents end of a drought cycle, while the second half resulted with an above-average year for precipitation, and included flood-scale large rain events in July 2002. The figure shows how each formational member responds to recharge, or lack thereof. After careful study of the graph, it is evident that a variety of conditions can occur and that the graphics presented in the previous discussion are clearly “snapshots” of a dynamic system. Figure 4.25 shows that the LGR portion of the aquifer responds most dramatically and quickest to measurable precipitation. Response to precipitation in excess of 0.5 inches can occur within 24 hours of the rainfall event. The near-immediate reaction to precipitation indicates that recharge occurs along exposed portions of the LGR in Salado Creek, or northward along the outcrop at Cibolo Creek.

Figure 4.24
Comparison of Groundwater Elevations within Well Clusters

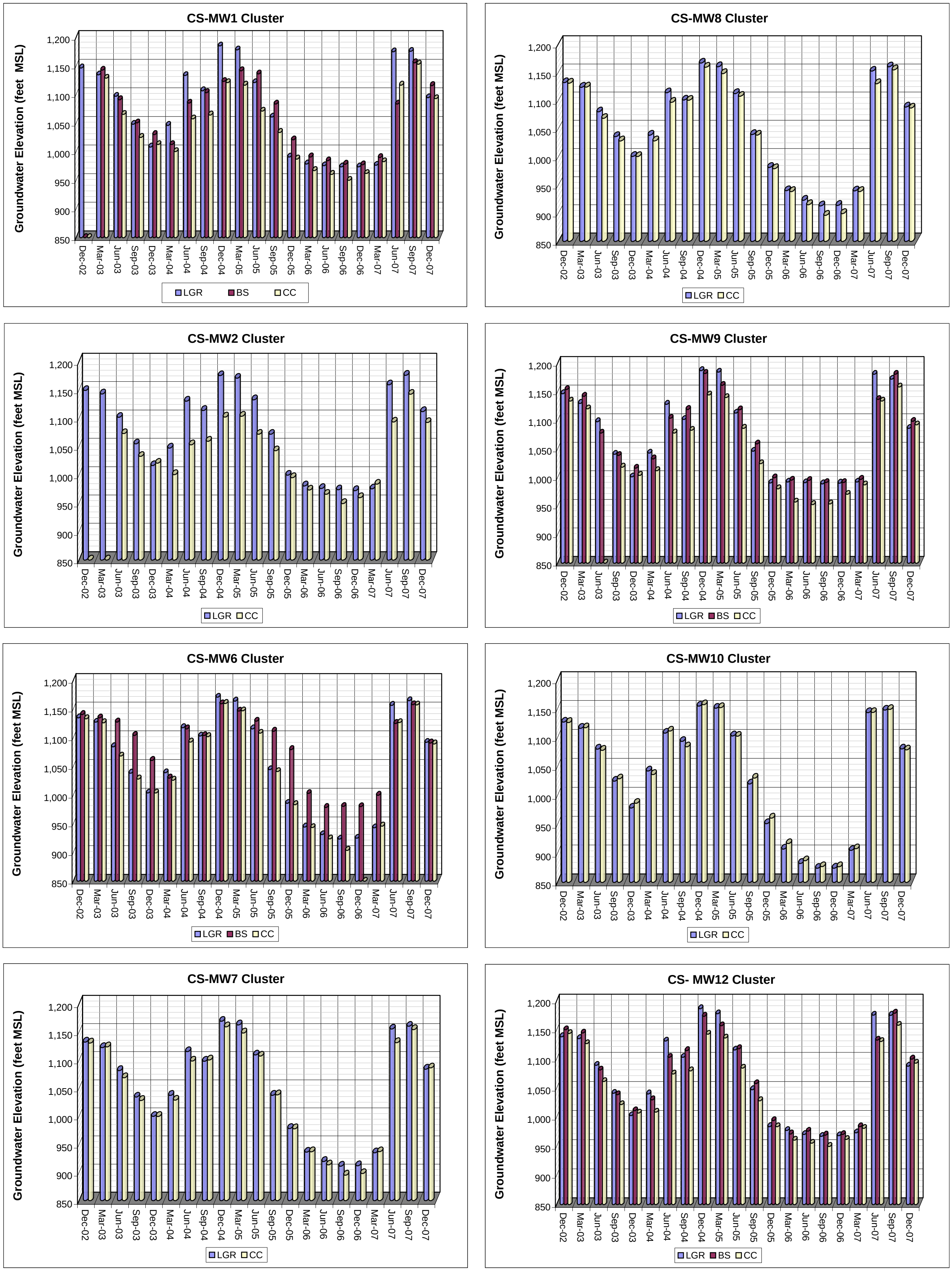
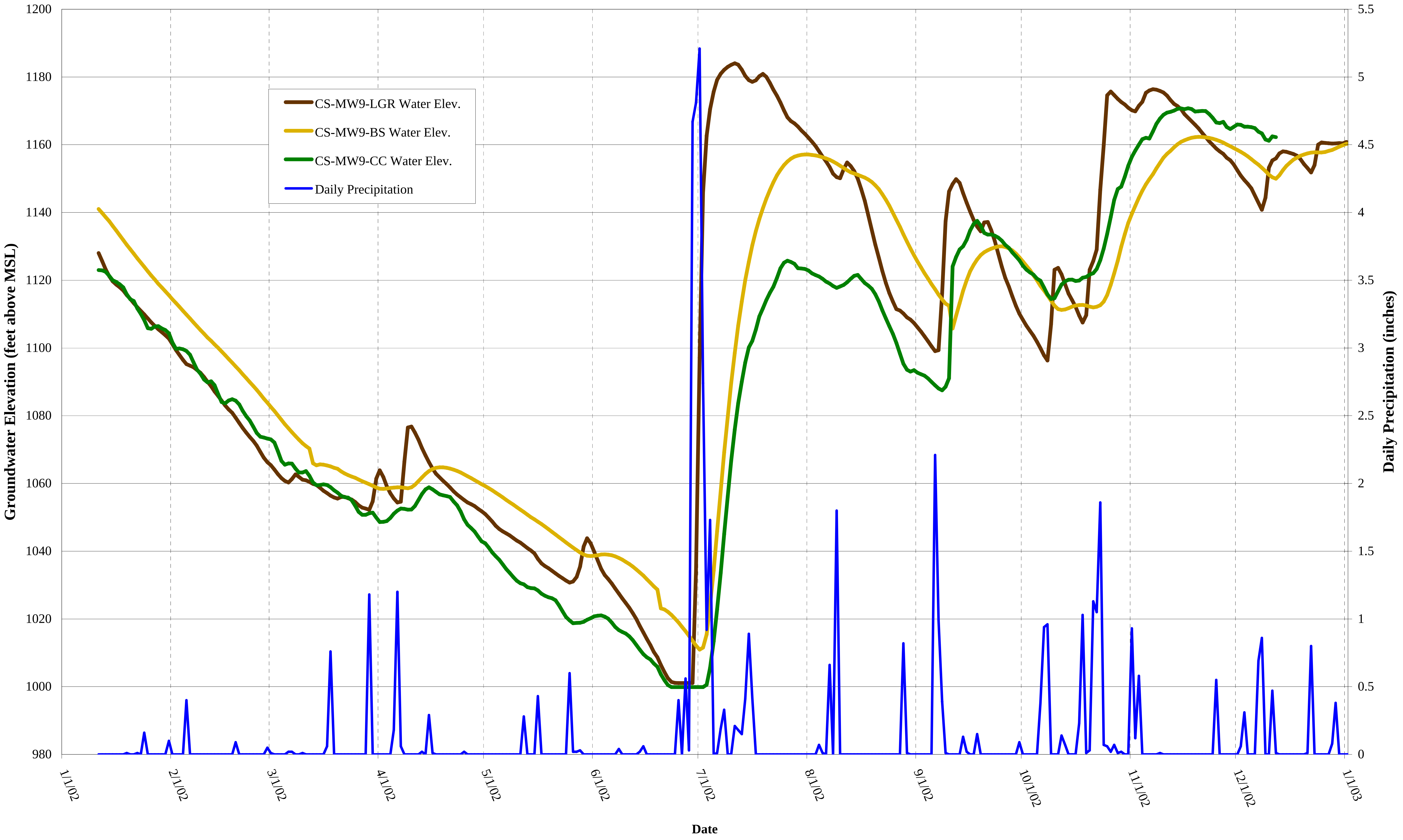


Figure 4.25
Hydrograph of CS-MW9 Cluster and Precipitation Data



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The hydrograph of the BS is much more subdued than the LGR, with a notable lag time between the precipitation and measurable groundwater response. Since the BS does not outcrop, it is dependent upon receiving recharge either through fractures or leakage through adjacent units. Response to precipitation in excess of 0.5 inches may be as short as 3 days (July 2002 flood) or 15 days (March 2002), with the average response within the range of 5 to 7 days. The CC hydrograph also mimics the LGR with an average lag-time response of 3 days. The CC hydrograph is more responsive to precipitation and less subdued than the BS, which would indicate that the CC is responding to direct recharge either on the outcrop area near the Guadalupe River, or elsewhere where there is significant hydraulic communication.

Interpretation from the hydrograph indicates that the BS is probably recharged by the LGR once the recharge event has increased its groundwater elevation above the head of the BS. The higher head in the LGR will force water laterally to areas of lower groundwater elevation, and downward into the BS by overcoming the entry pressure required infiltrating the less permeable matrix. The recharge stored in the LGR is quickly dissipated by discharge (springs, seeps, and wells), lateral down gradient movement, and loss to the BS. Once the head of the LGR becomes less than the head of the BS, vertical leakage to the BS lessens, if it occurs at all. After the BS has been “charged” with infiltrated LGR groundwater, the hydraulic head data indicates it would move downward into the underlying CC. Because the BS is less permeable than the LGR, it drains slowly into the CC, resulting in a sustained head greater than that observed in either the LGR or CC. The measured head within the CC well rarely exceeds the water levels present within the other two units, and may be implicitly related to what location (e.g., outcrop) the recharge event has occurred.

The hydrograph indicate that the three units do have a direct hydraulic connection. Groundwater from the LGR appears to be forced into the BS after heavy rainfall until the hydraulic gradient between the two units is reversed by a period of reduced recharge. Hydraulic data indicate that the BS slowly loses groundwater to the CC. However, recharge to the CC is mostly dependent upon direct precipitation upon the recharge areas as evidenced by its less subdued hydrograph and quicker hydraulic response to precipitation events. While the BS does not preclude groundwater migrating downward towards the CC from the LGR, it undoubtedly dampens the effect by reducing the amount and rate which groundwater may cross over when not structurally compromised. In the AOC-65 area where significant faulting is known to exist, a hydraulic connection between the three units is likely more pronounced, and significantly more recharge from the LGR to CC is thought to exist.

Multi-level Well Data

In August 2003, four Westbay MP38 multi-level wells were installed at CSSA and its immediate vicinity. Three of these wells were installed to approximately 310 feet in depth in a line starting near the Plume 2 source area, and moving southward towards the CS-MW8 well cluster. Each of these three wells (CS-WB01, -02, and -03) were completed with 10 monitoring intervals which observed HSCM layers UGR (D and E) and LGR(A through E). Layer LGR(F) was not penetrated at these locations during this technology evaluation to preclude any downhole migration of contaminants as a result of the well design. A fourth multi-level well (CS-WB04) was installed at an off-post location near private well RFR-10. Since this well is away from the source area, it was completed with 17 monitoring zones throughout the entire thickness of the Middle Trinity aquifer.

In August 2005, an additional four Westbay MP38 multi-level wells were installed at SWMU B-3 in support of ongoing and planned remedial activities. Three of these wells were installed through the entire thickness of the LGR (approximately 330 feet) to the east, west, and south of SWMU B-3. Each of these three wells (CS-WB06, -07, and -08) were completed with five monitoring intervals which observed HSCM layers UGR (D and E) and LGR(A through F). A fourth multi-level well (CS-WB05) was installed at the northern perimeter of the SWMU. In support of pumping, injection, and tracer testing, it was completed with eight monitoring zones throughout the entire thickness of the Middle Trinity aquifer.

Each multi-level zone is equipped with a sampling port from which discrete hydraulic measurements may be obtained using the Westbay MOSDAX tool. The design of the well allows for multiple hydraulic head measurements to be obtained over the entire length of the well. Single-point measurements may be collected manually, or may be collected continuously over multiple zones utilizing the MOSDAX string/datalogger array within a single well. Both methods of measurement have been used at these wells and have proved useful in characterizing potential groundwater flow within the aquifer. The nomenclature for the WB wells was developed before the HCSM, but the monitoring intervals generally follow the HCSM layers as follows in Table 4.3:

Table 4.3 Correlation of HCSM Model Layers and Westbay Monitoring Zones

HCSM Model Layer	CS-WB01, -02, -03	CS-WB04	CS-WB05	CS-WB06, -07, -08
UGR(D) UGR(E)	UGR-01	UGR-01	UGR-01	UGR-01
LGR(A)	LGR-01	LGR-01	LGR-01	LGR-01
LGR(B)	LGR-02	LGR-02		
	LGR-03	LGR-03		
LGR(C)	LGR-04	LGR-04	LGR-02	LGR-02
	LGR-05	LGR-05		
LGR(D)	LGR-06	LGR-06		
	LGR-07	LGR-07	LGR-03	LGR-03
LGR(E)	LGR-08	LGR-08		
	LGR-09	LGR-09		
LGR(F)		LGR-10	LGR-04A	LGR-04
		LGR-11	LGR-04B	
BS(A)		BS-01	BS-01	
BS(B)		BS-02		
CC(A)		CC-01	CC-01	
		CC-02		
CC(B)		CC-03	CC-02	

Figure 4.26 illustrates vertical profiling data from CS-WB01 for January through August 2004. January through April 21, 2004 data were manual measurements collected on a periodic basis. A MOSDAX datalogging string was used to collect 5-minute for the 112 day period between April 21 and August 12, 2004 (Figure 4.27). The data reflects the aquifer condition coming from a relatively dry year in 2003 (21.5 inches) into what became an abnormally wet year in 2004 (27.1 inches through August 2004).

Prior to mid-January 2004, precipitation had been scarce and the heads within the upper 310 feet of strata at AOC-65 exhibited a strong downward hydraulic gradient of 154 feet occurring within 214 feet of strata between CS-WB01-LGR-01 and -LGR-09. The CS-WB01-UGR-01 zone has remained dry for the entire monitoring period. Beginning mid-January, six months of steady precipitation recharged the aquifer while the periodic manual monitoring was conducted. Through April 8, 2004 over 10 inches of rain had fallen, and the aquifer was noticeably responding. The lower zones (CS-WB01-LGR-07, -08, and -09) responded most dramatically to the recharge, while zones CS-WB01-LGR-02, -03. -04, -05, and -06 exhibited moderate recharge responses. The nearest surface zones (CS-WB01-UGR-01 and -LGR-01) showed little to no response to recharge and infiltration. By mid-April, a complete gradient reversal had occurred with the lower zones exhibiting a higher head than the upper zones, with exception to CS-WB01-LGR-01, which appeared unaffected by recharge.

On April 21, 2004, continuous monitoring of all the CS-WB01 zones ensued using the MOSDAX datalogging string. Over the duration of the monitoring event, over 15.6 inches of precipitation was recorded at the southern CSSA weather station located near CS-WB01. The electronic monitoring devices were able to capture the cyclic nature of response to recharge and infiltration during the period. This included a 3-inch cumulative precipitation event over the span of 3 days between June 7-10, 2004. The data on the graphic is interesting because it implies that the lower zones respond to recharge faster than the upper zones. To illustrate this, the Table 4.4 below lists the response time to the start of a significant precipitation event beginning on June 7, 2004.

Table 4.4 CS-WB-01 Interval Response to Precipitation – June 7, 2004

HCSM Layer	CS-WB01 Zone	Hours to Respond	Order of Response
UGR(D) UGR(E)	UGR-01	Dry Zone	
LGR(A)	LGR-01	No Response	
LGR(B)	LGR-02	114.5	10
	LGR-03	48.5	6
LGR(C)	LGR-04	47.5	5
	LGR-05	53.3	9
LGR(D)	LGR-06	49.5	7
	LGR-07	30.5	3
LGR(E)	LGR-08	41.5	4
	LGR-09	28.5	1
LGR(F)	MW8-LGR	28.9	2
CC(A)	MW8-CC	52.8	8

Figure 4.26
CS-WB01 Hydraulic Profiling Data
January - August 2004

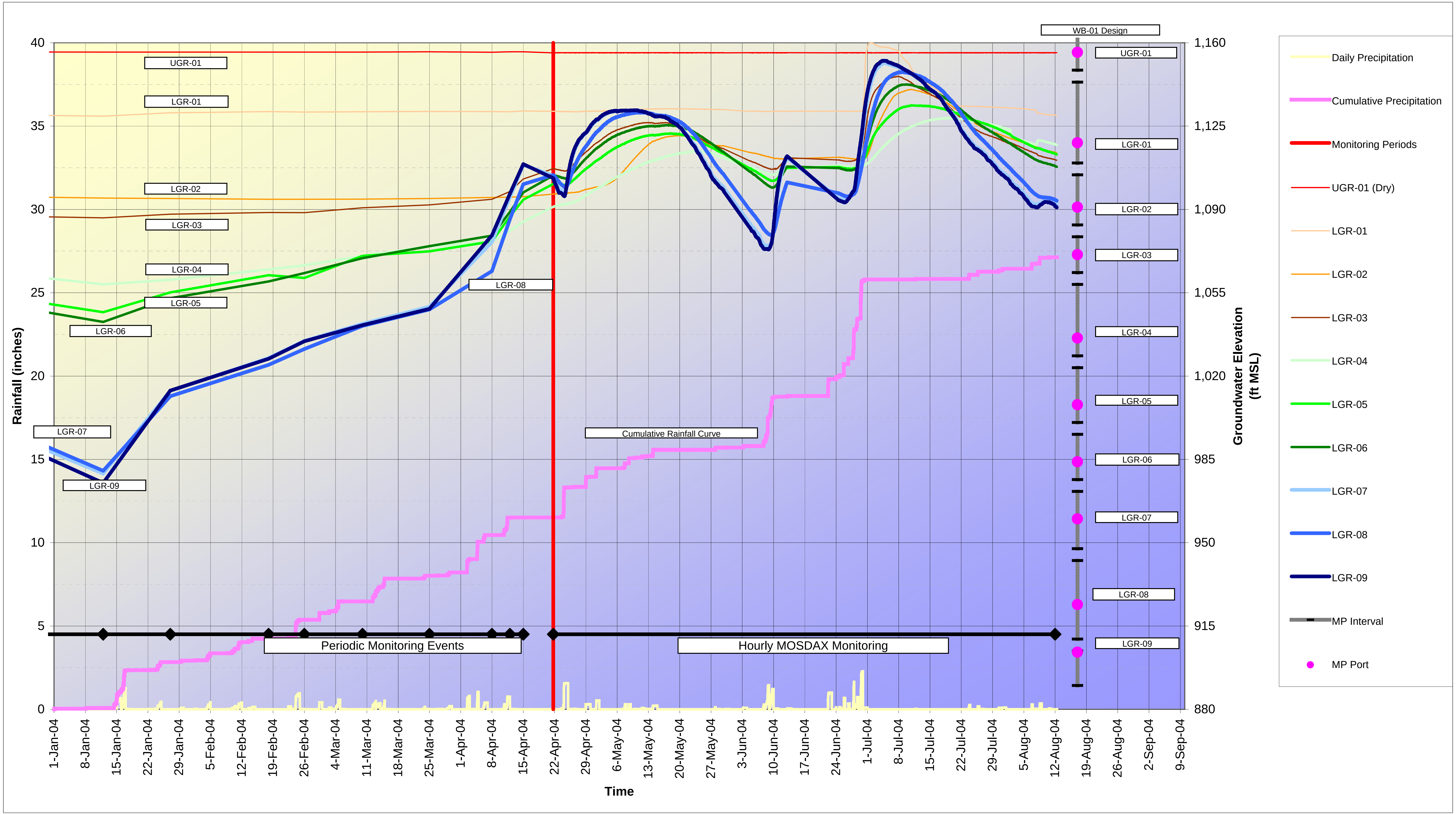

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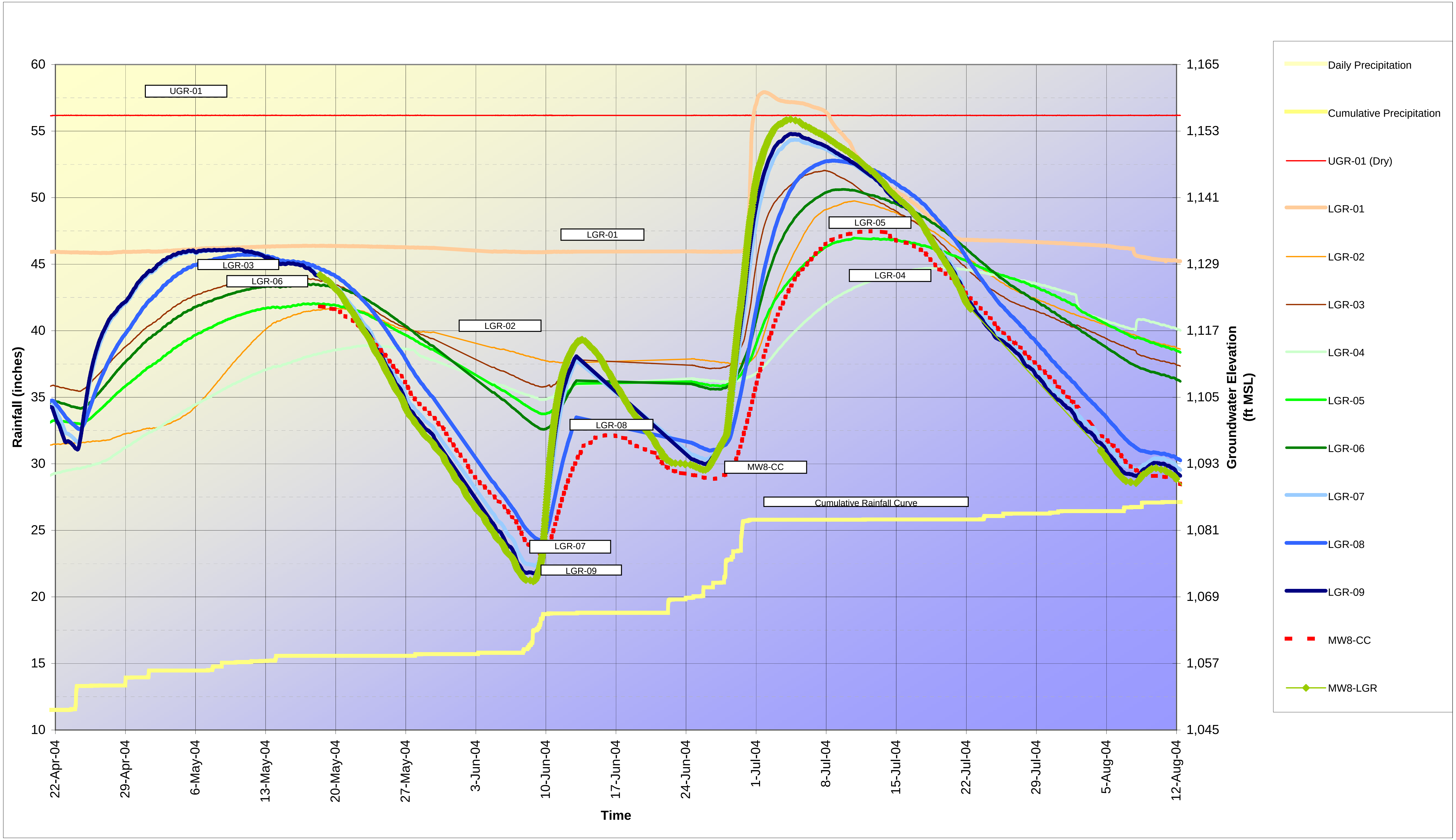
Figure 4.27
CS-WB01 and CS-MW8 Datalogging Event
April 22 - August 12, 2004



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In this example it is clear that the deeper HCSM zones LGR(E) and LGR(F) are the first to respond to a significant precipitation, with active recharge beginning to occur within 30 hours of the recharge event. It is likely that LGR(F) responds faster that LGR(E), but the differing resolution of datalogging settings at LGR(F) did not record the response as quickly as LGR(E). The obvious question is why the lower zones respond to recharge before the upper zones, seemingly by-passing the near-surface measurement ports. Several scenarios can account for this, including regional recharge or conduit recharge.

As implied, regional recharge would assume that the groundwater had already percolated to the lower zones elsewhere, and the first response measured at CS-WB-01 was merely a pressure gradient response the incoming flux of recharged groundwater. The source of this regional type of recharge could include the LGR outcrop to the north of CSSA or perhaps preferred pathways along structural features or creeks. Along those same lines, a nearby structural (e.g. fault) or karstic feature my provide a conduit system near CS-WB-01 that allows for recharge to fall quickly to the lower zones LGR(E) and LGR(F). It is likely that a combination of both scenarios is being measured in the CS-WB-01 data.

Regardless how recharge to depth occurs so quickly, the data recorder installed at CS-WB-01 repeatedly suggests that recharge events invoke a gradient reversal in the Lower Glen Rose such that the higher zones (LGR[A-D])are fed by the upward migration of groundwater via fractures or karst features. This upward leakage of groundwater is implied from the recharge response times given in Table 4.4, and is conceptualized in Figure 4.28. What appears to happen is that the lower reefal unit of LGR(F) is charged with a flux of groundwater from either regional or local conduit flow. Most of the flux is propelled downgradient within LGR(F), but excess pressure is also relieved in the form of vertical leakage. Where vertical fractures, jointing, or dissolutional features intersect LGR(F), some of that groundwater if forced upward into overlying strata via the permeable feature. That groundwater pressure is dissipated through the fracture network inherent to the limestone bedrock. In this example LGR(E and F) respond first, followed by subunits of LGR(D), LGR(C), and LGR(B) in sequential order. Within 55 hours, most zones including the MW8-CC well have started responding to the recharge event.

As the exception, multi-port zones CS-WB01-UGR-01, -LGR-01, and -LGR-02 do not appear to receive the recharge effect from lower zones in this example. Zone CS-WB01-LGR-02 responds slightly to the recharge event. Throughout the monitoring period, CS-WB01-UGR-01 has remained dry.

Another interesting observation is that multi-port zones CS-WB-LGR-01 and –LGR-02 do not respond to precipitation until the head of lower zones (LGR-07, -08, -09, and CS-MW8-LGR) exceed the head of these upper zones. In Figure 4.27, this phenomena is subtle in CS-WB01-LGR-02 on June 12, 2004, but coincides with the 115 hour of CS-WB01-LGR-02 given in Table 4.4. This same effect is significantly more pronounced in CS-WB01-LGR-01 on June 30, 2004. Prior to this date, groundwater in that zone had not responded to any event. However, once the head of the deeper zones exceeded the head of CS-WB01-LGR-01, the zone dramatically responded until groundwater levels gradually subsided below that elevation around July 22, 2004. Based on these observations, it is likely at CS-WB01-LGR-01 was very close to a

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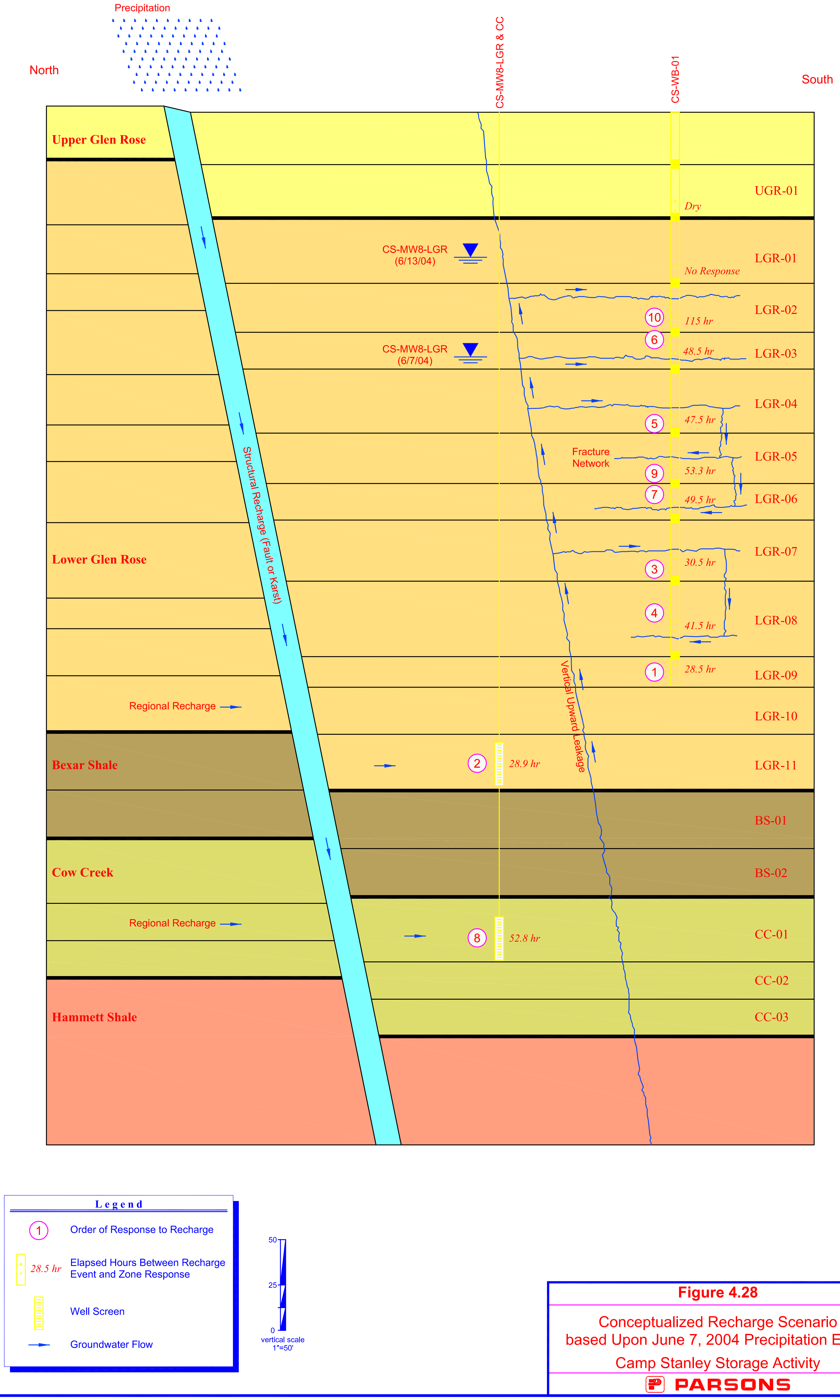

Figure 4.28

Conceptualized Recharge Scenario
based Upon June 7, 2004 Precipitation Event
Camp Stanley Storage Activity

PARSONS

recharge response in around the date of May 10, 2004. Likewise, the normally dry zone, CS-WB01-UGR-01 probably was also very close to a measurable groundwater response during the first week of July 2004. As seen in other cluster wells, the head of CS-MW8-LGR is typically greater than the head of CS-MW8-CC (Figure 4.27), except during period of declining water levels. This suggests that the LGR is able to discharge and dissipate groundwater from storage at a quicker rate than the underlying Cow Creek interval. With respect to recharge of the Cow Creek, the relatively quick response to a precipitation event (approximately 53 hours in Table 4.4) is likely in due to localized precipitation near CSSA. This implies that recharge from the Lower Glen Rose to the Cow Creek via the Bexar Shale is occurring.

4.5 HYDRAULIC PARAMETERS

4.5.1 Packer Testing

A total of 38 injection packer tests (seven for DO23 and 31 for RL83) were conducted in selected stratigraphic zones at eight drilling locations (CS-MW3 through CS-MW10) between November 2000 and September 2001. The generalized strategy was to perform two or more tests per formation (LGR, BS, and CC) that was to be monitored at that location. A total of 19 tests were conducted within the LGR, while seven tests and 12 tests were completed in the BS and CC Formations, respectively. Additional information regarding this work can be found in **Volume 5: Groundwater, Well Installation Report (CS-MW3 through CS-MW10).** Summary statistics by hydrologic unit are presented in Table 4.5. 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 BS. While it is understood that these geologic materials possess some coefficient of permeability, for the purposes of this report, those "no flow" field tests are reported with a null value (0).

Including the "no flow" tests, K values ranged from some degree of impermeability (0 gpd/ft^2) in all three formations (LGR, BS, and CC) to 32.51 gpd/ft^2 (1.33 m/day) in the LGR. When the entire test population is normalized to relative permeability, the data shows that the LGR and CC formations are 7.5 and 11 times more permeable than the BS, respectively.

From another point of view, when the 11 "no flow" zones are removed from the data set, the least permeable test conducted occurred in the LGR (68-73.5 ft bgs) with a hydraulic conductivity of 0.022 gpd/ft^2 (0.001 m/day). Within these data subset, the median and average formational permeabilities are implicitly increased as would be expected. The averaged LGR and CC hydraulic conductivities are greater than those permeable sections of the BS by a factor of 4.7 and 5.1, respectively.

According to the Handbook of Hydrology (Maidment, 1993) and with respect to the geologic terrain, the average LGR and CC formations are typified by lower-permeable karstified limestone, while the BS falls more closely toward a carbonate mud permeability. Another interpretation of the hydraulic conductivity measurements of the LGR and CC intervals is that they are indicative of a fractured flow regime, and those of the BS interval are suggestive of matrix flow.

Table 4.5 Statistical Summary of Injection Packer Tests (Hydraulic Conductivity)

Test Failure Rate for Entire Data Set (n=38)
(including tests where K=0.00E+00)

Hydrologic Unit	Permeable	Impermeable	% of "Permeable"	% of "Impermeable"	Ratio of Normalized Failure Rate compared to CC (x)
LGR	13	6	68.4%	31.6%	3.8
BS	3	4	42.9%	57.1%	6.9
CC	11	1	91.7%	8.3%	1.0

Summary Statistics for Entire Data Set (n=38)
(including tests where K=0)

Hydrologic Unit	Count (n)	gpd/ft^2 (m/day)				Ratio of Normalized Average Permeability compared to BS (x)
		Min	Max	Median	Average	
LGR	19	0.00 (0.00)	32.486 (1.324)	0.648 (0.026)	2.888 (0.118)	7.5
BS	7	0.00 (0.00)	2.246 (0.092)	0.00 (0.00)	0.386 (0.016)	1.0
CC	12	0.00 (0.00)	17.406 (0.709)	1.089 (0.044)	4.239 (0.173)	11.0

Summary Statistics for Subset (n=27)
(not including tests where K=0)

Hydrologic Unit	Count (n)	gpd/ft^2 (m/day)				Ratio of Normalized Average Permeability compared to BS (x)
		Min	Max	Median	Average	
LGR	13	0.022 (0.001)	32.486 (1.324)	1.159 (0.047)	4.221 (0.172)	4.7
BS	3	0.122 (0.005)	2.246 (0.092)	0.337 (0.014)	0.902 (0.037)	1.0
CC	11	0.546 (0.022)	17.406 (0.709)	1.093 (0.045)	4.624 (0.188)	5.1

Summary Statistics for Tests Performed within the Screened Interval

Hydrologic Unit	Count (n)	gpd/ft^2 (m/day)				Ratio of Normalized Average Permeability compared to BS (x)
		Min	Max	Median	Average	
LGR	8	0.397 (0.016)	6.5286 (0.266)	1.908 (0.045)	1.765 (0.072)	2.1
BS	3	0.00 (0.00)	2.246 (0.092)	0.337 (0.014)	0.861 (0.035)	1.0
CC	6	0.00 (0.00)	17.406 (0.709)	2.591 (0.106)	5.185 (0.211)	6.0

4.5.2 Pumping Tests

Pumping tests were performed in July-August 2001 (wells CS-10 and CS-16), and again in December 2005 (wells CS-MW16-LGR and CS-MW16-CC) to quantify key aquifer parameters of the Middle Trinity aquifer beneath CSSA. The analyses for evaluating principal aquifer characteristics included aquifer specific capacity, transmissivity, hydraulic conductivity, and storativity. With respect to both time and cost restraints, the aquifer tests were conducted utilizing the existing well network. No additional wells or PZs were installed as pumping or observation points. Groundwater pumping tests were conducted with respect to areas associated with CS-10 and the CS-16 well cluster. The December 2005 pumping tests at CS-MW16-LGR and CS-MW16-CC featured interval monitoring at multi-port well CS-WB05 to assess the response in different portions of the Middle Trinity aquifer under distinct LGR and CC pumping scenarios. Further information regarding the pumping tests may be found in **Volume 5: Groundwater, Groundwater Pumping Tests for CS-10 and CS-16 and Groundwater Pumping Tests for CS-MW16-LGR and CS-MW16-CC**.

CS-10

- The specific capacity of CS-10 was calculated as 1.13 gallons per minute per foot (gpm/ft) of drawdown.
- Response to pumping was identified within CS-9 and CS-10 during the pumping test. CS-11 did not respond to pumping. Parsons attributes the lack of response to pumping at CS-11 to an aquifer boundary condition located between CS-10 and CS-11 and between CS-9 and CS-11. The physical location of the boundary condition is apparently located closer to CS-10 than CS-9 with respect to CS-11.
- Transmissivity was calculated to be 2,400 gpd/ft (29.81 m^2/day). Storativity was calculated as 0.0005. The Middle Trinity aquifer exhibits confined properties at CS-10.
- The hydraulic conductivity for the Middle Trinity aquifer at CS-10 was calculated to be 12.08 gpd/ft^2 (0.493 m/day).

CS-16

- The pumping test was completed before the July 2002 upgrade while the open borehole completion extended 431 ft bgs into the CC.
- The specific capacity for CS-16 was calculated as 0.71 gpm/ft of drawdown.
- Response to pumping was limited to CS-16 and CS-D during the pumping test.
- Transmissivity was calculated to be 1,600 gpd/ft (19.87 m^2/day). Storativity was calculated as 0.00008. The Middle Trinity aquifer exhibits confined properties at CS-16.
- The hydraulic conductivity for CS-16 was calculated to be 12.08 gpd/ft^2 (0.493 m/day).

CS-MW16-LGR

- The pumping test was completed after the July 2002 upgrade when the open borehole completion was reduced to 314 ft bgs into the LGR.

- The specific capacity for CS-MW16-LGR was calculated as 0.36 gpm/ft of drawdown.
- Obvious response to CS-MW16-LGR pumping was limited to only 3 nearby LGR wells. Very shallow drawdowns between 0.2 and 0.7 feet were observed in more distant LGR wells up to 2,500 feet away. No BS or CC well water levels were influenced by CS-MW16-LGR pumping.
- Influence from pumping expanded horizontally through the LGR, but the BS blocked any downward effects of groundwater withdraw, leaving the underlying formations unaffected.
- Transmissivity was calculated to be 1,220 gpd/ft (15.15 m^2/day). Storativity was calculated as 0.000000122. The LGR aquifer exhibits confined properties at CS-MW16-LGR.
- The hydraulic conductivity for CS-16 was calculated to be 10.94 gpd/ft^2 (0.446 m/day).

<u>*CS-MW16-CC*</u>

- The specific capacity for CS-MW16-CC was calculated as 0.16 gpm/ft of drawdown.
- Moderate drawdown was observed in other CC wells up to 3,770 feet away. Monitored LGR zones showed no response to the induced CC groundwater gradient, indicating no significant hydraulic interconnection between the CC and LGR within the pumping well's radius of influence.
- The radius of influence spread laterally but its upward effects stopped at the BS. The BS was an effective hydraulic barrier, blocking the induced gradient from expanding into the LGR. The BS is generally acting as an impermeable barrier to vertical groundwater movement between the LGR and CC.
- Transmissivity was calculated to be 256 gpd/ft (3.18 m^2/day). Storativity was calculated as 9.17×10^{-7}. The CC aquifer exhibits confined properties at CS-MW16-CC.
- The hydraulic conductivity for CS-MW16-CC was calculated to be 3.41 gpd/ft^2 (0.139 m/day).

Results of the two pumping tests correspond to that reported by Ashworth (1983) and Hammond (1984). Table 4.6 summarizes results of the CSSA pumping tests with those values obtained from the literature review.

Table 4.6 Comparison of Middle Trinity aquifer Parameters at CSSA to Literature Review Values

	Ashworth (1983)	**Hammond (1984)**		**CSSA (2001)**		**CSSA (2005)**	
Aquifer Parameter	**(Middle Trinity aquifer)**	**Local System (Lower Glen Rose)**	**Regional System (Lower Glen Rose)**	**CS-10 (Middle Trinity aquifer)**	**CS-16 (Middle Trinity aquifer)**	**CS-MW16-LGR**	**CS-MW16-CC**
Specific Capacity (gpm/ft)	N/A	N/A	N/A	1.13	0.71	0.16	0.36
Transmissivity (gpd/ft) *(m^2/day)*	1,700 *(21.12)*	5,740 - 16,110 *(71.30-200.10)*	240 - 3,220 *(2.98-40.00)*	2,400 *(29.81)*	1,600 *(19.87)*	255.9 *(3.18)*	1,219.5 *(15.15)*
Hydraulic Conductivity (gpd/ft^2) *(m/day)*	N/A	29.68 - 74.2 (1.21 – 3.03)	0.72 - 21.2 (0.029 – 0.086)	12.08 (0.49)	8.90 (0.36)	3.41 (0.14)	10.94 (0.45)
Storativity	N/A	N/A	3×10^{-5}	3×10^{-5}	8×10^{-5}	9.17×10^{-6}	1.22×10^{-7}

N/A – Not Available from Literature Review

4.5.3 Hydrophysical™ Logging

AOC-65

In July 2003, Hydrophysical Logging (HpL) was performed at four locations by COLOG of Golden, Colorado. The process is capable of measuring the intervals where groundwater enters and exits a wellbore (inflow/outflow zones) by using the natural groundwater conductivity as a tracer. The HpL logging provides a characterization of ambient flow occurring during July 2003. At that time, water levels overall were decreasing in elevation at CSSA. The hydraulic conditions observed will be consistent with flow behavior during a period of declining water levels. Using hydraulic modeling algorithms a quantitative estimate of hydraulic conductivity and transmissivity can be assessed on an interval-specific basis. The methodology applied can characterize and quantify flow in the borehole under both non-stressed (ambient) and stressed (pumping) conditions.

The Hydrophysical logging technique involves pumping while injecting into the wellbore with deionized water (DI). During this process, profiles of the changes in fluid electrical conductivity of the fluid column are recorded. These changes occur when electrically contrasting formation water is drawn back into the borehole by pumping or by native formation pressures (for ambient flow characterization). A downhole wireline hydrophysical tool, which simultaneously measures fluid electrical conductivity (FEC) and temperature is employed to log the physical/chemical changes of the emplaced fluid.

The computer programs can be utilized to evaluate the inflow quantities of the formation water for each specific inflow location. The modeling program is used to estimate the interval-specific flow rates for the production test results based on "hand-picked" values of FEC and depth. Using the assumption of flow through porous media, these methods can accurately reflect the flow quantities for the identified water bearing intervals.

The HpL testing was performed in 4 coreholes during July 2003. The coreholes ultimately were converted into multi-level wells CS-WB-01, -02, -03, and -04. The HpL method was used to help identify zones of groundwater inflow and finalize the design of the multi-port systems.

Tables 4.7 and 4.8 list the interval-specific zones of groundwater flow measured and interpreted from the HpL surveys at CS-WB-01, -02, -03, and -04. Those shallower wells that only penetrate thru HCSM model layer LGR-E are listed in Table 4.7. These particular wells extend to a depth of 310 feet bgs, and include 25 feet of UGR and 285 feet of LGR. The basal 45 feet of the unit (LGR-F) was not penetrated near the Plume 2 source area. The HpL results indicate that groundwater within the upper 285 feet of the LGR is isolated, variable, and of low hydraulic conductivity. Between the three boreholes, the occurrence of groundwater was variable, but generally the water-bearing intervals where narrow and less than 2 feet in thickness. For the 23 water-bearing zones identified in Table 4.7, the average hydraulic conductivity was 10.04 gpd/ft^2 (0.41 m/day). That average value is more than twice the average LGR hydraulic conductivity, 4.221 gpd/ft^2 (0.172 m/day), determined during the injection packer testing (Section 4.5.1). It is likely that the injection packer tests are biased low since the 12-foot packer spacing was likely only testing a 2-foot interval of permeability.

Table 4.7
Summary of Hydrophysical Data at AOC-65
Camp Stanley Storage Activity - Boerne, Texas

	WB-01					WB-02					WB-03				
CSM Layer	**Interval of Flow** *(feet)*	**Interval Specific Hydraulic Conductivity** *(gpd/ft^2)*	**Transmissivity** *(gpd/ft)*	**Interval Specific Flow Rate During Pump Testing** *(gpm)*	**Percentage of Flow by CSM Layers A-E**	**Interval of Flow** *(feet)*	**Interval Specific Hydraulic Conductivity** *(ft/day)*	**Transmissivity** *(gpd/ft^2)*	**Interval Specific Flow Rate During Pump Testing** *(gpd/ft)*	**Percentage of Flow by CSM Layers A-E**	**Interval of Flow** *(feet)*	**Interval Specific Hydraulic Conductivity** *(gpd/ft^2)*	**Transmissivity** *(gpd/ft)*	**Interval Specific Flow Rate During Pump Testing** *(gpm)*	**Percentage of Flow by CSM Layers A-E**
LGR-C	169.2 - 169.5	5.693	1.706	0.008	2.95%						133.5 - 137.5	0.471	1.743	0.076	41.73%
	170.0 - 170.8	2.401	1.922	0.013							145.9 - 146.5	9.949	5.977	0.079	
											152.6 - 153.9	3.089	4.010	0.053	
											157.4 - 191.6	0.583	19.973	0.264	
LGR-D	209.4 - 211.9	0.209	0.426	0.005	83.01%						196.6 - 198.0	3.351	4.690	0.062	28.65%
	218.8 - 221.4	1.070	2.775	0.013							204.4 - 207.0	0.958	2.498	0.033	
											209.2 - 210.0	2.932	2.349	0.031	
											212.7 - 214.7	1.668	3.329	0.044	
	233.8 - 235.9	30.296	63.584	0.264							220.3 - 221.6	2.850	3.710	0.049	
	239.0 - 242.5	18.851	65.903	0.309							230.9 - 231.4	3.329	1.668	0.022	
											234.2 - 234.8	4.541	2.723	0.036	
											239.0 - 239.7	5.079	3.561	0.047	
LGR-E	271.5 - 272.9	5.184	7.256	0.034	14.04%					100.00%					29.62%
	295.6 - 296.4	3.471	2.775	0.013											
	305.5 - 308.1	5.745	14.961	0.053		301.4 - 303.8	118.192	282.764	0.909		243.0 - 306.0	1.077	67.774	0.335	

Table 4.8
Summary of Off-Post Hydrophysical Data at WB-04
Camp Stanley Storage Activity - Boerne, Texas

	WB-04							
CSM Layer	**Interval of Flow** ***(feet)***	**Interval Specific Hydraulic Conductivity** ***(gpd/ft^2)***	**Transmissivity** ***(gpd/ft)***	**Interval Specific Flow Rate During Pump Testing** ***(gpm)***	**Percentage of Flow by CSM LGR Layers A-E**	**Percentage of Flow by CSM LGR layers A-F**	**Percentage of Flow by CSM Layer**	**Percentage of Flow by Fomation**
LGR-C					0.00%	0.00%	0.00%	92.41%
LGR-D	208.2 - 210.8	0.142	0.359	0.033	60.23%	8.77%	8.11%	
	218.3 - 219.6	6.299	8.154	0.068				
	227.9 - 229.0	20.721	22.741	0.198				
	253.6 - 254.3	28.576	19.973	0.175				
LGR-E					39.77%	5.79%	5.35%	
	309.2 - 310.7	19.225	28.800	0.313				
LGR-F	332.2 - 335.3	96.499	299.221	2.730		85.43%	78.95%	
	360.0 - 362.6	46.080	119.688	1.000				
	370.5 - 371.8	65.155	84.530	0.721				
	375.6 - 376.7	0.658	0.726	0.165				
CC-A	464.2 - 466.9	38.375	103.979	0.264			7.59%	7.59%
	475.0 - 476.8	11.221	20.197	0.168				
	486.3 - 489.5	0.449	1.444	0.012				

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The HpL results from CS-WB-01, -02, and -03 are indicative of fractured flow within the bedrock. At each of these locations, no single HCSM layer stands out as a water-producing interval. Rather, random intervals of either fracture or matrix porosity are distributed chaotically throughout the bedrock matrix. As an example, CS-WB-02 was measured to only have one groundwater producing interval at 301 feet bgs. However, the closely spaced wells WB-01 and WB-02 were determined to have 9 zones and 13 zones, respectively. To further expound this point, several producing intervals were interpreted in excess of 30 feet in thickness at WB-03 would indicate that significant fracturing relative to WB-01 and -02 has occurred at that location. Overall, the transmissive properties of the HCSM Layers LGR(A-E) are low in comparison to Layer LGR(F) and the CC layers.

A good relative measure of hydrophysical properties was conducted at CS-WB04. At this location the well extends through the entire thickness of the Middle Trinity aquifer. As shown in Table 4.8, only five zones of groundwater flow were interpreted between HCSM layers LGR(D and E). The hydraulic conductivity of these layers at CS-WB-04 were consistent with those measurements on-post at CS-WB-01, -02, and -03. Conversely, significant increases in groundwater flow were measured in the reefal portion of layer LGR(F). The average hydraulic conductivity of LGR(F) was nearly 3.5 times greater than the average conductivity of LGR(D and E). The amount of total estimated flow from the LGR during the HpL testing resulted with 85 percent of the groundwater production originated from LGR(F), and only 9 percent and 6 percent originating from LGR(D) and LGR(E), respectively. When considering the entire thickness of the Middle Trinity aquifer, the Lower Glen Rose accounted for 92 percent of the entire production at CS-WB-04 and the Cow Creek accounted for the remaining 8 percent. No measurable flow was reported from the Bexar Shale interval.

The HpL interpretation estimates that 100 percent of the measured groundwater flow originates from only a total of 23 feet of permeable strata or fractures within the Lower Glen Rose and Cow Creek. In a borehole that was 510 feet deep with a water level of 160 feet below grade (at the time of testing), slightly less than 7 percent of the borehole length yielded measurable groundwater flow from the 350-foot saturated interval of the Middle Trinity aquifer. The small amount of major intervals contributing groundwater within in the Middle Trinity aquifer had not been quantified by any other investigative method previously. As expected, those results can be variable such that a similar analysis of CS-WB-01, -02, and -03 shows a range between 1 percent and 60 percent of the saturated thickness may contain water-bearing strata and/or fractures.

SWMU B-3

In August 2005, additional HpL was performed at CS-WB05 by RAS, Inc. of Golden, Colorado. The process and methodologies were similar to those performed by COLOG in 2003 at AOC-65. The methodology applied can characterize and quantify flow in the borehole under both non-stressed (ambient) and stressed (pumping) conditions.

Processing and interpretation of the geophysical and HpL logs in CS-WB05 under ambient conditions suggest the presence of three identifiable water-producing LGR (inflow) intervals (166-171, 203-215, and 295-305 feet bgs). During the ambient test, groundwater was observed to move downward through the borehole, and exit the well (outflow zone) within the CC interval, 430-448 feet bgs. Only the two deepest zones (295-305 ft bgs and 430-448 ft bgs) had flows large enough to be quantified. Inflow at 295-305 feet bgs showed a rate of 0.75 gpm, while 430-448 feet bgs had an outflow of 0.75 gpm.

The results of the CS-WB05 HpL basically confirmed the results of the more intensive HpL effort in 2003. Essentially, interval lengths of significant groundwater contribution from the borehole are small relative to the entire depth of the test well. When dominated by fabric selective porosity, the bulk of groundwater is produced from the LGR(F) interval of the Middle Trinity aquifer, with a significantly smaller portion originating from the CC intervals. Under ambient (non-pumping) conditions, the natural tendency within a borehole is for inflow from the LGR, downward migration through the wellbore, and exiting the wellbore into the porous sections of the CC (inflow). Under pumping conditions, the natural gradient is reversed, and inflow to the well is received from both the LGR and CC water-producing sections of the aquifer.

4.5.4 Hydraulic Characterization Considerations

In Section 4.5, three different methods have been presented in the determination of hydraulic conductivity (K) and transmissivity (T), including packer testing, pump testing, and HpL testing. These calculations are extremely sensitive to “aquifer thickness” (b), such that the relationship between the three is simply stated as:

$$T = K \times b$$

The test methodologies implemented typically directly measure either T or K, and the remaining term is calculated by assuming an aquifer thickness. In the case of packer testing (Section 4.5.1), the methodology resolves for K, but the test result is sensitive to the spacing length between the packers. As an example, if the calculations account for a packer spacing is 12 feet, but the actual permeable zone within that packer distance is only 2 feet, the resultant value for K may only be 25 percent of its true value. In limestone bedrock aquifers where the primary porosity is chiefly associated with fractures and karst features rather than matrix porosity, the resultant values for hydraulic conductivity will almost always be biased low. However, in most cases the characterization data needed to determine the effective permeable thickness cannot be ascertained.

In the case of pumping tests (Section 4.5.2), transmissivity is typically calculated from the discharge and drawdown data observed. Then, hydraulic conductivity is then empirically-derived from the previous equation (K = T/b) by assuming an aquifer thickness. In the case of the pumping test analyses, the aquifer thickness was generally assumed to be the distance between the static aquifer level and the base of the Cow Creek, minus the thickness of the Bexar Shale. At the time of the pumping tests, it was assumed that the contributing aquifer thickness was between 180 and 200 feet of both Lower Glen Rose and Cow Creek strata.

However, the HpL studies have indicated that the contributing thickness of the aquifer may be significantly less (23 feet at CS-WB-04). The implication is that the hydraulic conductivities derived during the packer and pumping tests underestimate the true value by a significant margin. In such an instance, the hydraulic conductivities presented in Table 4.6 may be underestimated by a factor of 4 to 8 times if the “effective aquifer thickness” is less than 50 feet at any given test location. At this time an “effective aquifer thickness” cannot be quantified into a basewide model.

4.6 HYDROLOGIC BUDGET

For a groundwater reservoir, inflow should be equal to outflow plus storage change. On an annual base, the assumption is inflow is the same as outflow. In a three-dimensional model, inflow is rainfall falling directly over the rock outcrop, runoff from the upper watershed is flowing into the study area, and lateral groundwater flowing in from an upgradient or up dip area. This lateral inflow of groundwater is quite significant because not all underground watersheds correspond to surface watersheds. It is quite possible that a large portion of the inflow is from the recharge of Cibolo and Balcones Creeks to the north and NW of CSSA where they cut into the LGR outcrop.

4.6.1 Precipitation

CSSA is located in the semi-arid Texas Hill Country. Rainfall is highly variable from year to year, and it is not uncommon for there to be cycles of dry years followed by normal or wet years. Data from the Boerne Station #410902 for the record between the years 1971 and 2000 indicate that the normalized annual precipitation for the vicinity is 37.36 inches (NWS, 2003). Likewise, for the city of San Antonio, the long-term mean annual rainfall is 29.06 inches, but the minimum and maximum recorded annual rainfalls are 10.11 inches and 52.28 inches, respectively (NOAA, 2003). For the period of record at CSSA, this same pattern of extreme fluctuations in rainfall is evident (Table 4.9).

Table 4.9 CSSA Annual Rainfall (1999 through 2006)

Year	Annual Rainfall (inches)	Source
1999	16.99	*CS-16 WEATHER STATION*
2000	32.51	*CS-16 WEATHER STATION*
2001	40.17	*CS-16 WEATHER STATION*
2002	51.87	*CS-16 WEATHER STATION*
2003	20.47	*CS-16 WEATHER STATION*
2004	50.93	*CS-16 WEATHER STATION*
2005	20.47	*AOC-65 WEATHER STATION*
2006	18.27	*CS-16 WEATHER STATION*
8-YEAR AVERAGE	31.46	

There is not a complete record for 1998; however, there was an extremely large magnitude storm recorded in October that corresponded with severe flooding throughout much of the region. The heavy rainfall in 1998 was followed by a sustained drought in subsequent years. Total rainfall in 1999 was significantly less than the long-term average for nearby San Antonio and Boerne. The drought persisted through most of 2000, despite the fact that the total rainfall for 2000 was near average. Nearly half of the total rainfall in 2000, or 15.07 inches, fell in the final three months of the year effectively ending the drought and raising the annual rainfall total to slightly above the long-term average. Rainfall in 2001 was also above average, but it was more evenly distributed throughout the year compared to 2000. Despite the relative evenness of the rainfall in 2001, there were two fairly large magnitude storms (each ~ 5 inches in a single day) in the latter part of the year.

The beginning of 2002 was marked by a lack of rainfall. From the beginning of the year through June 22 there was only 6.71 inches of rainfall. However, during the two-week period from June 23 through July 6 over 21 inches of rain fell. Total rainfall for 2002 ended up being significantly higher than average and approached the maximum recorded for San Antonio. Once again, the area fell into a short drought cycle in 2003 when only 20.57 inches of precipitation was received. However, with 2004 the rains returned, with multiple storms resulting in more than 2 or 3 inches of rain each event. The year of 2005 marked the beginning of a two-year drought that lasted until March 2007. During this timeframe , less than 21 inches of rain was received for each year of 2005 and 2006.

Beginning March 2007, CSSA received more than 45 inches of precipitation for the remainder of the year, and included several flood-scale events. However, the weather station record is incomplete for the year while the monitoring equipment was being incorporated into a automated basewide data collection system. Therefore, 2007 is not considered in the HCSM data. The 8-year average of precipitation at CSSA is approximately 31.46 inches per annum.

Using a Geographic Information System (GIS) utility, a digital terrain model (DTM) was analyzed to delineate the major boundaries and subunits that comprise the Cibolo, Salado, and Leon Creek watersheds. These watersheds and enumerated subunits are shown in Figure 4.29.

The following tables present calculated volumes of precipitation based upon normalized data from a 30-year period between 1971 and 2000 (Table 4.10) as measured in Boerne, Texas and site-specific data measured at the CS-16 weather station between 1999 and 2006 (Tables 4.11 through 4.18). Each table evaluates the amount of precipitation (measured in acre-ft) that has fallen upon the CSSA property as well as the corresponding watershed subunits within the model boundary. The volumetric unit of acre-ft is the amount of water that covers one acre with 12 inches of water (approximately 325,850 gallons). The CSSA facility consists of 4,004 acres within the 13,360-acre model area. Model-wide, 52 percent of the area is within the Salado Creek watershed; 35 percent overlaps with the Cibolo Creek watershed; and the remaining 13 percent consist of subunits of the Leon Creek watershed. These values are summarized in Table 4.19.

The 30-year record (1971-2000) from the Boerne weather station indicates that an average mean rainfall of 37.36 inches per year equates to 12,466 acre-ft/yr of water on the CSSA property, and a total of nearly 41,600 acre-ft/yr within the model area. Likewise, the site-measured rainfall ranges between 5,669 acre-ft/yr (1999) to 17,307 (2002) acre-ft/yr within the CSSA facility. The volume of precipitation received within the model area based upon the site-measured data ranges between 18,915 acre-ft/yr (1999) to 57,743 acre-ft/yr (2002). The data show that the 8-year average (1999-2006) is 84 percent of the 30-year period of record (1971-2000), and that the range of values measured by the CS-16 weather station in the short-term corresponds somewhat below the long-term precipitation normal.

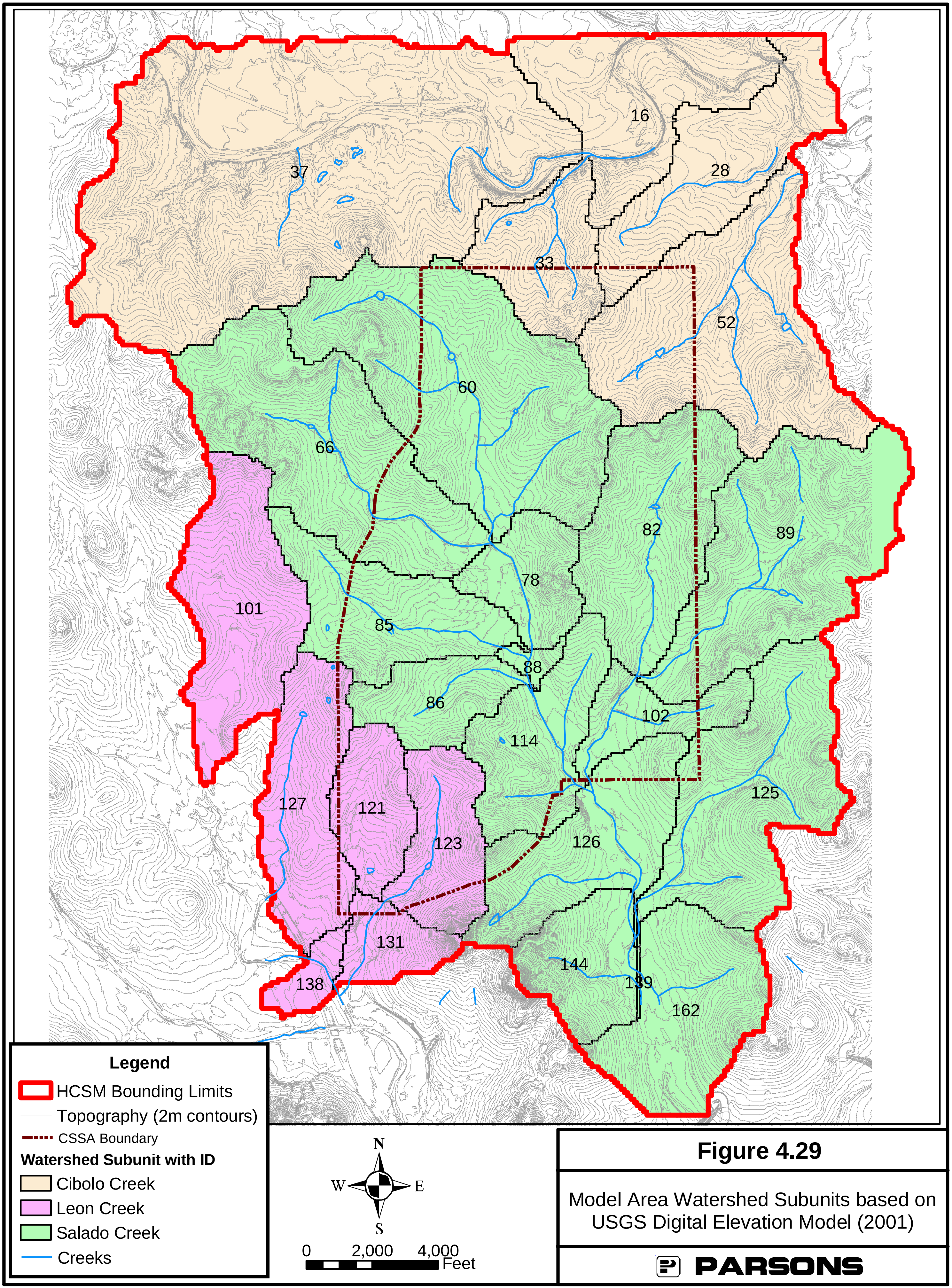

Figure 4.29

Model Area Watershed Subunits based on USGS Digital Elevation Model (2001)

PARSONS

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Table 4.10
Volume of Annual Precipitation within CSSA and Surrounding Watersheds
(Based upon 1971-2000 Precipitation Normals for Boerne, TX)

Precipitation Data (Inches)		**Average Monthly Precipitation at Boerne Station #410902 (1971 through 2000)**												SubTotals	Estimated Aquifer Recharge		
		January	February	March	April	May	June	July	August	September	October	November	December	Annual	2.5%	4.0%	6.6%
		1.79	2.24	2.57	2.87	4.66	4.77	2.23	3.05	3.61	4.09	3.11	2.37	37.36	0.93	1.49	2.47
	Acreage	**Camp Stanley Storage Activity (Acre-feet)**															
CSSA	4,004.0	597.3	747.4	857.5	957.6	1,554.9	1,591.6	744.1	1,017.7	1,204.5	1,364.7	1,037.7	790.8	12,465.8	311.6	498.6	822.7
SubUnit	Acreage	**Salado Creek Watershed (Acre-feet)**															
60	1,122.2	167.4	209.5	240.3	268.4	435.8	446.1	208.5	285.2	337.6	382.5	290.8	221.6	3,493.8	87.3	139.8	230.6
66	871.8	130.0	162.7	186.7	208.5	338.5	346.5	162.0	221.6	262.3	297.1	225.9	172.2	2,714.2	67.9	108.6	179.1
78	234.9	35.0	43.8	50.3	56.2	91.2	93.4	43.6	59.7	70.7	80.0	60.9	46.4	731.2	18.3	29.2	48.3
82	593.1	88.5	110.7	127.0	141.9	230.3	235.8	110.2	150.8	178.4	202.2	153.7	117.1	1,846.6	46.2	73.9	121.9
85	433.2	64.6	80.9	92.8	103.6	168.2	172.2	80.5	110.1	130.3	147.7	112.3	85.6	1,348.8	33.7	54.0	89.0
86	230.2	34.3	43.0	49.3	55.1	89.4	91.5	42.8	58.5	69.2	78.5	59.7	45.5	716.6	17.9	28.7	47.3
88	34.0	5.1	6.4	7.3	8.1	13.2	13.5	6.3	8.6	10.2	11.6	8.8	6.7	105.9	2.6	4.2	7.0
89	847.1	126.4	158.1	181.4	202.6	329.0	336.7	157.4	215.3	254.8	288.7	219.5	167.3	2,637.3	65.9	105.5	174.1
102	195.0	29.1	36.4	41.8	46.6	75.7	77.5	36.2	49.6	58.7	66.5	50.5	38.5	607.2	15.2	24.3	40.1
114	387.0	57.7	72.2	82.9	92.6	150.3	153.8	71.9	98.4	116.4	131.9	100.3	76.4	1,204.8	30.1	48.2	79.5
125	717.2	107.0	133.9	153.6	171.5	278.5	285.1	133.3	182.3	215.8	244.5	185.9	141.7	2,233.0	55.8	89.3	147.4
126	489.7	73.0	91.4	104.9	117.1	190.2	194.7	91.0	124.5	147.3	166.9	126.9	96.7	1,524.7	38.1	61.0	100.6
139	4.9	0.7	0.9	1.0	1.2	1.9	1.9	0.9	1.2	1.5	1.7	1.3	1.0	15.2	0.4	0.6	1.0
144	287.6	42.9	53.7	61.6	68.8	111.7	114.3	53.4	73.1	86.5	98.0	74.5	56.8	895.3	22.4	35.8	59.1
162	515.7	76.9	96.3	110.5	123.3	200.3	205.0	95.8	131.1	155.2	175.8	133.7	101.9	1,605.7	40.1	64.2	106.0
	6,963.7	**1,038.8**	**1,299.9**	**1,491.4**	**1,665.5**	**2,704.2**	**2,768.1**	**1,294.1**	**1,769.9**	**2,094.9**	**2,373.5**	**1,804.8**	**1,375.3**	**21,680.4**	**542.0**	**867.2**	**1,430.9**
SubUnit	Acreage	**Leon Creek Watershed (Acre-feet)**															
101	562.9	84.0	105.1	120.6	134.6	218.6	223.7	104.6	143.1	169.3	191.9	145.9	111.2	1,752.5	43.8	70.1	115.7
121	231.1	34.5	43.1	49.5	55.3	89.7	91.9	42.9	58.7	69.5	78.8	59.9	45.6	719.4	18.0	28.8	47.5
123	291.3	43.5	54.4	62.4	69.7	113.1	115.8	54.1	74.0	87.6	99.3	75.5	57.5	907.0	22.7	36.3	59.9
127	434.6	64.8	81.1	93.1	103.9	168.8	172.7	80.8	110.5	130.7	148.1	112.6	85.8	1,352.9	33.8	54.1	89.3
131	151.5	22.6	28.3	32.4	36.2	58.8	60.2	28.1	38.5	45.6	51.6	39.3	29.9	471.5	11.8	18.9	31.1
138	82.3	12.3	15.4	17.6	19.7	32.0	32.7	15.3	20.9	24.8	28.0	21.3	16.3	256.2	6.4	10.2	16.9
	1,753.6	**261.6**	**327.3**	**375.6**	**419.4**	**681.0**	**697.1**	**325.9**	**445.7**	**527.5**	**597.7**	**454.5**	**346.3**	**5,459.6**	**136.5**	**218.4**	**360.3**
SubUnit	Acreage	**Cibolo Creek Watershed (Acre-feet)**															
16	564.0	84.1	105.3	120.8	134.9	219.0	224.2	104.8	143.4	169.7	192.2	146.2	111.4	1,755.9	43.9	70.2	115.9
28	513.7	76.6	95.9	110.0	122.9	199.5	204.2	95.5	130.6	154.5	175.1	133.1	101.5	1,599.4	40.0	64.0	105.6
33	333.4	49.7	62.2	71.4	79.7	129.5	132.5	62.0	84.7	100.3	113.6	86.4	65.8	1,037.9	25.9	41.5	68.5
37	2,300.3	343.1	429.4	492.6	550.1	893.3	914.4	427.5	584.6	692.0	784.0	596.2	454.3	7,161.5	179.0	286.5	472.7
52	930.1	138.7	173.6	199.2	222.4	361.2	369.7	172.8	236.4	279.8	317.0	241.0	183.7	2,895.6	72.4	115.8	191.1
	4,641.4	**692.3**	**866.4**	**994.0**	**1,110.1**	**1,802.4**	**1,845.0**	**862.5**	**1,179.7**	**1,396.3**	**1,582.0**	**1,202.9**	**916.7**	**14,450.3**	**361.3**	**578.0**	**953.7**
Watershed Subtotals	**13,358.8**	**1,992.7**	**2,493.6**	**2,861.0**	**3,195.0**	**5,187.7**	**5,310.1**	**2,482.5**	**3,395.4**	**4,018.8**	**4,553.1**	**3,462.1**	**2,638.4**	**41,590.3**	**1,039.8**	**1,663.6**	**2,745.0**

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Table 4.11

Volume of Annual Precipitation within CSSA and Surrounding Watersheds

(Based upon 1999 Precipitation at CS-16 Weather Station)

Precipitation Data (Inches)		Average Monthly Precipitation at CSSA Station CS-16 (1999)												SubTotals	Estimated Aquifer Recharge		
		January	February	March	April	May	June	July	August	September	October	November	December	Annual	2.5%	4.0%	6.6%
		0.06	0.33	2.94	1.48	1.8	4.63	1.22	0.75	1.24	1.98	0.15	0.41	16.99	0.42	0.68	1.12
	Acreage	**Camp Stanley Storage Activity (Acre-feet)**															
CSSA	4,004.0	20.0	110.1	981.0	493.8	600.6	1,544.9	407.1	250.3	413.7	660.7	50.1	136.8	5,669.0	141.7	226.8	374.2
SubUnit	Acreage	**Salado Creek Watershed (Acre-feet)**															
60	1,122.2	5.6	30.9	274.9	138.4	168.3	433.0	114.1	70.1	116.0	185.2	14.0	38.3	1,588.9	39.7	63.6	104.9
66	871.8	4.4	24.0	213.6	107.5	130.8	336.4	88.6	54.5	90.1	143.8	10.9	29.8	1,234.3	30.9	49.4	81.5
78	234.9	1.2	6.5	57.5	29.0	35.2	90.6	23.9	14.7	24.3	38.8	2.9	8.0	332.5	8.3	13.3	21.9
82	593.1	3.0	16.3	145.3	73.2	89.0	228.9	60.3	37.1	61.3	97.9	7.4	20.3	839.8	21.0	33.6	55.4
85	433.2	2.2	11.9	106.1	53.4	65.0	167.2	44.0	27.1	44.8	71.5	5.4	14.8	613.4	15.3	24.5	40.5
86	230.2	1.2	6.3	56.4	28.4	34.5	88.8	23.4	14.4	23.8	38.0	2.9	7.9	325.9	8.1	13.0	21.5
88	34.0	0.2	0.9	8.3	4.2	5.1	13.1	3.5	2.1	3.5	5.6	0.4	1.2	48.2	1.2	1.9	3.2
89	847.1	4.2	23.3	207.5	104.5	127.1	326.8	86.1	52.9	87.5	139.8	10.6	28.9	1,199.4	30.0	48.0	79.2
102	195.0	1.0	5.4	47.8	24.1	29.3	75.3	19.8	12.2	20.2	32.2	2.4	6.7	276.1	6.9	11.0	18.2
114	387.0	1.9	10.6	94.8	47.7	58.0	149.3	39.3	24.2	40.0	63.9	4.8	13.2	547.9	13.7	21.9	36.2
125	717.2	3.6	19.7	175.7	88.5	107.6	276.7	72.9	44.8	74.1	118.3	9.0	24.5	1,015.5	25.4	40.6	67.0
126	489.7	2.4	13.5	120.0	60.4	73.5	189.0	49.8	30.6	50.6	80.8	6.1	16.7	693.4	17.3	27.7	45.8
139	4.9	0.0	0.1	1.2	0.6	0.7	1.9	0.5	0.3	0.5	0.8	0.1	0.2	6.9	0.2	0.3	0.5
144	287.6	1.4	7.9	70.5	35.5	43.1	111.0	29.2	18.0	29.7	47.4	3.6	9.8	407.1	10.2	16.3	26.9
162	515.7	2.6	14.2	126.4	63.6	77.4	199.0	52.4	32.2	53.3	85.1	6.4	17.6	730.2	18.3	29.2	48.2
	6,963.7	**34.8**	**191.5**	**1,706.1**	**858.9**	**1,044.6**	**2,686.8**	**708.0**	**435.2**	**719.6**	**1,149.0**	**87.0**	**237.9**	**9,859.5**	**246.5**	**394.4**	**650.7**
SubUnit	Acreage	**Leon Creek Watershed (Acre-feet)**															
101	562.9	2.8	15.5	137.9	69.4	84.4	217.2	57.2	35.2	58.2	92.9	7.0	19.2	797.0	19.9	31.9	52.6
121	231.1	1.2	6.4	56.6	28.5	34.7	89.2	23.5	14.4	23.9	38.1	2.9	7.9	327.2	8.2	13.1	21.6
123	291.3	1.5	8.0	71.4	35.9	43.7	112.4	29.6	18.2	30.1	48.1	3.6	10.0	412.5	10.3	16.5	27.2
127	434.6	2.2	12.0	106.5	53.6	65.2	167.7	44.2	27.2	44.9	71.7	5.4	14.8	615.3	15.4	24.6	40.6
131	151.5	0.8	4.2	37.1	18.7	22.7	58.4	15.4	9.5	15.7	25.0	1.9	5.2	214.4	5.4	8.6	14.2
138	82.3	0.4	2.3	20.2	10.1	12.3	31.7	8.4	5.1	8.5	13.6	1.0	2.8	116.5	2.9	4.7	7.7
	1,753.6	**8.8**	**48.2**	**429.6**	**216.3**	**263.0**	**676.6**	**178.3**	**109.6**	**181.2**	**289.3**	**21.9**	**59.9**	**2,482.8**	**62.1**	**99.3**	**163.9**
SubUnit	Acreage	**Cibolo Creek Watershed (Acre-feet)**															
16	564.0	2.8	15.5	138.2	69.6	84.6	217.6	57.3	35.3	58.3	93.1	7.1	19.3	798.5	20.0	31.9	52.7
28	513.7	2.6	14.1	125.9	63.4	77.1	198.2	52.2	32.1	53.1	84.8	6.4	17.6	727.4	18.2	29.1	48.0
33	333.4	1.7	9.2	81.7	41.1	50.0	128.6	33.9	20.8	34.4	55.0	4.2	11.4	472.0	11.8	18.9	31.2
37	2,300.3	11.5	63.3	563.6	283.7	345.0	887.5	233.9	143.8	237.7	379.5	28.8	78.6	3,256.8	81.4	130.3	214.9
52	930.1	4.7	25.6	227.9	114.7	139.5	358.9	94.6	58.1	96.1	153.5	11.6	31.8	1,316.8	32.9	52.7	86.9
	4,641.4	**23.2**	**127.6**	**1,137.2**	**572.4**	**696.2**	**1,790.8**	**471.9**	**290.1**	**479.6**	**765.8**	**58.0**	**158.6**	**6,571.5**	**164.3**	**262.9**	**433.7**
Watershed Subtotals	**13,358.8**	**66.8**	**367.4**	**3,272.9**	**1,647.6**	**2,003.8**	**5,154.3**	**1,358.1**	**834.9**	**1,380.4**	**2,204.2**	**167.0**	**456.4**	**18,913.8**	**472.8**	**756.6**	**1,248.3**

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Table 4.12
Volume of Annual Precipitation within CSSA and Surrounding Watersheds
(Based upon 2000 Precipitation at CS-16 Weather Station)

Precipitation Data (Inches)		Average Monthly Precipitation at CSSA Station CS-16 (2000)												SubTotals	Estimated Aquifer Recharge		
		January	February	March	April	May	June	July	August	September	October	November	December	Annual	2.5%	4.0%	6.6%
		0.97	1.68	1.02	3.05	3.75	4.72	0.56	0.87	0.82	6.98	6.47	1.62	32.51	0.81	1.30	2.15
	Acreage	**Camp Stanley Storage Activity (Acre-feet)**															
CSSA	4,004.0	323.7	560.6	340.3	1,017.7	1,251.3	1,574.9	186.9	290.3	273.6	2,329.0	2,158.8	540.5	10,847.5	271.2	433.9	715.9
SubUnit	Acreage	**Salado Creek Watershed (Acre-feet)**															
60	1,122.2	90.7	157.1	95.4	285.2	350.7	441.4	52.4	81.4	76.7	652.8	605.1	151.5	3,040.3	76.0	121.6	200.7
66	871.8	70.5	122.1	74.1	221.6	272.4	342.9	40.7	63.2	59.6	507.1	470.0	117.7	2,361.8	59.0	94.5	155.9
78	234.9	19.0	32.9	20.0	59.7	73.4	92.4	11.0	17.0	16.0	136.6	126.6	31.7	636.3	15.9	25.5	42.0
82	593.1	47.9	83.0	50.4	150.8	185.4	233.3	27.7	43.0	40.5	345.0	319.8	80.1	1,606.9	40.2	64.3	106.1
85	433.2	35.0	60.7	36.8	110.1	135.4	170.4	20.2	31.4	29.6	252.0	233.6	58.5	1,173.7	29.3	46.9	77.5
86	230.2	18.6	32.2	19.6	58.5	71.9	90.5	10.7	16.7	15.7	133.9	124.1	31.1	623.6	15.6	24.9	41.2
88	34.0	2.8	4.8	2.9	8.6	10.6	13.4	1.6	2.5	2.3	19.8	18.3	4.6	92.2	2.3	3.7	6.1
89	847.1	68.5	118.6	72.0	215.3	264.7	333.2	39.5	61.4	57.9	492.7	456.7	114.4	2,295.0	57.4	91.8	151.5
102	195.0	15.8	27.3	16.6	49.6	61.0	76.7	9.1	14.1	13.3	113.5	105.2	26.3	528.4	13.2	21.1	34.9
114	387.0	31.3	54.2	32.9	98.4	120.9	152.2	18.1	28.1	26.4	225.1	208.6	52.2	1,048.4	26.2	41.9	69.2
125	717.2	58.0	100.4	61.0	182.3	224.1	282.1	33.5	52.0	49.0	417.2	386.7	96.8	1,943.1	48.6	77.7	128.2
126	489.7	39.6	68.6	41.6	124.5	153.0	192.6	22.9	35.5	33.5	284.9	264.0	66.1	1,326.7	33.2	53.1	87.6
139	4.9	0.4	0.7	0.4	1.2	1.5	1.9	0.2	0.4	0.3	2.8	2.6	0.7	13.3	0.3	0.5	0.9
144	287.6	23.2	40.3	24.4	73.1	89.9	113.1	13.4	20.8	19.6	167.3	155.0	38.8	779.0	19.5	31.2	51.4
162	515.7	41.7	72.2	43.8	131.1	161.2	202.9	24.1	37.4	35.2	300.0	278.1	69.6	1,397.2	34.9	55.9	92.2
	6,963.7	**562.9**	**974.9**	**591.9**	**1,769.9**	**2,176.2**	**2,739.1**	**325.0**	**504.9**	**475.9**	**4,050.6**	**3,754.6**	**940.1**	**18,865.9**	**471.6**	**754.6**	**1,245.1**
SubUnit	Acreage	**Leon Creek Watershed (Acre-feet)**															
101	562.9	45.5	78.8	47.8	143.1	175.9	221.4	26.3	40.8	38.5	327.4	303.5	76.0	1,525.0	38.1	61.0	100.6
121	231.1	18.7	32.3	19.6	58.7	72.2	90.9	10.8	16.8	15.8	134.4	124.6	31.2	626.0	15.7	25.0	41.3
123	291.3	23.6	40.8	24.8	74.0	91.0	114.6	13.6	21.1	19.9	169.5	157.1	39.3	789.3	19.7	31.6	52.1
127	434.6	35.1	60.8	36.9	110.5	135.8	170.9	20.3	31.5	29.7	252.8	234.3	58.7	1,177.3	29.4	47.1	77.7
131	151.5	12.2	21.2	12.9	38.5	47.3	59.6	7.1	11.0	10.3	88.1	81.7	20.4	410.3	10.3	16.4	27.1
138	82.3	6.7	11.5	7.0	20.9	25.7	32.4	3.8	6.0	5.6	47.9	44.4	11.1	222.9	5.6	8.9	14.7
	1,753.6	**141.7**	**245.5**	**149.1**	**445.7**	**548.0**	**689.8**	**81.8**	**127.1**	**119.8**	**1,020.0**	**945.5**	**236.7**	**4,750.8**	**118.8**	**190.0**	**313.6**
SubUnit	Acreage	**Cibolo Creek Watershed (Acre-feet)**															
16	564.0	45.6	79.0	47.9	143.4	176.3	221.8	26.3	40.9	38.5	328.1	304.1	76.1	1,528.0	38.2	61.1	100.8
28	513.7	41.5	71.9	43.7	130.6	160.5	202.1	24.0	37.2	35.1	298.8	277.0	69.4	1,391.8	34.8	55.7	91.9
33	333.4	26.9	46.7	28.3	84.7	104.2	131.1	15.6	24.2	22.8	193.9	179.7	45.0	903.2	22.6	36.1	59.6
37	2,300.3	185.9	322.0	195.5	584.6	718.8	904.8	107.3	166.8	157.2	1,338.0	1,240.2	310.5	6,231.8	155.8	249.3	411.3
52	930.1	75.2	130.2	79.1	236.4	290.6	365.8	43.4	67.4	63.6	541.0	501.5	125.6	2,519.7	63.0	100.8	166.3
	4,641.4	**375.2**	**649.8**	**394.5**	**1,179.7**	**1,450.4**	**1,825.6**	**216.6**	**336.5**	**317.2**	**2,699.8**	**2,502.5**	**626.6**	**12,574.4**	**314.4**	**503.0**	**829.9**
Watershed Subtotals	**13,358.8**	**1,079.8**	**1,870.2**	**1,135.5**	**3,395.4**	**4,174.6**	**5,254.4**	**623.4**	**968.5**	**912.8**	**7,770.3**	**7,202.6**	**1,803.4**	**36,191.1**	**904.8**	**1,447.6**	**2,388.6**

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Table 4.13
Volume of Annual Precipitation within CSSA and Surrounding Watersheds
(Based upon 2001 Precipitation at CS-16 Weather Station)

Precipitation Data (Inches)		Average Monthly Precipitation at CSSA Station CS-16 (2001)												SubTotals	Estimated Aquifer Recharge		
		January	February	March	April	May	June	July	August	September	October	November	December	Annual	2.5%	4.0%	6.6%
		3.3	1.61	4.11	2.15	3.93	1.88	0.1	11.19	2	1.8	5.69	2.41	40.17	1.00	1.61	2.65
	Acreage	Camp Stanley Storage Activity (Acre-feet)															
CSSA	4,004.0	1,101.1	537.2	1,371.4	717.4	1,311.3	627.3	33.4	3,733.7	667.3	600.6	1,898.6	804.1	13,403.4	335.1	536.1	884.6
SubUnit	Acreage	Salado Creek Watershed (Acre-feet)															
60	1,122.2	308.6	150.6	384.4	201.1	367.5	175.8	9.4	1,046.5	187.0	168.3	532.1	225.4	3,756.6	93.9	150.3	247.9
66	871.8	239.7	117.0	298.6	156.2	285.5	136.6	7.3	813.0	145.3	130.8	413.4	175.1	2,918.3	73.0	116.7	192.6
78	234.9	64.6	31.5	80.4	42.1	76.9	36.8	2.0	219.0	39.1	35.2	111.4	47.2	786.2	19.7	31.4	51.9
82	593.1	163.1	79.6	203.1	106.3	194.3	92.9	4.9	553.1	98.9	89.0	281.2	119.1	1,985.5	49.6	79.4	131.0
85	433.2	119.1	58.1	148.4	77.6	141.9	67.9	3.6	404.0	72.2	65.0	205.4	87.0	1,450.2	36.3	58.0	95.7
86	230.2	63.3	30.9	78.8	41.2	75.4	36.1	1.9	214.6	38.4	34.5	109.1	46.2	770.5	19.3	30.8	50.9
88	34.0	9.4	4.6	11.7	6.1	11.1	5.3	0.3	31.7	5.7	5.1	16.1	6.8	113.9	2.8	4.6	7.5
89	847.1	233.0	113.7	290.1	151.8	277.4	132.7	7.1	789.9	141.2	127.1	401.7	170.1	2,835.7	70.9	113.4	187.2
102	195.0	53.6	26.2	66.8	34.9	63.9	30.6	1.6	181.9	32.5	29.3	92.5	39.2	652.9	16.3	26.1	43.1
114	387.0	106.4	51.9	132.5	69.3	126.7	60.6	3.2	360.9	64.5	58.0	183.5	77.7	1,295.4	32.4	51.8	85.5
125	717.2	197.2	96.2	245.7	128.5	234.9	112.4	6.0	668.8	119.5	107.6	340.1	144.0	2,400.9	60.0	96.0	158.5
126	489.7	134.7	65.7	167.7	87.7	160.4	76.7	4.1	456.7	81.6	73.5	232.2	98.4	1,639.3	41.0	65.6	108.2
139	4.9	1.3	0.7	1.7	0.9	1.6	0.8	0.0	4.6	0.8	0.7	2.3	1.0	16.4	0.4	0.7	1.1
144	287.6	79.1	38.6	98.5	51.5	94.2	45.1	2.4	268.1	47.9	43.1	136.4	57.8	962.6	24.1	38.5	63.5
162	515.7	141.8	69.2	176.6	92.4	168.9	80.8	4.3	480.9	86.0	77.4	244.5	103.6	1,726.4	43.2	69.1	113.9
	6,963.7	**1,915.0**	**934.3**	**2,385.1**	**1,247.7**	**2,280.6**	**1,091.0**	**58.0**	**6,493.7**	**1,160.6**	**1,044.6**	**3,302.0**	**1,398.5**	**23,311.0**	**582.8**	**932.4**	**1,538.5**
SubUnit	Acreage	Leon Creek Watershed (Acre-feet)															
101	562.9	154.8	75.5	192.8	100.9	184.3	88.2	4.7	524.9	93.8	84.4	266.9	113.0	1,884.3	47.1	75.4	124.4
121	231.1	63.5	31.0	79.1	41.4	75.7	36.2	1.9	215.5	38.5	34.7	109.6	46.4	773.5	19.3	30.9	51.1
123	291.3	80.1	39.1	99.8	52.2	95.4	45.6	2.4	271.7	48.6	43.7	138.1	58.5	975.3	24.4	39.0	64.4
127	434.6	119.5	58.3	148.8	77.9	142.3	68.1	3.6	405.2	72.4	65.2	206.1	87.3	1,454.7	36.4	58.2	96.0
131	151.5	41.6	20.3	51.9	27.1	49.6	23.7	1.3	141.2	25.2	22.7	71.8	30.4	507.0	12.7	20.3	33.5
138	82.3	22.6	11.0	28.2	14.7	26.9	12.9	0.7	76.7	13.7	12.3	39.0	16.5	275.5	6.9	11.0	18.2
	1,753.6	**482.2**	**235.3**	**600.6**	**314.2**	**574.3**	**274.7**	**14.6**	**1,635.2**	**292.3**	**263.0**	**831.5**	**352.2**	**5,870.2**	**146.8**	**234.8**	**387.4**
SubUnit	Acreage	Cibolo Creek Watershed (Acre-feet)															
16	564.0	155.1	75.7	193.2	101.1	184.7	88.4	4.7	525.9	94.0	84.6	267.4	113.3	1,888.0	47.2	75.5	124.6
28	513.7	141.3	68.9	176.0	92.0	168.2	80.5	4.3	479.1	85.6	77.1	243.6	103.2	1,719.7	43.0	68.8	113.5
33	333.4	91.7	44.7	114.2	59.7	109.2	52.2	2.8	310.9	55.6	50.0	158.1	67.0	1,116.0	27.9	44.6	73.7
37	2,300.3	632.6	308.6	787.8	412.1	753.3	360.4	19.2	2,145.0	383.4	345.0	1,090.7	462.0	7,700.1	192.5	308.0	508.2
52	930.1	255.8	124.8	318.5	166.6	304.6	145.7	7.8	867.3	155.0	139.5	441.0	186.8	3,113.4	77.8	124.5	205.5
	4,641.4	**1,276.4**	**622.7**	**1,589.7**	**831.6**	**1,520.1**	**727.2**	**38.7**	**4,328.1**	**773.6**	**696.2**	**2,200.8**	**932.2**	**15,537.2**	**388.4**	**621.5**	**1,025.5**
Watershed Subtotals	**13,358.8**	**3,673.7**	**1,792.3**	**4,575.4**	**2,393.4**	**4,375.0**	**2,092.9**	**111.3**	**12,457.0**	**2,226.5**	**2,003.8**	**6,334.3**	**2,682.9**	**44,718.4**	**1,118.0**	**1,788.7**	**2,951.4**

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Table 4.14
Volume of Annual Precipitation within CSSA and Surrounding Watersheds
(Based upon 2002 Precipitation at CS-16 Weather Station)

Precipitation Data (Inches)		Average Monthly Precipitation at CSSA Station CS-16 (2002)												SubTotals	Estimated Aquifer Recharge		
		January	February	March	April	May	June	July	August	September	October	November	December	Annual	2.5%	4.0%	6.6%
		0.83	0.54	2.06	1.78	1.38	10.59	13.39	3.37	3.99	8.08	2.19	3.67	51.87	1.30	2.07	3.42
	Acreage	**Camp Stanley Storage Activity (Acre-feet)**															
CSSA	4,004.0	276.9	180.2	687.4	593.9	460.5	3,533.5	4,467.8	1,124.5	1,331.3	2,696.0	730.7	1,224.6	17,307.3	432.7	692.3	1,142.3
SubUnit	Acreage	**Salado Creek Watershed (Acre-feet)**															
60	1,122.2	77.6	50.5	192.6	166.5	129.1	990.4	1,252.2	315.2	373.1	755.6	204.8	343.2	4,850.8	121.3	194.0	320.2
66	871.8	60.3	39.2	149.7	129.3	100.3	769.4	972.8	244.8	289.9	587.0	159.1	266.6	3,768.4	94.2	150.7	248.7
78	234.9	16.2	10.6	40.3	34.8	27.0	207.3	262.1	66.0	78.1	158.1	42.9	71.8	1,015.1	25.4	40.6	67.0
82	593.1	41.0	26.7	101.8	88.0	68.2	523.4	661.8	166.6	197.2	399.4	108.2	181.4	2,563.8	64.1	102.6	169.2
85	433.2	30.0	19.5	74.4	64.3	49.8	382.3	483.4	121.7	144.0	291.7	79.1	132.5	1,872.6	46.8	74.9	123.6
86	230.2	15.9	10.4	39.5	34.1	26.5	203.1	256.8	64.6	76.5	155.0	42.0	70.4	995.0	24.9	39.8	65.7
88	34.0	2.4	1.5	5.8	5.0	3.9	30.0	38.0	9.6	11.3	22.9	6.2	10.4	147.1	3.7	5.9	9.7
89	847.1	58.6	38.1	145.4	125.7	97.4	747.6	945.2	237.9	281.7	570.4	154.6	259.1	3,661.6	91.5	146.5	241.7
102	195.0	13.5	8.8	33.5	28.9	22.4	172.1	217.6	54.8	64.9	131.3	35.6	59.7	843.1	21.1	33.7	55.6
114	387.0	26.8	17.4	66.4	57.4	44.5	341.5	431.8	108.7	128.7	260.6	70.6	118.3	1,672.7	41.8	66.9	110.4
125	717.2	49.6	32.3	123.1	106.4	82.5	633.0	800.3	201.4	238.5	482.9	130.9	219.4	3,100.2	77.5	124.0	204.6
126	489.7	33.9	22.0	84.1	72.6	56.3	432.2	546.4	137.5	162.8	329.7	89.4	149.8	2,116.8	52.9	84.7	139.7
139	4.9	0.3	0.2	0.8	0.7	0.6	4.3	5.5	1.4	1.6	3.3	0.9	1.5	21.1	0.5	0.8	1.4
144	287.6	19.9	12.9	49.4	42.7	33.1	253.8	320.9	80.8	95.6	193.6	52.5	87.9	1,243.0	31.1	49.7	82.0
162	515.7	35.7	23.2	88.5	76.5	59.3	455.1	575.5	144.8	171.5	347.3	94.1	157.7	2,229.3	55.7	89.2	147.1
	6,963.7	**481.7**	**313.4**	**1,195.4**	**1,033.0**	**800.8**	**6,145.5**	**7,770.3**	**1,955.6**	**2,315.4**	**4,688.9**	**1,270.9**	**2,129.7**	**30,100.7**	**752.5**	**1,204.0**	**1,986.6**
SubUnit	Acreage	**Leon Creek Watershed (Acre-feet)**															
101	562.9	38.9	25.3	96.6	83.5	64.7	496.7	628.1	158.1	187.2	379.0	102.7	172.1	2,433.1	60.8	97.3	160.6
121	231.1	16.0	10.4	39.7	34.3	26.6	203.9	257.8	64.9	76.8	155.6	42.2	70.7	998.8	25.0	40.0	65.9
123	291.3	20.2	13.1	50.0	43.2	33.5	257.1	325.1	81.8	96.9	196.2	53.2	89.1	1,259.3	31.5	50.4	83.1
127	434.6	30.1	19.6	74.6	64.5	50.0	383.5	484.9	122.0	144.5	292.6	79.3	132.9	1,878.4	47.0	75.1	124.0
131	151.5	10.5	6.8	26.0	22.5	17.4	133.7	169.0	42.5	50.4	102.0	27.6	46.3	654.7	16.4	26.2	43.2
138	82.3	5.7	3.7	14.1	12.2	9.5	72.6	91.8	23.1	27.4	55.4	15.0	25.2	355.7	8.9	14.2	23.5
	1,753.6	**121.3**	**78.9**	**301.0**	**260.1**	**201.7**	**1,547.6**	**1,956.7**	**492.5**	**583.1**	**1,180.8**	**320.0**	**536.3**	**7,580.0**	**189.5**	**303.2**	**500.3**
SubUnit	Acreage	**Cibolo Creek Watershed (Acre-feet)**															
16	564.0	39.0	25.4	96.8	83.7	64.9	497.7	629.3	158.4	187.5	379.8	102.9	172.5	2,437.9	60.9	97.5	160.9
28	513.7	35.5	23.1	88.2	76.2	59.1	453.4	573.2	144.3	170.8	345.9	93.8	157.1	2,220.6	55.5	88.8	146.6
33	333.4	23.1	15.0	57.2	49.5	38.3	294.2	372.0	93.6	110.8	224.5	60.8	102.0	1,441.0	36.0	57.6	95.1
37	2,300.3	159.1	103.5	394.9	341.2	264.5	2,030.0	2,566.7	646.0	764.8	1,548.8	419.8	703.5	9,942.9	248.6	397.7	656.2
52	930.1	64.3	41.9	159.7	138.0	107.0	820.8	1,037.8	261.2	309.2	626.2	169.7	284.4	4,020.2	100.5	160.8	265.3
	4,641.4	**321.0**	**208.9**	**796.8**	**688.5**	**533.8**	**4,096.1**	**5,179.1**	**1,303.5**	**1,543.3**	**3,125.2**	**847.1**	**1,419.5**	**20,062.6**	**501.6**	**802.5**	**1,324.1**
Watershed Subtotals	**13,358.8**	**924.0**	**601.1**	**2,293.3**	**1,981.5**	**1,536.3**	**11,789.1**	**14,906.1**	**3,751.6**	**4,441.8**	**8,994.9**	**2,438.0**	**4,085.6**	**57,743.2**	**1,443.6**	**2,309.7**	**3,811.1**

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Table 4.15
Volume of Annual Precipitation within CSSA and Surrounding Watersheds
(Based upon 2003 Precipitation at CSSA Weather Stations)

Precipitation Data (Inches)		Average Monthly Precipitation at CSSA Station CS-16 (2002)												SubTotals	Estimated Aquifer Recharge		
		January	February	March	April	May	June	July	August	September	October	November	December	Annual	2.5%	4.0%	6.6%
		1.57	2.26	1.1	0.15	0.08	4.51	3.27	0.93	4.04	2.06	0.48	0.12	20.57	0.51	0.82	1.36
	Acreage	**Camp Stanley Storage Activity (Acre-feet)**															
CSSA	4,004.0	523.9	754.1	367.0	50.1	26.7	1,504.8	1,091.1	310.3	1,348.0	687.4	160.2	40.0	6,863.5	171.6	274.5	453.0
SubUnit	Acreage	**Salado Creek Watershed (Acre-feet)**															
60	1,122.2	146.8	211.4	102.9	14.0	7.5	421.8	305.8	87.0	377.8	192.6	44.9	11.2	1,923.7	48.1	76.9	127.0
66	871.8	114.1	164.2	79.9	10.9	5.8	327.7	237.6	67.6	293.5	149.7	34.9	8.7	1,494.4	37.4	59.8	98.6
78	234.9	30.7	44.2	21.5	2.9	1.6	88.3	64.0	18.2	79.1	40.3	9.4	2.3	402.6	10.1	16.1	26.6
82	593.1	77.6	111.7	54.4	7.4	4.0	222.9	161.6	46.0	199.7	101.8	23.7	5.9	1,016.7	25.4	40.7	67.1
85	433.2	56.7	81.6	39.7	5.4	2.9	162.8	118.1	33.6	145.9	74.4	17.3	4.3	742.6	18.6	29.7	49.0
86	230.2	30.1	43.4	21.1	2.9	1.5	86.5	62.7	17.8	77.5	39.5	9.2	2.3	394.6	9.9	15.8	26.0
88	34.0	4.5	6.4	3.1	0.4	0.2	12.8	9.3	2.6	11.5	5.8	1.4	0.3	58.3	1.5	2.3	3.8
89	847.1	110.8	159.5	77.7	10.6	5.6	318.4	230.8	65.7	285.2	145.4	33.9	8.5	1,452.1	36.3	58.1	95.8
102	195.0	25.5	36.7	17.9	2.4	1.3	73.3	53.1	15.1	65.7	33.5	7.8	2.0	334.3	8.4	13.4	22.1
114	387.0	50.6	72.9	35.5	4.8	2.6	145.4	105.4	30.0	130.3	66.4	15.5	3.9	663.3	16.6	26.5	43.8
125	717.2	93.8	135.1	65.7	9.0	4.8	269.6	195.4	55.6	241.5	123.1	28.7	7.2	1,229.5	30.7	49.2	81.1
126	489.7	64.1	92.2	44.9	6.1	3.3	184.1	133.4	38.0	164.9	84.1	19.6	4.9	839.5	21.0	33.6	55.4
139	4.9	0.6	0.9	0.4	0.1	0.0	1.8	1.3	0.4	1.6	0.8	0.2	0.0	8.4	0.2	0.3	0.6
144	287.6	37.6	54.2	26.4	3.6	1.9	108.1	78.4	22.3	96.8	49.4	11.5	2.9	492.9	12.3	19.7	32.5
162	515.7	67.5	97.1	47.3	6.4	3.4	193.8	140.5	40.0	173.6	88.5	20.6	5.2	884.1	22.1	35.4	58.3
	6,963.7	**911.1**	**1,311.5**	**638.3**	**87.0**	**46.4**	**2,617.2**	**1,897.6**	**539.7**	**2,344.5**	**1,195.4**	**278.5**	**69.6**	**11,937.0**	**298.4**	**477.5**	**787.8**
SubUnit	Acreage	**Leon Creek Watershed (Acre-feet)**															
101	562.9	73.6	106.0	51.6	7.0	3.8	211.6	153.4	43.6	189.5	96.6	22.5	5.6	964.9	24.1	38.6	63.7
121	231.1	30.2	43.5	21.2	2.9	1.5	86.8	63.0	17.9	77.8	39.7	9.2	2.3	396.1	9.9	15.8	26.1
123	291.3	38.1	54.9	26.7	3.6	1.9	109.5	79.4	22.6	98.1	50.0	11.7	2.9	499.4	12.5	20.0	33.0
127	434.6	56.9	81.8	39.8	5.4	2.9	163.3	118.4	33.7	146.3	74.6	17.4	4.3	744.9	18.6	29.8	49.2
131	151.5	19.8	28.5	13.9	1.9	1.0	56.9	41.3	11.7	51.0	26.0	6.1	1.5	259.6	6.5	10.4	17.1
138	82.3	10.8	15.5	7.5	1.0	0.5	30.9	22.4	6.4	27.7	14.1	3.3	0.8	141.1	3.5	5.6	9.3
	1,753.6	**229.4**	**330.3**	**160.7**	**21.9**	**11.7**	**659.1**	**477.9**	**135.9**	**590.4**	**301.0**	**70.1**	**17.5**	**3,006.0**	**75.1**	**120.2**	**198.4**
SubUnit	Acreage	**Cibolo Creek Watershed (Acre-feet)**															
16	564.0	73.8	106.2	51.7	7.1	3.8	212.0	153.7	43.7	189.9	96.8	22.6	5.6	966.8	24.2	38.7	63.8
28	513.7	67.2	96.8	47.1	6.4	3.4	193.1	140.0	39.8	173.0	88.2	20.5	5.1	880.6	22.0	35.2	58.1
33	333.4	43.6	62.8	30.6	4.2	2.2	125.3	90.8	25.8	112.2	57.2	13.3	3.3	571.5	14.3	22.9	37.7
37	2,300.3	301.0	433.2	210.9	28.8	15.3	864.5	626.8	178.3	774.4	394.9	92.0	23.0	3,943.0	98.6	157.7	260.2
52	930.1	121.7	175.2	85.3	11.6	6.2	349.6	253.4	72.1	313.1	159.7	37.2	9.3	1,594.3	39.9	63.8	105.2
	4,641.4	**607.3**	**874.1**	**425.5**	**58.0**	**30.9**	**1,744.4**	**1,264.8**	**359.7**	**1,562.6**	**796.8**	**185.7**	**46.4**	**7,956.2**	**198.9**	**318.2**	**525.1**
Watershed Subtotals	**13,358.8**	**1,747.8**	**2,515.9**	**1,224.6**	**167.0**	**89.1**	**5,020.7**	**3,640.3**	**1,035.3**	**4,497.4**	**2,293.3**	**534.4**	**133.6**	**22,899.1**	**572.5**	**916.0**	**1,511.3**

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Table 4.16
Volume of Annual Precipitation within CSSA and Surrounding Watersheds
(Based upon 2004 Precipitation at CSSA Weather Stations)

Precipitation Data (Inches)		Average Monthly Precipitation at CSSA Station CS-16 (2002)												SubTotals	Estimated Aquifer Recharge		
		January	February	March	April	May	June	July	August	September	October	November	December	Annual	2.5%	4.0%	6.6%
		2.91	2.71	2.47	5.78	1.52	10.39	0.88	3	4.96	5.18	10.95	0.18	50.93	1.27	2.04	3.36
	Acreage	**Camp Stanley Storage Activity (Acre-feet)**															
CSSA	4,004.0	971.0	904.2	824.2	1,928.6	507.2	3,466.8	293.6	1,001.0	1,655.0	1,728.4	3,653.7	60.1	16,993.6	424.8	679.7	1,121.6
SubUnit	Acreage	**Salado Creek Watershed (Acre-feet)**															
60	1,122.2	272.1	253.4	231.0	540.5	142.1	971.7	82.3	280.6	463.9	484.4	1,024.0	16.8	4,762.9	119.1	190.5	314.4
66	871.8	211.4	196.9	179.4	419.9	110.4	754.8	63.9	217.9	360.3	376.3	795.5	13.1	3,700.1	92.5	148.0	244.2
78	234.9	57.0	53.0	48.3	113.1	29.7	203.3	17.2	58.7	97.1	101.4	214.3	3.5	996.8	24.9	39.9	65.8
82	593.1	143.8	133.9	122.1	285.7	75.1	513.6	43.5	148.3	245.2	256.0	541.2	8.9	2,517.4	62.9	100.7	166.1
85	433.2	105.1	97.8	89.2	208.7	54.9	375.1	31.8	108.3	179.1	187.0	395.3	6.5	1,838.7	46.0	73.5	121.4
86	230.2	55.8	52.0	47.4	110.9	29.2	199.3	16.9	57.5	95.1	99.4	210.0	3.5	976.9	24.4	39.1	64.5
88	34.0	8.3	7.7	7.0	16.4	4.3	29.5	2.5	8.5	14.1	14.7	31.0	0.5	144.4	3.6	5.8	9.5
89	847.1	205.4	191.3	174.4	408.0	107.3	733.5	62.1	211.8	350.1	365.7	773.0	12.7	3,595.3	89.9	143.8	237.3
102	195.0	47.3	44.0	40.1	93.9	24.7	168.9	14.3	48.8	80.6	84.2	178.0	2.9	827.8	20.7	33.1	54.6
114	387.0	93.8	87.4	79.7	186.4	49.0	335.1	28.4	96.7	159.9	167.0	353.1	5.8	1,642.4	41.1	65.7	108.4
125	717.2	173.9	162.0	147.6	345.5	90.8	621.0	52.6	179.3	296.5	309.6	654.5	10.8	3,044.1	76.1	121.8	200.9
126	489.7	118.8	110.6	100.8	235.9	62.0	424.0	35.9	122.4	202.4	211.4	446.9	7.3	2,078.5	52.0	83.1	137.2
139	4.9	1.2	1.1	1.0	2.4	0.6	4.2	0.4	1.2	2.0	2.1	4.5	0.1	20.8	0.5	0.8	1.4
144	287.6	69.7	64.9	59.2	138.5	36.4	249.0	21.1	71.9	118.9	124.1	262.4	4.3	1,220.5	30.5	48.8	80.5
162	515.7	125.1	116.5	106.2	248.4	65.3	446.5	37.8	128.9	213.2	222.6	470.6	7.7	2,188.9	54.7	87.6	144.5
	6,963.7	**1,688.7**	**1,572.6**	**1,433.4**	**3,354.2**	**882.1**	**6,029.4**	**510.7**	**1,740.9**	**2,878.3**	**3,006.0**	**6,354.4**	**104.5**	**29,555.2**	**738.9**	**1,182.2**	**1,950.6**
SubUnit	Acreage	**Leon Creek Watershed (Acre-feet)**															
101	562.9	136.5	127.1	115.9	271.1	71.3	487.4	41.3	140.7	232.7	243.0	513.6	8.4	2,389.0	59.7	95.6	157.7
121	231.1	56.0	52.2	47.6	111.3	29.3	200.1	16.9	57.8	95.5	99.7	210.9	3.5	980.7	24.5	39.2	64.7
123	291.3	70.7	65.8	60.0	140.3	36.9	252.3	21.4	72.8	120.4	125.8	265.8	4.4	1,236.5	30.9	49.5	81.6
127	434.6	105.4	98.1	89.4	209.3	55.0	376.3	31.9	108.6	179.6	187.6	396.5	6.5	1,844.4	46.1	73.8	121.7
131	151.5	36.7	34.2	31.2	72.9	19.2	131.1	11.1	37.9	62.6	65.4	138.2	2.3	642.8	16.1	25.7	42.4
138	82.3	20.0	18.6	16.9	39.6	10.4	71.2	6.0	20.6	34.0	35.5	75.1	1.2	349.2	8.7	14.0	23.0
	1,753.6	**425.2**	**396.0**	**361.0**	**844.7**	**222.1**	**1,518.3**	**128.6**	**438.4**	**724.8**	**757.0**	**1,600.2**	**26.3**	**7,442.6**	**186.1**	**297.7**	**491.2**
SubUnit	Acreage	**Cibolo Creek Watershed (Acre-feet)**															
16	564.0	136.8	127.4	116.1	271.7	71.4	488.3	41.4	141.0	233.1	243.5	514.7	8.5	2,393.7	59.8	95.7	158.0
28	513.7	124.6	116.0	105.7	247.5	65.1	444.8	37.7	128.4	212.3	221.8	468.8	7.7	2,180.4	54.5	87.2	143.9
33	333.4	80.8	75.3	68.6	160.6	42.2	288.6	24.4	83.3	137.8	143.9	304.2	5.0	1,414.9	35.4	56.6	93.4
37	2,300.3	557.8	519.5	473.5	1,108.0	291.4	1,991.6	168.7	575.1	950.8	992.9	2,099.0	34.5	9,762.7	244.1	390.5	644.3
52	930.1	225.5	210.0	191.4	448.0	117.8	805.3	68.2	232.5	384.4	401.5	848.7	14.0	3,947.4	98.7	157.9	260.5
	4,641.4	**1,125.5**	**1,048.2**	**955.4**	**2,235.6**	**587.9**	**4,018.7**	**340.4**	**1,160.4**	**1,918.5**	**2,003.6**	**4,235.3**	**69.6**	**19,699.0**	**492.5**	**788.0**	**1,300.1**
Watershed Subtotals	**13,358.8**	**3,239.5**	**3,016.9**	**2,749.7**	**6,434.5**	**1,692.1**	**11,566.5**	**979.6**	**3,339.7**	**5,521.6**	**5,766.5**	**12,189.9**	**200.4**	**56,696.8**	**1,417.4**	**2,267.9**	**3,742.0**

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Table 4.17

Volume of Annual Precipitation within CSSA and Surrounding Watersheds

(Based upon 2005 Precipitation at CSSA Weather Stations)

Precipitation Data (Inches)		Average Monthly Precipitation at CSSA Station CS-16 (2002)												SubTotals	Estimated Aquifer Recharge		
		January	February	March	April	May	June	July	August	September	October	November	December	Annual	2.5%	4.0%	6.6%
		2.3	2.4	2.32	0.24	3.16	1.18	2.44	3.17	0.85	1.96	0.4	0.05	20.47	0.51	0.82	1.35
	Acreage	**Camp Stanley Storage Activity (Acre-feet)**															
CSSA	4,004.0	767.4	800.8	774.1	80.1	1,054.4	393.7	814.1	1,057.7	283.6	654.0	133.5	16.7	6,830.2	170.8	273.2	450.8
SubUnit	Acreage	**Salado Creek Watershed (Acre-feet)**															
60	1,122.2	215.1	224.4	217.0	22.4	295.5	110.4	228.2	296.5	79.5	183.3	37.4	4.7	1,914.3	47.9	76.6	126.3
66	871.8	167.1	174.4	168.5	17.4	229.6	85.7	177.3	230.3	61.8	142.4	29.1	3.6	1,487.1	37.2	59.5	98.2
78	234.9	45.0	47.0	45.4	4.7	61.8	23.1	47.8	62.0	16.6	38.4	7.8	1.0	400.6	10.0	16.0	26.4
82	593.1	113.7	118.6	114.7	11.9	156.2	58.3	120.6	156.7	42.0	96.9	19.8	2.5	1,011.8	25.3	40.5	66.8
85	433.2	83.0	86.6	83.8	8.7	114.1	42.6	88.1	114.4	30.7	70.8	14.4	1.8	739.0	18.5	29.6	48.8
86	230.2	44.1	46.0	44.5	4.6	60.6	22.6	46.8	60.8	16.3	37.6	7.7	1.0	392.7	9.8	15.7	25.9
88	34.0	6.5	6.8	6.6	0.7	9.0	3.3	6.9	9.0	2.4	5.6	1.1	0.1	58.0	1.5	2.3	3.8
89	847.1	162.4	169.4	163.8	16.9	223.1	83.3	172.2	223.8	60.0	138.4	28.2	3.5	1,445.0	36.1	57.8	95.4
102	195.0	37.4	39.0	37.7	3.9	51.4	19.2	39.7	51.5	13.8	31.9	6.5	0.8	332.7	8.3	13.3	22.0
114	387.0	74.2	77.4	74.8	7.7	101.9	38.1	78.7	102.2	27.4	63.2	12.9	1.6	660.1	16.5	26.4	43.6
125	717.2	137.5	143.4	138.7	14.3	188.9	70.5	145.8	189.5	50.8	117.1	23.9	3.0	1,223.5	30.6	48.9	80.7
126	489.7	93.9	97.9	94.7	9.8	129.0	48.2	99.6	129.4	34.7	80.0	16.3	2.0	835.4	20.9	33.4	55.1
139	4.9	0.9	1.0	0.9	0.1	1.3	0.5	1.0	1.3	0.3	0.8	0.2	0.0	8.3	0.2	0.3	0.6
144	287.6	55.1	57.5	55.6	5.8	75.7	28.3	58.5	76.0	20.4	47.0	9.6	1.2	490.5	12.3	19.6	32.4
162	515.7	98.9	103.1	99.7	10.3	135.8	50.7	104.9	136.2	36.5	84.2	17.2	2.1	879.8	22.0	35.2	58.1
	6,963.7	**1,334.7**	**1,392.7**	**1,346.3**	**139.3**	**1,833.8**	**684.8**	**1,416.0**	**1,839.6**	**493.3**	**1,137.4**	**232.1**	**29.0**	**11,878.9**	**297.0**	**475.2**	**784.0**
SubUnit	Acreage	**Leon Creek Watershed (Acre-feet)**															
101	562.9	107.9	112.6	108.8	11.3	148.2	55.4	114.5	148.7	39.9	91.9	18.8	2.3	960.2	24.0	38.4	63.4
121	231.1	44.3	46.2	44.7	4.6	60.8	22.7	47.0	61.0	16.4	37.7	7.7	1.0	394.2	9.9	15.8	26.0
123	291.3	55.8	58.3	56.3	5.8	76.7	28.6	59.2	77.0	20.6	47.6	9.7	1.2	497.0	12.4	19.9	32.8
127	434.6	83.3	86.9	84.0	8.7	114.4	42.7	88.4	114.8	30.8	71.0	14.5	1.8	741.3	18.5	29.7	48.9
131	151.5	29.0	30.3	29.3	3.0	39.9	14.9	30.8	40.0	10.7	24.7	5.0	0.6	258.4	6.5	10.3	17.1
138	82.3	15.8	16.5	15.9	1.6	21.7	8.1	16.7	21.7	5.8	13.4	2.7	0.3	140.4	3.5	5.6	9.3
	1,753.6	**336.1**	**350.7**	**339.0**	**35.1**	**461.8**	**172.4**	**356.6**	**463.2**	**124.2**	**286.4**	**58.5**	**7.3**	**2,991.4**	**74.8**	**119.7**	**197.4**
SubUnit	Acreage	**Cibolo Creek Watershed (Acre-feet)**															
16	564.0	108.1	112.8	109.0	11.3	148.5	55.5	114.7	149.0	40.0	92.1	18.8	2.4	962.1	24.1	38.5	63.5
28	513.7	98.5	102.7	99.3	10.3	135.3	50.5	104.5	135.7	36.4	83.9	17.1	2.1	876.4	21.9	35.1	57.8
33	333.4	63.9	66.7	64.5	6.7	87.8	32.8	67.8	88.1	23.6	54.5	11.1	1.4	568.7	14.2	22.7	37.5
37	2,300.3	440.9	460.1	444.7	46.0	605.7	226.2	467.7	607.7	162.9	375.7	76.7	9.6	3,923.9	98.1	157.0	259.0
52	930.1	178.3	186.0	179.8	18.6	244.9	91.5	189.1	245.7	65.9	151.9	31.0	3.9	1,586.5	39.7	63.5	104.7
	4,641.4	**889.6**	**928.3**	**897.3**	**92.8**	**1,222.2**	**456.4**	**943.8**	**1,226.1**	**328.8**	**758.1**	**154.7**	**19.3**	**7,917.5**	**197.9**	**316.7**	**522.6**
Watershed Subtotals	**13,358.8**	**2,560.4**	**2,671.8**	**2,582.7**	**267.2**	**3,517.8**	**1,313.6**	**2,716.3**	**3,528.9**	**946.2**	**2,181.9**	**445.3**	**55.7**	**22,787.8**	**569.7**	**911.5**	**1,504.0**

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Table 4.18
Volume of Annual Precipitation within CSSA and Surrounding Watersheds
(Based upon 2006 Precipitation at CSSA Weather Stations)

Precipitation Data (Inches)		Average Monthly Precipitation at CSSA Station CS-16 (2002)												SubTotals	Estimated Aquifer Recharge		
		January	February	March	April	May	June	July	August	September	October	November	December	Annual	2.5%	4.0%	6.6%
		0.71	0.41	1.4	1.58	2.87	3.2	0.41	1.05	1.96	2.15	0.51	2.02	18.27	0.46	0.73	1.21
	Acreage	**Camp Stanley Storage Activity (Acre-feet)**															
CSSA	4,004.0	236.9	136.8	467.1	527.2	957.6	1,067.7	136.8	350.4	654.0	717.4	170.2	674.0	6,096.1	152.4	243.8	402.3
SubUnit	Acreage	**Salado Creek Watershed (Acre-feet)**															
60	1,122.2	66.4	38.3	130.9	147.8	268.4	299.3	38.3	98.2	183.3	201.1	47.7	188.9	1,708.6	42.7	68.3	112.8
66	871.8	51.6	29.8	101.7	114.8	208.5	232.5	29.8	76.3	142.4	156.2	37.1	146.8	1,327.3	33.2	53.1	87.6
78	234.9	13.9	8.0	27.4	30.9	56.2	62.6	8.0	20.5	38.4	42.1	10.0	39.5	357.6	8.9	14.3	23.6
82	593.1	35.1	20.3	69.2	78.1	141.9	158.2	20.3	51.9	96.9	106.3	25.2	99.8	903.0	22.6	36.1	59.6
85	433.2	25.6	14.8	50.5	57.0	103.6	115.5	14.8	37.9	70.8	77.6	18.4	72.9	659.6	16.5	26.4	43.5
86	230.2	13.6	7.9	26.9	30.3	55.1	61.4	7.9	20.1	37.6	41.2	9.8	38.7	350.5	8.8	14.0	23.1
88	34.0	2.0	1.2	4.0	4.5	8.1	9.1	1.2	3.0	5.6	6.1	1.4	5.7	51.8	1.3	2.1	3.4
89	847.1	50.1	28.9	98.8	111.5	202.6	225.9	28.9	74.1	138.4	151.8	36.0	142.6	1,289.7	32.2	51.6	85.1
102	195.0	11.5	6.7	22.8	25.7	46.6	52.0	6.7	17.1	31.9	34.9	8.3	32.8	297.0	7.4	11.9	19.6
114	387.0	22.9	13.2	45.1	51.0	92.6	103.2	13.2	33.9	63.2	69.3	16.4	65.1	589.2	14.7	23.6	38.9
125	717.2	42.4	24.5	83.7	94.4	171.5	191.3	24.5	62.8	117.1	128.5	30.5	120.7	1,092.0	27.3	43.7	72.1
126	489.7	29.0	16.7	57.1	64.5	117.1	130.6	16.7	42.9	80.0	87.7	20.8	82.4	745.6	18.6	29.8	49.2
139	4.9	0.3	0.2	0.6	0.6	1.2	1.3	0.2	0.4	0.8	0.9	0.2	0.8	7.4	0.2	0.3	0.5
144	287.6	17.0	9.8	33.5	37.9	68.8	76.7	9.8	25.2	47.0	51.5	12.2	48.4	437.8	10.9	17.5	28.9
162	515.7	30.5	17.6	60.2	67.9	123.3	137.5	17.6	45.1	84.2	92.4	21.9	86.8	785.2	19.6	31.4	51.8
	6,963.7	**412.0**	**237.9**	**812.4**	**916.9**	**1,665.5**	**1,857.0**	**237.9**	**609.3**	**1,137.4**	**1,247.7**	**296.0**	**1,172.2**	**10,602.3**	**265.1**	**424.1**	**699.7**
SubUnit	Acreage	**Leon Creek Watershed (Acre-feet)**															
101	562.9	33.3	19.2	65.7	74.1	134.6	150.1	19.2	49.3	91.9	100.9	23.9	94.8	857.0	21.4	34.3	56.6
121	231.1	13.7	7.9	27.0	30.4	55.3	61.6	7.9	20.2	37.7	41.4	9.8	38.9	351.8	8.8	14.1	23.2
123	291.3	17.2	10.0	34.0	38.4	69.7	77.7	10.0	25.5	47.6	52.2	12.4	49.0	443.6	11.1	17.7	29.3
127	434.6	25.7	14.8	50.7	57.2	103.9	115.9	14.8	38.0	71.0	77.9	18.5	73.2	661.6	16.5	26.5	43.7
131	151.5	9.0	5.2	17.7	19.9	36.2	40.4	5.2	13.3	24.7	27.1	6.4	25.5	230.6	5.8	9.2	15.2
138	82.3	4.9	2.8	9.6	10.8	19.7	21.9	2.8	7.2	13.4	14.7	3.5	13.9	125.3	3.1	5.0	8.3
	1,753.6	**103.8**	**59.9**	**204.6**	**230.9**	**419.4**	**467.6**	**59.9**	**153.4**	**286.4**	**314.2**	**74.5**	**295.2**	**2,669.9**	**66.7**	**106.8**	**176.2**
SubUnit	Acreage	**Cibolo Creek Watershed (Acre-feet)**															
16	564.0	33.4	19.3	65.8	74.3	134.9	150.4	19.3	49.4	92.1	101.1	24.0	94.9	858.7	21.5	34.3	56.7
28	513.7	30.4	17.6	59.9	67.6	122.9	137.0	17.6	45.0	83.9	92.0	21.8	86.5	782.2	19.6	31.3	51.6
33	333.4	19.7	11.4	38.9	43.9	79.7	88.9	11.4	29.2	54.5	59.7	14.2	56.1	507.6	12.7	20.3	33.5
37	2,300.3	136.1	78.6	268.4	302.9	550.1	613.4	78.6	201.3	375.7	412.1	97.8	387.2	3,502.1	87.6	140.1	231.1
52	930.1	55.0	31.8	108.5	122.5	222.4	248.0	31.8	81.4	151.9	166.6	39.5	156.6	1,416.0	35.4	56.6	93.5
	4,641.4	**274.6**	**158.6**	**541.5**	**611.1**	**1,110.1**	**1,237.7**	**158.6**	**406.1**	**758.1**	**831.6**	**197.3**	**781.3**	**7,066.6**	**176.7**	**282.7**	**466.4**
Watershed Subtotals	**13,358.8**	**790.4**	**456.4**	**1,558.5**	**1,758.9**	**3,195.0**	**3,562.3**	**456.4**	**1,168.9**	**2,181.9**	**2,393.4**	**567.7**	**2,248.7**	**20,338.7**	**508.5**	**813.5**	**1,342.4**

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Table 4.19

Synopsis of Local Precipitation with Respect to the Conceptual Site Model Area (13,359 Acres)

Measurement Period		**1971-2000**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**1999-2006 Average**
Precipitation *(inches per year)*		37.36	16.99	32.51	40.17	51.87	20.47	50.93	20.47	18.27	31.46
Model Area Unit	**Acreage**	**Volume of Recharge *(Acre-feet)***									
CSSA	4,004	12,466	5,669	10,848	13,403	17,307	6,864	16,994	6,830	6,096	10,501
HCSM Area											
Salado Creek	6,964	21,680	9,859	18,866	23,311	30,101	11,937	29,555	11,879	10,602	18,264
Leon Creek	1,754	5,460	2,483	4,751	5,870	7,580	3,006	7,443	2,991	2,670	4,599
Cibolo Creek	4,641	14,450	6,572	12,574	15,537	20,063	7,956	19,699	7,918	7,067	12,173
CSM Area Total	13,359	41,590	18,914	36,191	44,718	57,743	22,899	56,697	22,788	20,339	35,036

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4.6.2 Recharge

The primary sources of recharge to the Trinity aquifer in the Hill Country area are from rainfall on the outcrop, seepage losses through headwater creeks, and perhaps lakes during high stage levels. The outcrops in the model area, including the Upper and Lower members of the Glen Rose Limestone, receive all of the direct recharge. The BS and CC Limestone, as well as the Lower Trinity aquifer sediments are recharged by vertical leakage from overlying strata.

Several investigators have estimated recharge rates for the Trinity aquifer (Table 4.20). Most of them used stream base flow to estimate recharge. From a study of base flow gains in the Guadalupe River between the Comfort and Spring Branch gauging stations during a 20-year period between 1940 and 1960, Ashworth (1983) estimated a mean annual effective recharge rate of 4 percent of mean annual rainfall for the Hill Country. Kuniansky (1989) estimated base flow for 11 drainage basins in the Hill Country area for a 28-month period between December 1974 and March 1977 and estimated an annual recharge rate of about 11 percent of mean annual rainfall. However, Kuniansky and Holligan (1994) reduced this recharge rate to seven percent of mean annual rainfall to calibrate a groundwater model that included the Trinity aquifer.

Bluntzer (1992) calculated long-term mean annual base flow from the Pedernales, Blanco, Guadalupe, Medina, and Sabinal Rivers and Cibolo and Seco Creeks to be 369,100 acre-ft/yr, which is equivalent to a recharge rate of 6.7 percent of mean annual precipitation (using a long-term mean annual precipitation of 30 in/yr. However, Bluntzer (1992) suggests that a recharge rate of 5 percent is more appropriate to account for human impacts on base flow such as nearby groundwater pumpage, stream-flow diversions, municipal and irrigation return flows, and retention structures. Bluntzer (1992) also noted that base flow was highly variable over time.

Table 4.20 Estimates of Recharge Rates expressed as Percent of Rainfall in the Trinity aquifer in the Hill Country area

(after TWDB, 2000)

Source	Year	Value
Ashworth	1983	4%
Kuniansky	1989	11%
Kuniansky and Holligan	1994	7%
Bluntzer (calculated)	1992	6.7%
Bluntzer (estimated)	1992	5%
TWDB (estimated)	2000	6.6%
TWDB (numerical model calibration)	2000	4%
Camp Stanley Vicinity (TWDB model)	2000	2.5%

The TWDB analysis suggests that differences in recharge rates reflect biases in the record of analysis due to variation of precipitation. The higher recharge rate estimated by Kuniansky (1989) is likely due to the higher than normal precipitation between December 1974 and March 1977, her record of analysis. Ashworth's (1983) recharge rate is probably biased toward a lower value because his record of analysis includes the 1950's drought. To account for differences between the recharge rates, the TWDB developed a technique to estimate base flow for the drainage basin defined by the Guadalupe River gauging stations between Comfort and Spring Branch. The TWDB used the program to estimate base flow from 1940 to 1990 and adjusted parameters to attain the best fit with Ashworth's 4 percent and Kuniansky's 11 percent base flow values for the same stream reach. Using this technique, the TWDB estimated a recharge rate of 6.6 percent of mean annual precipitation. The recharge value ultimately achieved the TWDB calibrated model for the Hill Country area is 4 percent. Using the graphic in Figure 4.30, the TWDB estimated the amount of recharge near CSSA to be about 2.5 percent of the annual precipitation.

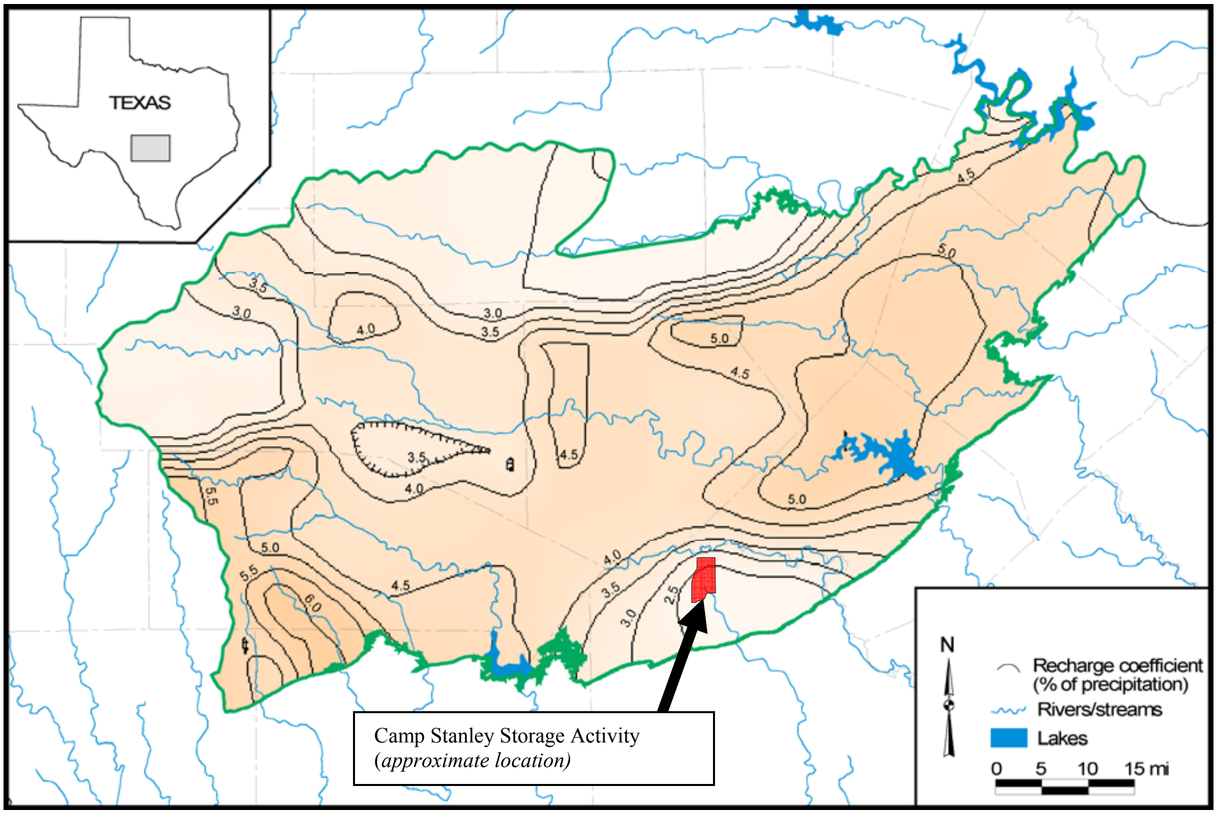
Estimates of recharge volumes to the HCSM are also given in Tables 4.10 to 4.18, presented previously in Section 4.6.1, and summarized in Table 4.21. The recharge estimates presented in this report are based upon the findings published by the TWDB. These values include recharge coefficients corresponding to the 2.5 percent (CSSA area), 4 percent (TWDB model calibration), and 6.6 percent (TWDB calculation). The 30-year period of record (Table 4.10) indicates the mean annual recharge to the aquifer should range between 312 and 823 acre-ft within the CSSA facility boundary. Likewise, the available recharge to the established HCSM boundary would range between 1,040 and 2,750 acre-ft. The 8-year data collected at weather station results in precipitation/recharge estimates that range between 45 and 139 percent of 30-year period of record. As with the precipitation, the 8-year average (1999-2006) is nearly 84 percent of the 30-year average.

4.6.3 Groundwater Discharge

CSSA has kept accurate records for pumping activities since 1980, with exception of 1981. Table 4.22 presents the groundwater discharge records for the facility expressed in acre-ft. The table shows that the highest demand of groundwater withdrawal has historically occurred during the late summer months of July, August, and September. The facilities peak use of groundwater occurred in 1983, and consistently remained above 80 acre-ft per year until 1990. Since then, consumption has been reduced by nearly sixty percent of the 1980's consumption. Over the past 27 years, the CSSA facility has utilized as little as 28.2 acre-ft, and as much as 129.5 acre-ft, with a period-of-record average of 57.0 acre-ft. Current groundwater extraction volume is approximately 40 acre-ft/yr.

The amount of groundwater utilized by neighboring entities within the HCSM area is much more difficult to determine. Several methods were used to evaluate the use of Middle Trinity aquifer by off-post consumers. Within the HCSM model area, it is expected that the largest groundwater users would be the municipalities of Fair Oaks Ranch, Leon Springs Villas, and Hidden Springs Estates, with Fair Oaks Ranch having the highest population density by far. Based upon available data from Fair Oaks, residential use of groundwater was 1,030 and 1,130 acre-ft for the years of 1997 and 1998, respectively. However, this total reflects the entire municipality, much of which does not intersect with the HCSM boundary. Approximately 70 percent of the residential wells (25 of 36) are located within the HCSM boundary, which may equate to as much as 790 acre-ft/yr. In 1999, the average Fair Oaks household connection used

Figure 4.30 Recharge Coefficients (Percent of Rainfall that Recharges the Aquifer) for the Trinity aquifer in the Hill Country Area



(modified after TWDB Report 353, September 2000)

Table 4.21

Estimates of Groundwater Recharge with Respect to the Conceptual Site Model Area (13,359 Acres)

Measurement Period			**1971-2000**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**1999-2006 Average**
Precipitation *(inches per year)*			37.36	16.99	32.51	40.17	51.87	20.47	50.93	20.47	18.27	31.46
% of 30-year Record (1971-2000)				45.5%	87.0%	107.5%	138.8%	54.8%	136.3%	54.8%	48.9%	84.2%
Model Area Unit	**Acreage**	**Recharge Coefficient (%)**	**Volume of Recharge *(Acre-feet)***									
CSSA	4,004	2.5	312	142	271	335	433	172	425	171	152	263
		4.0	499	227	434	536	692	275	680	273	244	420
		6.6	823	374	716	885	1,142	453	1,122	451	402	693
HCSM Area												
Salado Creek	6,964	2.5	542	246	472	583	753	298	739	297	265	457
		4.0	867	394	755	932	1,204	477	1,182	475	424	731
		6.6	1,431	651	1,245	1,539	1,987	788	1,951	784	700	1,205
Leon Creek	1,754	2.5	136	62	119	147	189	75	186	75	67	115
		4.0	218	99	190	235	303	120	298	120	107	184
		6.6	360	164	314	387	500	198	491	197	176	304
Cibolo Creek	4,641	2.5	361	164	314	388	502	199	492	198	177	304
		4.0	578	263	503	621	803	318	788	317	283	487
		6.6	954	434	830	1,025	1,324	525	1,300	523	466	803
HCSM Area Total	13,359	2.5	1,040	473	905	1,118	1,444	572	1,417	570	508	876
		4.0	1,664	757	1,448	1,789	2,310	916	2,268	912	814	1,401
		6.6	2,745	1,248	2,389	2,951	3,811	1,511	3,742	1,504	1,342	2,312

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Table 4.22
Annual Groundwater Discharge from CSSA Wells
1980-2007

Month	***Groundwater Usage per Year (Acre-feet)***																											***Monthly Statistics***			
	1980	**1982**	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**Totals**	**Minimum**	**Maximum**	**Average**
January	5.6	6.2	6.8	7.5	4.0	5.7	5.7	9.5	10.3	3.4	2.9	9.8	5.6	4.6	3.2	2.7	3.1	3.6	3.4	2.9	2.4	3.1	3.5	5.0	2.9	3.2	2.8	129.5	2.4	10.3	4.8
February	5.4	4.7	5.6	8.0	3.9	5.6	5.2	7.1	10.1	2.7	2.6	2.9	3.6	2.2	2.8	2.5	2.1	1.3	1.9	1.7	1.5	2.0	4.1	8.1	1.4	2.3	3.4	104.8	1.3	10.1	3.9
March	5.3	4.4	6.1	9.0	5.2	6.2	5.9	8.6	11.6	3.5	3.1	2.8	2.5	5.1	4.5	2.8	1.9	1.8	2.7	2.1	1.8	4.2	4.1	10.8	2.2	3.4	3.0	124.5	1.8	11.6	4.6
April	4.6	5.0	10.8	8.7	5.4	7.4	7.8	9.6	10.5	3.4	3.9	2.9	2.6	2.7	2.4	3.4	1.7	1.7	2.7	2.2	2.1	2.5	4.4	2.0	3.3	3.1	3.1	119.9	1.7	10.8	4.4
May	5.4	5.6	7.9	10.3	5.6	8.7	10.3	8.6	8.3	3.4	3.3	2.5	4.4	1.9	4.2	3.0	1.2	3.6	4.0	2.1	2.2	4.6	4.0	2.3	2.9	4.0	2.8	127.2	1.2	10.3	4.7
June	5.5	6.6	18.7	8.3	5.1	6.5	7.8	7.5	6.1	5.9	3.9	4.0	5.3	3.4	3.5	2.9	2.8	3.8	2.6	1.7	3.7	3.0	3.2	3.3	3.2	2.1	2.7	132.9	1.7	18.7	4.9
July	7.5	9.6	17.6	10.5	6.0	7.0	9.1	8.0	5.2	5.4	3.8	4.0	7.5	5.2	2.6	2.7	2.2	5.0	2.0	2.6	3.8	2.9	5.3	3.9	3.8	2.3	4.9	150.3	2.0	17.6	5.6
August	5.8	7.4	14.8	8.8	9.2	9.6	14.4	9.9	5.3	3.8	4.9	4.5	9.1	4.2	7.9	4.3	2.7	3.3	3.2	4.4	4.5	2.7	5.3	7.6	3.8	2.5	4.2	168.0	2.5	14.8	6.2
September	4.8	7.6	11.9	10.8	7.8	6.7	10.5	8.6	5.9	4.7	4.8	4.3	8.4	3.5	3.4	2.9	2.8	2.4	3.6	2.3	3.9	2.5	3.6	2.2	3.3	1.9	2.5	137.7	1.9	11.9	5.1
October	4.6	6.1	10.6	7.3	5.0	5.3	9.6	9.1	4.7	4.1	3.7	6.1	5.1	3.7	3.1	2.9	2.7	4.1	2.7	1.7	3.0	2.0	4.7	2.2	2.4	2.1	3.7	122.0	1.7	10.6	4.5
November	0.4	7.0	11.6	5.6	5.0	5.8	9.1	8.6	3.6	3.5	2.8	4.3	3.9	3.0	2.3	3.0	3.2	1.9	2.4	1.6	2.3	2.8	3.3	1.6	2.9	2.6	4.3	108.2	0.4	11.6	4.0
December	5.4	7.9	7.2	3.7	4.7	5.1	6.7	9.5	6.3	3.3	5.0	4.2	1.8	2.2	3.7	5.0	3.3	1.8	3.7	2.9	1.5	2.5	4.2	2.6	3.6	3.1	3.1	114.2	1.5	9.5	4.2
Annual Totals (acre-feet)	60.3	78.0	129.5	98.4	66.8	79.6	102.0	104.6	87.9	47.0	44.7	52.1	59.9	41.7	43.5	38.3	29.6	34.5	34.8	28.2	32.8	34.9	49.7	51.5	35.6	32.6	40.6	**1,539.2**	Acre-feet Total Pumpage		
	Summary Statistics by Year (Acre-feet)																														
Minimum	0.4	4.4	5.6	3.7	3.9	5.1	5.2	7.1	3.6	2.7	2.6	2.5	1.8	1.9	2.3	2.5	1.2	1.3	1.9	1.6	1.5	2.0	3.2	1.6	1.4	1.9	2.5	**28.2**	Yearly Minimum		
Maximum	7.5	9.6	18.7	10.8	9.2	9.6	14.4	9.9	11.6	5.9	5.0	9.8	9.1	5.2	7.9	5.0	3.3	5.0	4.0	4.4	4.5	4.6	5.3	10.8	3.8	4.0	4.9	**129.5**	Yearly Maximum		
Average	5.0	6.5	10.8	8.2	5.6	6.6	8.5	8.7	7.3	3.9	3.7	4.3	5.0	3.5	3.6	3.2	2.5	2.9	2.9	2.3	2.7	2.9	4.1	4.3	3.0	2.7	3.4	**57.0**	Yearly Average		

approximately 700 gallons per day. This figure includes any municipal uses such as irrigation of common areas and golf courses. Significantly less data are available regarding water use for other municipalities within the HCSM.

As an alternative method, groundwater use was evaluated by population of residents within the HCSM data. According to the year 2000 Census data, approximately 3,900 persons maintain residence within the HCSM area. Of this population, 2,630 persons live within the Fair Oaks municipality. The SAWS calculates the per capita water consumption as approximately 150 gallons per day per person. This consumption equals about 650 acre-ft/yr from within the model area, with 440 acre-ft being used within the Fair Oaks intersection with the HCSM boundary. It is likely that this estimate is biased low considering the previous method of estimation for Fair Oaks may utilize over 750 acre-ft/yr within the model area. The combined average groundwater consumption between CSSA and residential use has been estimated in this report as 713 acre-ft/yr.

Since 2003, significant development and infrastructure changes have occurred in the HCSM area. To keep pace with continued development and demand, Fair Oaks Ranch now supplements their groundwater production system with treated water purchased from the Gaudalupe-Blanco River Authority (GBRA) that originates from Canyon Lake. For the purposes of this report, it is assumed that the wells are still operating at the 1997-1998 capacity used to estimate total aquifer withdrawal.

At the same time, a large subdivision is being developed between CSSA and Fair Oaks Ranch, in the western portion of the model area. However, the municipal water supply for this development is being provided by SAWS from an external water source, and not the Middle Trinity aquifer in the HCSM area. Within the same timeframe, SAWS also purchased the Leon Springs Villa water supply municipality to the south of CSSA. SAWS now supplies an external water source to Leon Springs Villa, and has abandoned the existing Middle Trinity aquifer supply wells and disinfection systems previously utilized.

In addition, several new single-home properties have been constructed along Ralph Fair Road that produce Middle Trinity aquifer groundwater from private supply wells. In turn, several former private supply wells have been abandoned to make room for the new development. While the HCSM area has seen significant growth over the past 5 years, the advent of external public water supplies (SAWS and GBRA) has minimized the further exploitation of the local aquifer system.

Within the CSSA or the HCSM area, groundwater is not known to discharge to the land surface in the form of springs. Seeps along outcrops and bedding planes are observed to occur after periods of precipitation, but these features are short-lived, and are consumed within the hydrologic budget by either evapotranspiration or recharge back to the aquifer. To account for the possibility of periodic spring discharge in unidentified locations, it has been assumed that 1 acre-foot per year is lost to spring discharge within CSSA, and 3 acre-ft/yr is discharged within the model area. The underlying assumption that has been made is that springflow accounts for less than 1 percent of groundwater water discharge since it is not widely observed within the model area.

4.6.4 Surface Water/Streams

Stormwater runoff results in the formation of surface impoundments or streams. Within the hydrologic cycle, surface water can lose volume by evaporation, and/or recharge to underlying aquifers, or it can gain volume by groundwater base flow. Within the Texas Hill Country, the long-term contribution of groundwater base flow results in perennial streams and rivers within the region. Based on the work of others, the TWDB has estimated that the annual base flow contribution to Salado Creek within their model area was 1.93 inches per year (in terms of annual rainfall). While Salado Creek is certainly a viable gaining stream south of CSSA, the same is not true at the post. CSSA and the HCSM area are located near the top of the Salado Creek watershed, and at this location it is an intermittent stream, which likely recharges the LGR directly. During normal runoff events, "disappearing streams" have been observed, indicating that surface water recharges the aquifer. On rare occasions during extreme flooding events, these features, known as estavelles, have also been observed to discharge groundwater to the stream when the water table is extremely high. However, for the most part drainage features in and around the HCSM area are losing streams that serve to convey surface water away from the facility, and contribute recharge to the underlying aquifer.

Surface water impoundments within the HCSM area are limited to sparse stock tanks that rarely exceed several acres in size. These features are not considered significant within the local hydrologic budget, and therefore are not further addressed.

4.6.5 Intra-Aquifer Interaction

Under the current studies performed at CSSA, there has been little revealed that quantifies the flow of groundwater between the formational units. Fortunately, modeling work performed by the TWDB has resulted in some estimations, which describe the movement between aquifers. According the TWDB, about 37 percent of the water that recharges and flows into the Upper Trinity aquifer moves from the Upper Trinity aquifer into the Middle Trinity aquifer. This number is significant because according to their model, more water moves into the Middle Trinity aquifer through cross-formational flow than through direct infiltration on the outcrop.

The TWDB model shows that about 64,000 acre-ft/yr moves from the Upper and Middle Trinity aquifer in the direction of the Edwards BFZ Aquifer. Some of the water that moves in this direction flows directly from the Trinity aquifer into the Edwards BFZ Aquifer and some continues to flow in the Trinity aquifer, but down dip beneath the Edwards aquifer. The flow is estimated at 660 acre-ft/yr per linear mile for the boundary within Comal and Bexar Counties. If this is the case, one can assume, by the law of conservation, that groundwater leaves CSSA towards the SE or south-SW at a rate of 660 acre-ft/year per mile because of its proximity to the Edwards BFZ recharge zone. The down gradient southern perimeter of CSSA is about 2.25 miles, therefore the estimated groundwater exiting the facility is 1,500 acre-ft/year.

4.6.6 Evapotranspiration

Evapotranspiration is the water lost to the atmosphere by two processes: evaporation and transpiration. Evaporation is the loss from open bodies of water, such as lakes and reservoirs, wetlands, bare soil, and snow cover; while transpiration is the loss from living-plant surfaces. Apart from precipitation, it is the most significant component of the hydrologic budget. In the United States, evapotranspiration averages about 67 percent of the average annual precipitation and ranges from 40 percent of the precipitation in the NW and NE to about 100 percent of the precipitation in the SW (Hanson, 1991).

Evapotranspiration varies regionally and seasonally; during a drought it varies according to weather and wind conditions. Several factors other than the physical characteristics of the water, soil, and plant surface also affect the evapotranspiration process. The more important factors include net solar radiation, surface area of open bodies of water, wind speed, density and type of vegetative cover, availability of soil moisture, root depth, reflective land-surface characteristics, and season of year (Hanson, 1991).

Assuming that moisture is available, evapotranspiration is dependent primarily on the solar energy available to vaporize the water. Because of the importance of solar energy, evapotranspiration also varies with latitude, season of year, time of day, and cloud cover. Another important climatic factor that contributes to evapotranspiration is wind speed. Winds affect evapotranspiration by bringing heat energy into an area and removing the vaporized moisture. A 5-mile-per-hour wind will increase still-air evapotranspiration by 20 percent; a 15-mile-per-hour wind will increase still-air evapotranspiration by 50 percent (Hanson, 1991).

The seasonal trend of evapotranspiration within a given climatic region follows the seasonal trend of solar radiation and air temperature. Minimum evapotranspiration rates generally occur during the coldest months of the year; maximum rates, which generally coincide with the summer season, when water may be in short supply, also depend on the availability of soil moisture and plant maturity (Hanson, 1991).

Changes in evapotranspiration during a drought depend largely on the availability of moisture at the onset of a drought and the severity and duration of a drought. Evaporation from open bodies of water during a drought increases, but transpiration by plants, particularly shallow-rooted plants, generally decreases. During a drought, transpiration by plants may decrease, as plants attempt to conserve water. The magnitude of the decrease in transpiration depends on the plants' root and leaf characteristics (Hanson, 1991).

For this HCSM, the United States average of 67 percent loss by evapotranspiration is used as a calculation in the hydrologic budget.

4.6.7 Water Balance

To help assist in the determination of the fate of groundwater beneath CSSA and the HCSM model area, an attempt to balance the total inflow and outflow of the watershed(s) was undertaken. The general premise of a balanced hydrologic budget is that outflow from a watershed equals the volume of the inflow. In its purest form, precipitation (P) inflow is equal to the sum of the outflow parameters Q_s (surface component runoff), Q_d (groundwater component of runoff), R (recharge), D (discharge), ET (evapotranspiration), and ΔS_g (change in aquifer storage).

$$P = Q_s + Q_d + R + D + E + \Delta S_g$$

To solve this equation, terms that are not applicable, such as Q_d since there are no perennial gaining streams, are eliminated. Based on the 1971 to 2000 period-of-record climatic data, the precipitation normal is 37.36 inches per year. Based upon the TWDB and others, it can be assumed that groundwater recharge is approximately 4 percent of the total annual rainfall, which would be 1.49 inches per year for the 30 year record. A significant factor when considering the water balance is the amount of water that is lost to the atmosphere as vapor resulting from evaporation of surface water, surface soils, and transpiration by plants. The USGS estimates in Texas that between 15 and 25 inches of the annual rainfall is lost to evapotranspiration processes. For the 30-year record, that equates to a maximum loss of as much as 67 percent of the annual rainfall, and may exceed the annual rainfall during periods of drought, removing water from storage. By measuring or estimating in these terms, the amount of surface runoff can be empirically-derived. When inflow is less than outflow, groundwater mining (or dewatering) occurs as reflected in the change of storage. Dewatering of the Trinity aquifer is of concern to the TWDB and regional planners, as water level drawdown is a certainty in the near future due to projected population increases and climatic drought cycles.

Table 4.23, Table 4.24, and Figure 4.31 show the resulting water balance calculations for CSSA and the HCSM area based on the estimates and criteria given previously. The calculations are based on the environmental data from the long-term 30-year record as the regional normal. Likewise, the extreme conditions as measured by the CS-16 weather station are also evaluated to determine a range of values. The top of Table 4.23 shows that over a 30 year average (37.36 inches), approximately 12,466 acre-ft of precipitation fell within the 4,004-acre boundary of the facility. Given the volume of precipitation, the hydrologic budget is balanced by assuming that 4 percent of the annual precipitation recharges the aquifer (499 acre-ft), and 67 percent is lost to evapotranspiration (8,352 acre-ft) on an annual basis. Therefore, the remaining 29 percent of annual precipitation occurs in the form of surface runoff within the watershed. The same water balance ratios have been assumed for more extreme years of drought and above-average precipitation. During 1999, the precipitation amount was approximately 45 percent of the 30-year normal, while the 2002 amount was 39 percent greater than normal. The same assumptions have been made for the entire HCSM area on Table 4.20, in which CSSA occupies nearly 30 percent of the watershed.

The values of recharge to the aquifer are of particular interest because how they are implicitly related to groundwater discharge. An underlying principle of the hydrologic system is that water entering the aquifer is eventually discharged from the aquifer either by pumping, springs, surface water base flow, or interaction with other aquifers. When averaged over many years of record, the amount of discharge will equal the amount of recharge, discounting the temporal effects of storage. Based upon these assumptions, the fate of recharge has been estimated for the range of climatic conditions given in Tables 4.23 and 4.24, and diagrammed in Figure 4.31.

Table 4.23 and Figure 4.31 show that under normal climatic conditions assuming the 27-year average of pumping at CSSA (57 acre-ft), only 11.4 percent of the recharge (499 acre-ft) that falls within the CSSA boundary is consumed by the facility. A small fraction (0.2 percent) of recharge is assumed to be lost by temporal springs or seeps. The remaining 88.4 percent either remains in storage or outflows to the south-SE towards the Edwards BFZ aquifer. Likewise, during a 17-inch annual precipitation record, CSSA can be expected to utilize 25.1 percent of its recharge, or 8.2 percent of its recharge during an above-average year (2002). These values are significant because they indicate that CSSA uses much less groundwater than is estimated to recharge within the 4,000-acre facility.

Table 4.23
Water Balance for CSSA
Using Precipitation Minimum, Maximum, and Normals

1971-2000 Precipitation Normals		CSSA			
	Acreage	4004	*(Inches)*	*(Acre-feet)*	*%*
	Inflow	**Precipitation**			
		-1971-2000 Normal (Boerne, TX)	**37.36**	**12,465.79**	
	Outflow	**67% Evapotranspiration (ET)**	**25.03**	*8,352.08*	**67.0%**
		Runoff (ET-R)	**10.83**	*3,615.08*	**29.0%**
		4% Recharge (R)	**1.49**	*498.63*	**4.0%**
			37.36	**12,465.79**	***100.0%***
	Groundwater Discharge *(with respect to Recharge)*	**Discharge**	**1.49**	**498.63**	
		-CSSA Wells (27 year average)	0.17	*57.01*	*11.4%*
		-Springs/Seeps (Estimated)	0.003	*1.00*	*0.2%*
		-Aquifer Storage/Outflow	1.32	440.62	*88.4%*

Below-Average Precipitation		CSSA			
	Acreage	4004	*(Inches)*	*(Acre-feet)*	*%*
	Inflow	**Precipitation**			
		-1999 (CS-16 Weather Station)	**16.99**	**5,669.00**	
	Outflow	**67% Evapotranspiration (ET)**	**11.38**	*3,798.23*	**67.0%**
		Runoff (ET-R)	**4.93**	*1,644.01*	**29.0%**
		4% Recharge (R)	**0.68**	*226.76*	**4.0%**
			16.99	**5,669.00**	***100.0%***
	Groundwater Discharge *(with respect to Recharge)*	**Discharge**	**0.68**	**226.76**	
		-CSSA Wells (27 year average)	0.17	*57.01*	*25.1%*
		-Springs/Seeps (Estimated)	0.001	*0.45*	*0.2%*
		-Aquifer Storage/Outflow	0.51	169.30	*74.7%*

Above-Average Precipitation		CSSA			
	Acreage	4004	*(Inches)*	*(Acre-feet)*	*%*
	Inflow	**Precipitation**			
		-2002 (CS-16 Weather Station)	**51.87**	**17,307.29**	
	Outflow	**67% Evapotranspiration (ET)**	**34.75**	*11,595.88*	**67.0%**
		Runoff (ET-R)	**15.04**	*5,019.11*	**29.0%**
		4% Recharge (R)	**2.07**	*692.29*	**4.0%**
			51.87	**17,307.29**	***100.0%***
	Groundwater Discharge *(with respect to Recharge)*	**Discharge**	**2.07**	**692.29**	
		-CSSA Wells (27 year average)	0.17	*57.01*	*8.2%*
		-Springs/Seeps (Estimated)	0.004	*1.39*	*0.2%*
		-Aquifer Storage/Outflow	1.90	633.90	*91.6%*

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Table 4.24
Water Balance for Conceptual Site Model Area
Using Precipitation Minimum, Maximum, and Normals

		Conceptual Site Model Area			
	Acreage	13358.8	*(Inches)*	*(Acre-feet)*	%
1971-2000 Precipitation Normals	**Inflow**	**Precipitation**			
		-1971-2000 Normal (Boerne, TX)	**37.36**	**41,590.27**	
	Outflow	**67% Evapotranspiration (ET)**	**25.03**	*27,865.48*	**67.0%**
		Runoff (ET-R)	**10.83**	*12,061.18*	**29.0%**
		4% Recharge (R)	**1.49**	*1,663.61*	**4.0%**
			37.36	**41,590.27**	***100.0%***
	Groundwater Discharge *(with respect to Recharge)*	**Discharge**	**1.49**	**1,663.61**	
		-Groundwater Withdrawal	0.64	*713*	*42.9%*
		-Springs/Seeps (Estimated)	0.003	*3.0*	*0.2%*
		-Aquifer Storage/Outflow	0.85	947	*57.0%*

		Conceptual Site Model Area			
	Acreage	13358.8	*(Inches)*	*(Acre-feet)*	%
Below-Average Precipitation	**Inflow**	**Precipitation**			
		-1999 (CS-16 Weather Station)	**16.99**	**18,913.77**	
	Outflow	**67% Evapotranspiration (ET)**	**11.38**	*12,672.23*	**67.0%**
		Runoff (ET-R)	**4.93**	*5,484.99*	**29.0%**
		4% Recharge (R)	**0.68**	*756.55*	**4.0%**
			16.99	**18,913.77**	***100.0%***
	Groundwater Discharge *(with respect to Recharge)*	**Discharge**	**0.68**	**756.55**	
		-Groundwater Withdrawal	0.64	*713*	*94.3%*
		-Springs/Seeps (Estimated)	0.001	*1.36*	*0.2%*
		-Aquifer Storage/Outflow	0.04	42.04	*5.6%*

		Conceptual Site Model Area			
	Acreage	13358.8	*(Inches)*	*(Acre-feet)*	%
Above-Average Precipitation	**Inflow**	**Precipitation**			
		-2002 (CS-16 Weather Station)	**51.87**	**57,743.23**	
	Outflow	**67% Evapotranspiration (ET)**	**34.75**	*38,687.97*	**67.0%**
		Runoff (ET-R)	**15.04**	*16,745.54*	**29.0%**
		4% Recharge (R)	**2.07**	*2,309.73*	**4.0%**
			51.87	**57,743.23**	***100.0%***
	Groundwater Discharge *(with respect to Recharge)*	**Discharge**	**2.07**	**2,309.73**	
		-Groundwater Withdrawal	0.64	*713*	*30.9%*
		-Springs/Seeps (Estimated)	0.004	*4.2*	*0.2%*
		-Aquifer Storage/Outflow	1.43	1,592	*68.9%*

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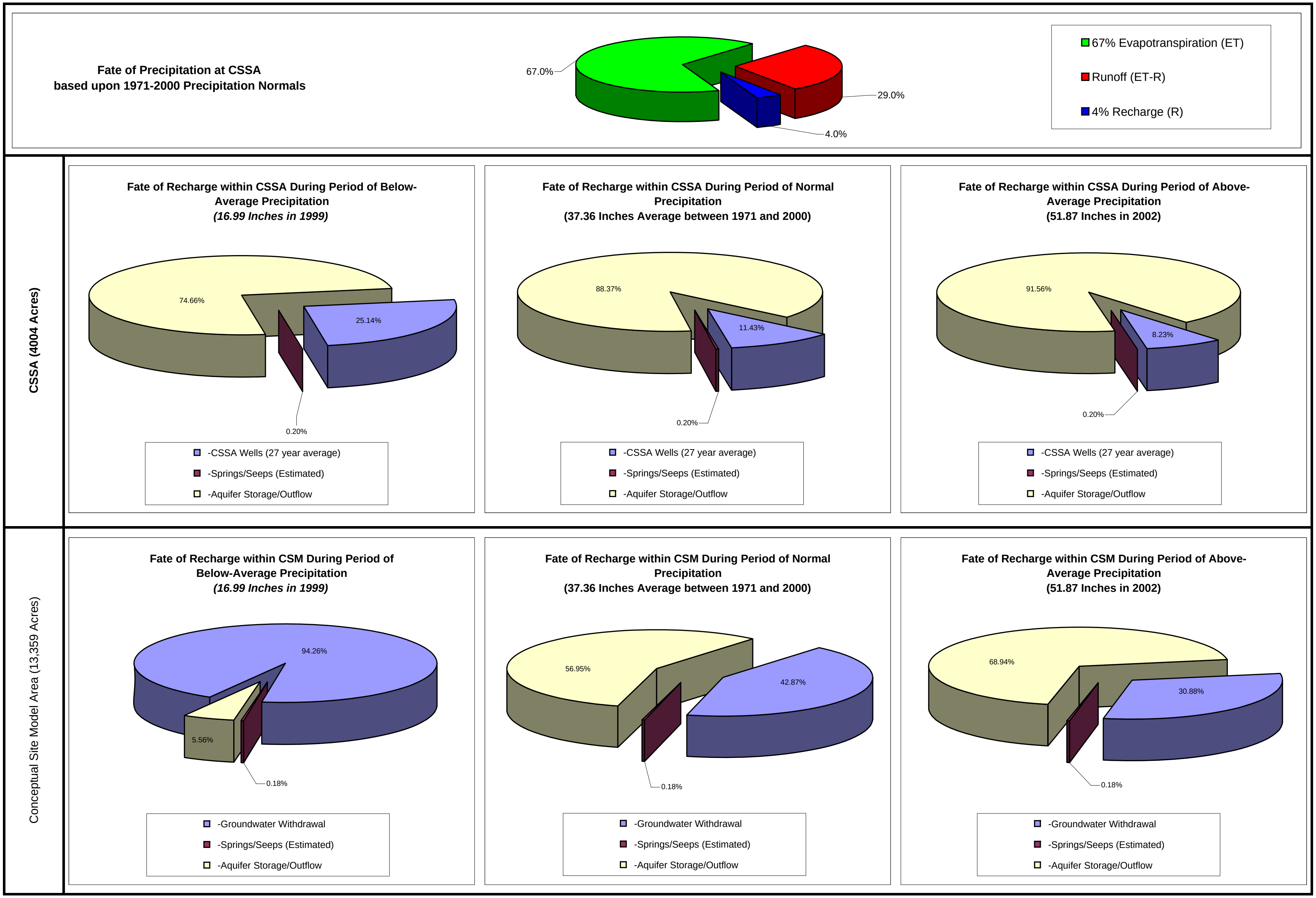
Figure 4.31
Fate of Recharge within the Aquifer for CSSA and Conceptual Site Model Area



Fate of Precipitation at CSSA based upon 1971-2000 Precipitation Normals

Fate of Recharge within CSSA During Period of Below-Average Precipitation *(16.99 Inches in 1999)*

Fate of Recharge within CSSA During Period of Normal Precipitation (37.36 Inches Average between 1971 and 2000)

Fate of Recharge within CSSA During Period of Above-Average Precipitation (51.87 Inches in 2002)

Fate of Recharge within CSM During Period of Below-Average Precipitation *(16.99 Inches in 1999)*

Fate of Recharge within CSM During Period of Normal Precipitation (37.36 Inches Average between 1971 and 2000)

Fate of Recharge within CSM During Period of Above-Average Precipitation (51.87 Inches in 2002)

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The more regional scale represented by the HCSM area (Table 4.24) indicates that over 43 percent (35 percent residential and 8 percent CSSA) of the available recharge is discharged through wells by groundwater consumers during normal annual rainfall. Less than 1 percent is assumed to discharge via springs or seeps, and the remaining 56 percent goes to aquifer storage and outflow. During an increased year of precipitation (2002), it is estimated that a little over 30 percent of available groundwater is utilized by area consumers, with the rest contributing to increasing the aquifer storage or outflow. However, during a year of reduced precipitation such as 1999, Table 4.24 and Figure 4.31 show that nearly 95 percent of aquifer recharge can be consumed by area groundwater users.

General observations of water levels at CSSA during droughts show that these estimates are biased low since it is apparent that significant losses to aquifer storage can occur during periods of 20 inches of rain or less. The estimates are most sensitive to the percent of precipitation that contributes to recharge and total groundwater withdrawal. By decreasing these factors by as little a 0.5 percent, the calculations will indicate the loss of aquifer storage. The commercial use of groundwater within the HCSM area is also unquantified, and therefore was not used in this analysis.

SECTION 5
CONTAMINANT DISTRIBUTION AND OCCURRENCE

5.1 CONTAMINANTS OF CONCERN

The COC at CSSA are based on historically detected analytes (since the inception of the groundwater monitoring program in 1991) and process knowledge. Analytes detected above regulatory standards in soil and groundwater at CSSA is limited to a short list of chlorinated VOCs and metals. Appendix B includes a table of historical detections of contaminants in groundwater for both VOCs and metals. Of the analytes detected at CSSA, only a handful of organic and inorganic compounds exceed the appropriate Action Level (AL) or MCL as given in Table 5.1.

Table 5.1 Contaminant Detections in Groundwater Above MCLs, 1992-2007

VOCs	**Metals**
PCE	**Cadmium**
TCE	**Chromium**
***cis*-1,2-DCE**	**Copper**
***trans*-1,2-DCE**	**Lead**
	Mercury

The VOCs are components of solvents that were commonly used to clean grease and dirt from metal surfaces. At CSSA, solvents were used to degrease ordnance materiel. In 1995, CSSA discontinued the use of VOC solvents and replaced them with citrus-based cleaners. Until the late 1970s, there were no formal environmental regulations regarding the use or disposal of spent solvent. CSSA, like most other industrial facilities at the time, had no formal solvent disposal procedures. Based on investigations that have been completed-to-date, spent solvents may have been disposed of in SWMUs B-3 and O-1. SWMU B-3 was an on-site landfill where solvents were placed; it was closed in 1992. SWMU O-1 was a vinyl-lined oxidation pond that was used between 1975 and 1985 for the evaporation of spent liquids from ordnance maintenance activities. Another potential VOC source area has been identified near the SW corner of the facility. This area, designated AOC-65, is located at the Building 90 area, which is where solvents were used.

Volatile organic groundwater contamination at CSSA is caused by a group of chemical compounds commonly referred to as halogenated (chlorinated) solvents. PCE, TCE, and *cis*-1,2-DCE are the three most common VOCs found in the CSSA groundwater contamination plumes. Also, vinyl chloride (VC) is an important degradation product of halogenated compounds because of its inherent toxicity, with an EPA drinking water MCL of 1 µg/L. Likewise, the EPA drinking water MCLs for PCE and TCE are both 5 µg/L and the MCL for *cis*-1,2-DCE is 70 µg/L. Concentrations below the MCL are considered safe for drinking water. While other VOC constituents have been detected in CSSA groundwater, these three compounds are by far the most pervasive and likely to exceed the MCLs. Other notable compounds detected in CSSA groundwater below the MCLs include bromodichloromethane, bromoform, chloroform, dibromochloromethane, dichlorodifluoromethane, DCE (1,1 and *trans*-1,2 isomers), methylene chloride, naphthalene, and toluene.

At CSSA the inorganic constituents in groundwater normally analyzed for include arsenic, barium, cadmium, chromium, copper, lead, mercury, nickel, and zinc. Although there have been some metals exceedances on-post, they have been sporadic and limited largely to wells located in the interior areas of the post. With the exception of lead, two or less detections of the remaining inorganics listed on Table 5.1 have been reported in on-post wells. The occurrence of chromium, and mercury above the MCLs is a new phenomenon that have been reported in new wells (CS-MW23 and -MW25) that were installed in 2007.

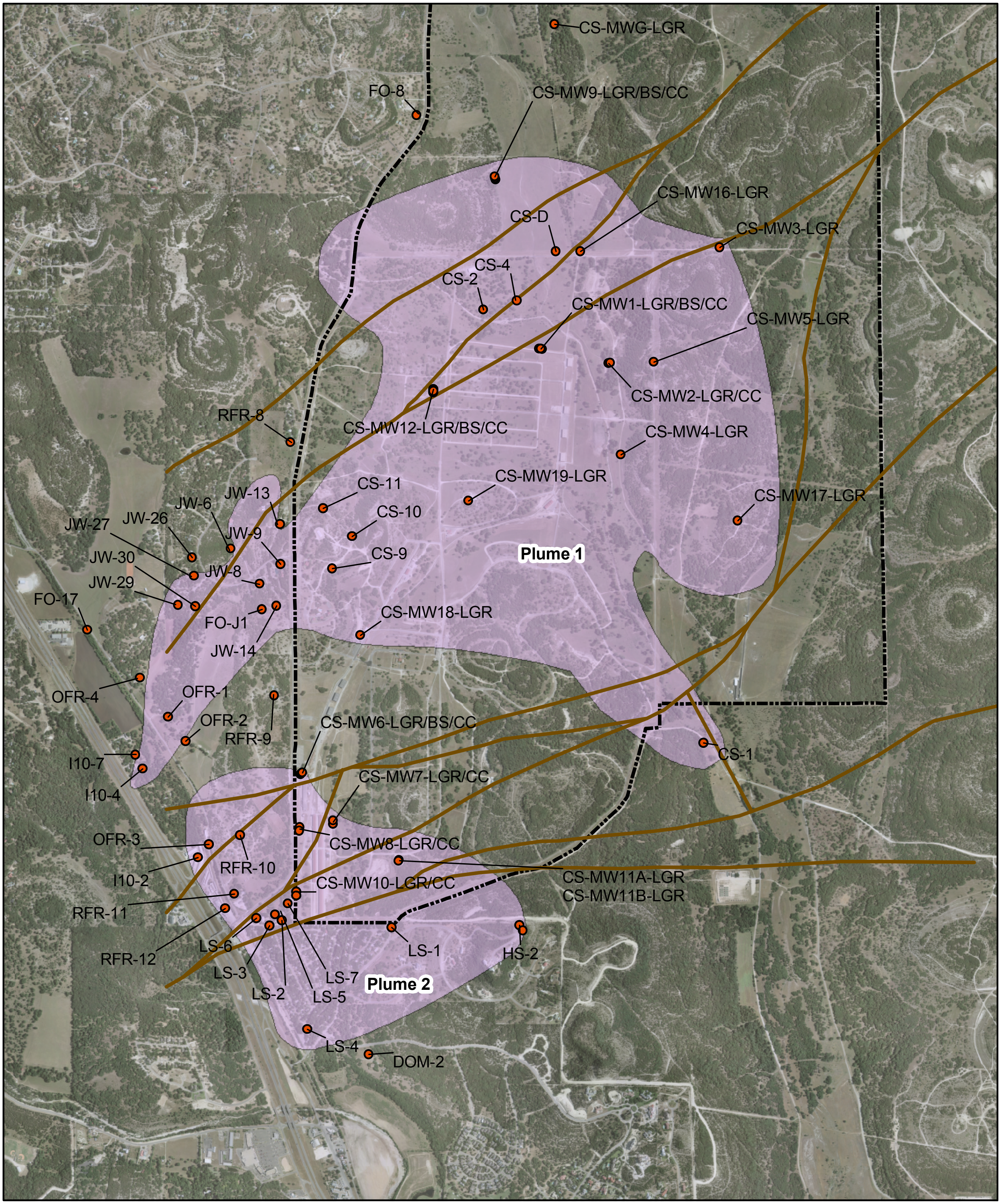
Currently metals are not sampled at off-post locations due to the minimal or lack of on-post metals detections exceeding MCLs. With the exception of one location, historical samples obtained for off-post wells between 1995 and 2001 did not yield any metals concentrations above the MCLs. For the one well that exceeded the lead MCL, the 1996 follow-up sample resulted with no lead detection. Additional data from local water utility purveyors demonstrated that no public water wells exceed the MCLs for metals constituents.

5.2 EXTENT OF VOC CONTAMINATION

The HCSM uses a layered approach to describe the hydrogeologic condition of the aquifer. The following sections describe the type and concentrations of VOC contaminants detected within the model layers. Data points include groundwater samples collected from on-post monitoring wells and supply wells, and selected off-post domestic and public supply wells. Well types used to characterize the groundwater include on-post monitoring wells specifically screened within target intervals of the aquifer, as well as on- and off-post open boreholes completed in various intervals of the Middle Trinity aquifer. The groundwater plumes are characterized by more than 40 on-post wells and 45 off-post well locations.

In this HCSM, the plumes are defined by groundwater sampling results from December 2002 through December 2007 quarterly monitoring events. These events have been selected since they represent the greatest density of sampling locations over the 10 years of periodic monitoring at CSSA. Since the objective of the off-post private and public wells is to provide a sustainable source of potable water, those wells are usually completed throughout the entire thickness of the Middle Trinity aquifer. Typical completions are open borehole, with older wells having as little as 10 feet of surface casing. Newer wells are more likely to have 200 more feet of surface casing. These well completions are designed to maximize quantities of available LGR and CC groundwater, whereas most CSSA wells individually monitor those units.

Figure 5.1 shows the location and maximum extent of the three most prevalent contaminants (PCE, TCE, and *cis*-1,2-DCE) detected between December 2002 and December 2007 within the Middle Trinity aquifer beneath CSSA. The larger, centrally located area of contamination is referred to as Plume 1, while the latter in the SW quadrant is referred to as Plume 2. Plume 1 is a result of activities at SWMUs B-3 and O-1, and is mostly confined to within the limits of the facility. Some contaminant impact measured in off-post wells to the west of CSSA has been attributed to Plume 1. Contamination within Plume 2 is believed to originate from the industrialized portion of the facility at Building 90. Much of this plume appears to have migrated off-post to the west and south of CSSA.



● Water Wells Sampled

Faults

— Faults

▨ Maximum Extent of VOCs

Figure 5.1

Maximum Extent of VOC Detections
within the Middle Trinity Aquifer
December 2002 through December 2007

PARSONS

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Through September 2007, VC has been a CSSA analyte in over 700 on-post samples. During that time, 30 detections (approximately than 3 percent of the sample population) ranging from 0.03 µg/L to 1.3 µg/L have been reported in 11 on-post wells. These wells include CS-D, CS-MW1-LGR, CS-MW1-BS, CS-MW1-CC, CS-MW2-LGR, CS-MW4-LGR, CS-MW9-BS, CS-MW12-BS, CS-MW12-CC, CS-MW16-CC, and CS-MW19-LGR. All of these samples are trace detections ranging between the laboratory MDL and the AFCEE RL (F-flagged data). Only one result originating from CS-MW16-CC has exceeded the AFCEE RL, and was reported at 1.3 µg/L upon its initial sampling in September 2003. Subsequent events have resulted in trace detections of less than 0.6 µg/L. Well CS-MW12-BS has the most detections of VC, with a total of 11 reported trace concentrations between March 2003 and September 2007. The current regulatory MCL is 2 µg/L. As of September 2007, no detections of VC have been reported in off-post wells sampled by CSSA. The presence of VC in groundwater, albeit small, is an indicator that the degradation of larger-chain chlorinated hydrocarbons is occurring.

The inherent difference in well design off-post has made the occurrence of contaminants within each of the model layers difficult to define. While stratification of the contaminants within the geologic layers has been well-demonstrated on-post, it is difficult to be certain in which interval the contamination is occurring in an open borehole well. Extensive groundwater sampling at cluster wells within the Middle Trinity aquifer has generally shown that VOC contamination occurs primarily in the LGR. Limited VOC concentrations have been reported in the BS and CC, but are typically below the CSSA RL.

One exception to this rule has been noted in the vicinity of former water supply well CS-16. This well was completed (open borehole) throughout the entire thickness of the Middle Trinity aquifer. It is believed that this construction style likely resulted in cross-contamination of the CC from the LGR. As a response to the potential for cross contamination, CS-16 has recently been re-completed by plugging of the BS and CC portions of the open borehole completion, leaving 114 feet of LGR open in the well, now redesignated as CS-16-LGR. To assess if cross contamination had occurred, a second well (CS-MW16-CC) was drilled in the vicinity of CS-16-LGR and is completed with 25 feet of screen in the CC. Sampling of CS-MW16-CC has indicated that PCE concentrations in excess of 200 µg/L within the CC at this location, and is evidence for the potential for inter-aquifer cross contamination within open borehole completions located proximal to contaminant source areas.

Based on these observations, this HCSM has assumed that VOC contamination in open borehole completions, both on- and off-post are most representative of contaminant conditions within the LGR portion of the aquifer. While this does not preclude impact to the underlying strata, those affects are currently suspected to be minimal and localized in comparison to the contaminant concentrations in the LGR. Hence, the open borehole completions (both on- and off-post) are only considered in the LGR (Layer 2) portion of the model.

Representations of the PCE, TCE, and cis-1,2-DCE groundwater plumes are presented Appendix C. When reviewing these maps, it is important to note that typically two analytical laboratories are used for the chemical analysis of groundwater for any given sampling event. Normally, one lab provides on-post results, while the latter provides the off-post results. This approach helps minimize the risk associated with laboratory errors affecting the entire population of data points. However, as a result, differing laboratory-dependent MDLs are reported for a particular compound. In the case of PCE for example, the on-post laboratory uses a MDL of 0.05 µg/L, while the off-post lab uses a 0.06 µg/L MDL.

This is an important consideration when attempting to image the size and plume geometry to the lowest of analytical levels. For the purpose of this report, the differences between the on- and off-post MDLs are considered negligible are basically treated equally as non-detections. Thereby the lowest contour level was interpreted to represent the minimum plume area which accounted for any detection above a respective MDL. In some sampling events, wells at the edge of the plume vary from detection to non-detection as a temporal effect. To account for this fringe variability, a well which had a ”F-flagged” detection (concentration reported between the MDL and the RL) in the prior sampling event was considered to be within the margin of the plume. This methodology would help dampen the effect of seemingly expanding and shrinking plume margins based solely upon the reporting of “F-flagged” data.

The remainder of the groundwater plume has been mapped using logarithmic concentration lines to represent the varying ranges of contamination detected in sampled wells. Beginning at 0.1 µg/L, each isoconcentration line increases exponentially by a factor of ten. This method of contouring allows for evenly-spaced isoconcentration lines in those source areas where there are drastic concentration changes in relatively small areas.

In March 2006, CSSA implemented a Long-Term Monitoring Optimization (LTMO) process which reduced the number and frequency the monitoring points that would be sampled during a quarterly event (see Environmental Encyclopedia **Volume 5 – Final Three-Tiered LTMO Evaluation**). Depending on the data quality objectives, a particular sampling interval for a well may be reduced to a semi-annual, annual, biennial sampling schedule, or even excluded from future monitoring. Because of the decreased sampling population since LTMO implementation, representations for 2006 and 2007 plumes are compiled to represent the maximum detection in any given well on a annual basis. Therefore, Figures C-63 through C-68 represent a plume geometry and concentrations that is biased high relative to an normal quarterly event plume representation.

5.2.1 UGR (Layer 1)

Of the UGR intervals, only UGR(D) and UGR(E) have been investigated during RFI and groundwater investigation activities. These are the only intervals of the UGR that have lateral groundwater movement occurring without being cropped out by the intersecting land surface. Vertical movement of groundwater to lower strata also occurs in these intervals where the interval is bisected by faults or fractures. Drilling data suggests that the UGR units UGR(D) and UGR(E) yield very little water, except at times when significant precipitation has occurred. Groundwater occurrence within unit D is probably laterally discontinuous and heavily dependent upon significant recharge and localized bioherms or fracture systems. Numerous RFI borings ranging in depths between 10 and 35 ft bgs has demonstrated that very little to no groundwater is readily available from the immediate near surface. Thus far, no freely yielding groundwater unit has been encountered within the UGR postwide. Past experience has shown that most 30-foot borings will eventually accumulate small quantities of water if allowed to stay open long enough.

Plume 1

With respect to investigational work within Plume 1 that addresses the UGR, the only location where significant data has been collected is in the vicinity of the source area at SWMU B-3. At this location, only a thin layer (less than 20 feet) has not been eroded from the area. Nonetheless, SWMU B-3 has been carved into UGR during past waste management activities. Because SWMU B-3 has been focused upon as a significant contaminant source area, work addressing the UGR has been conducted in this locality.

Original investigations and remedial actions at B-3 included the installation and operation of vapor extraction wells (VEWs) within the landfill trenches. Within the operational history of the vapor extraction system, sporadic groundwater samples collected from the VEWs resulted in *cis*-1,2-DCE being reported in excess of 27,000 µg/L, as well as nearly 3,000 µg/L of PCE. These VEWs were removed from service in 2006 when the excavation and disposal of the source area soils and debris was completed.

As part of future remedial actions, four Westbay multi-port wells (CS-WB-05, -06, -07, and -08) were installed around the perimeter of the SWMU. Three of these wells (WB-06 through WB-08) have discrete interval sampling points constructed within the UGR(D) and UGR(E) portions of the interval. Sampling results from these sampling locations between July 2007 and January 2008 indicate concentrations of *cis*-1,2-DCE (110 µg/L), *trans*-1,2,-DCE (0.47 µg/L), PCE (50 µg/L), and TCE (28 µg/L) are present at the margins of the SWMU. However, like AOC-65, the occurrence of perched groundwater within the UGR is sporadic and fully dependent upon significant precipitation to temporally saturate the interval.

Plume 2

Only a handful of wells near AOC-65 monitor the lower portion of interval UGR(D) and UGR(E). Specific investigations of interval UGR(E) in the vicinity of Plume 2 included the shallow PZs (-2, -4, and -6) at AOC-65 are mostly completed within this depth interval, and groundwater samples from these wells routinely result with solvent contamination that is in excess of the main plume within the LGR. Some Westbay intervals are completed in the UGR(D) and UGR(E) zones but do not typically contain groundwater. At AOC-65 (Plume 2), lesser concentrations of PCE generally ranging between 30 µg/L and 60 µg/L are perched above the LGR. The greatest concentrations of solvents are reported within the near subsurface adjacent to the source area. These include 22,000 µg/L at CS-WB03-UGR-01 and 3,400 µg/L from well AOC65-MW2A that is only 19 ft in depth.

During the July 2002 floods, this zone was saturated to the point where cascading groundwater and venting air could be heard in the open boreholes of AOC65-VEW13, -VEW14, -VMP6, -VMP7, and existing well AOC65–MW2B. Otherwise, this interval is generally low-yielding and is non-responsive except to the heaviest rain events (flood scale). However, groundwater does persist in these wells, in almost a sump-like fashion. Nearly 16 months of monitoring (March 2003 through June 2004) show that water levels are mostly unwavering in this zone. Once the 2002 flooding effect had dissipated, groundwater fluctuations within this zone at AOC-65 typically varied by only several tenths of feet. By way of comparison, the deeper PZs (-1, -3, and -5) screened at the base of LGR(B) fluctuated by more than 50 feet during the same 16-month monitoring period.

Westbay intervals such as CS-WB01-UGR-01 and LGR-01 showed little to no response to recharge and infiltration. Interval CS-WB02-UGR01 is almost always devoid of groundwater except after the heaviest of rains.

Between the September 2003 and September 2004 monitoring periods, the UGR(E) portion of the Westbay monitoring zones remained without groundwater except for on instance in July 2004 at CS-WB02-UGR01. At that time, 3.45 µg/L PCE and 2.12 µg/L TCE were detected in this portion of the stratigraphy. Nearly 9 inches of rain fell at the facility over an 11-day period in November 2004 which was temporarily sufficient to saturate the uppermost UGR-01 intervals in the AOC-65 multi-port wells. Results indicate that a persistent source still exists, and that periodic flushing by intense rainfall can mobilize these perched contaminants that are probably otherwise bound to the matrix during the rest of the year.

5.2.2 LGR (Layer 2)

The LGR portion of the HCSM has the greatest occurrence and concentration of contaminants associated with past disposal activities in the Plume 1 and Plume 2 source areas. PCE, TCE, and *cis*-1,2-DCE have been detected in both on- and off-post monitoring wells throughout the central and southern portions of the model area (Appendix C). Temporal data has been interpreted to show two distinct plumes, one located within the central portion of CSSA (Plume 1) and the other in the SW corner of the model area (Plume 2). In general, the on-post plumes are separated by a set of wells that are consistently at, or below the laboratory MDLs. These wells include from west to east: CS-MW6-LGR, CS-MW18-LGR, CS-MW23-LGR, and CS-MW22-LGR. However, arguably the two plumes have co-mingled off-post to the west of CSSA in the vicinity of I10-4 and OFR-3. While the plumes still appear remain distinct with respect to TCE and *cis*-1,2-DCE, there no longer is a discernable boundary between plume margins with respect to PCE when mapping the plume down to the MDL concentration level.

Plume 1

PCE

PCE within Plume 1 is centered around wells CS-D and CS-16-LGR. During a 5-year hiatus of data between February 1996 and June 2001, CS-D presumably began showing an increasing trend in contaminant concentration (Figure 5.2). Likewise, CS-16-LGR has shown a subtle decrease in contaminant concentration (Figure 5.3) since November 1998, possibly indicating the plume may be migrating westerly within the LGR. Since 2001, PCE concentrations at CS-D normally exceed 100 µg/L, while CS-16-LGR typically ranges between 20 µg/L and 100 µg/L. However, Plume 1 has not yet been detected to the west of CS-D in CS-MW24-LGR since its installation in Spring 2007.

Historically, concentrations in excess of 10 µg/L are usually present to the south at CS-MW1-LGR and occasionally CS-MW2-LGR. Additionally, PCE concentrations in excess of 1 µg/L can be expected to occur at CS-MW2-LGR, CS-MW5-LGR, and CS-MW20-LGR. The remainder of Plume 1 is defined by detections greater than the MDL (0.05µg/L) but less than 1µg/L. The total area that is encompassed by the 1 µg/L contour line is approximately 360 acres.

Figure 5.2
VOC Concentrations at CS-D since 1991

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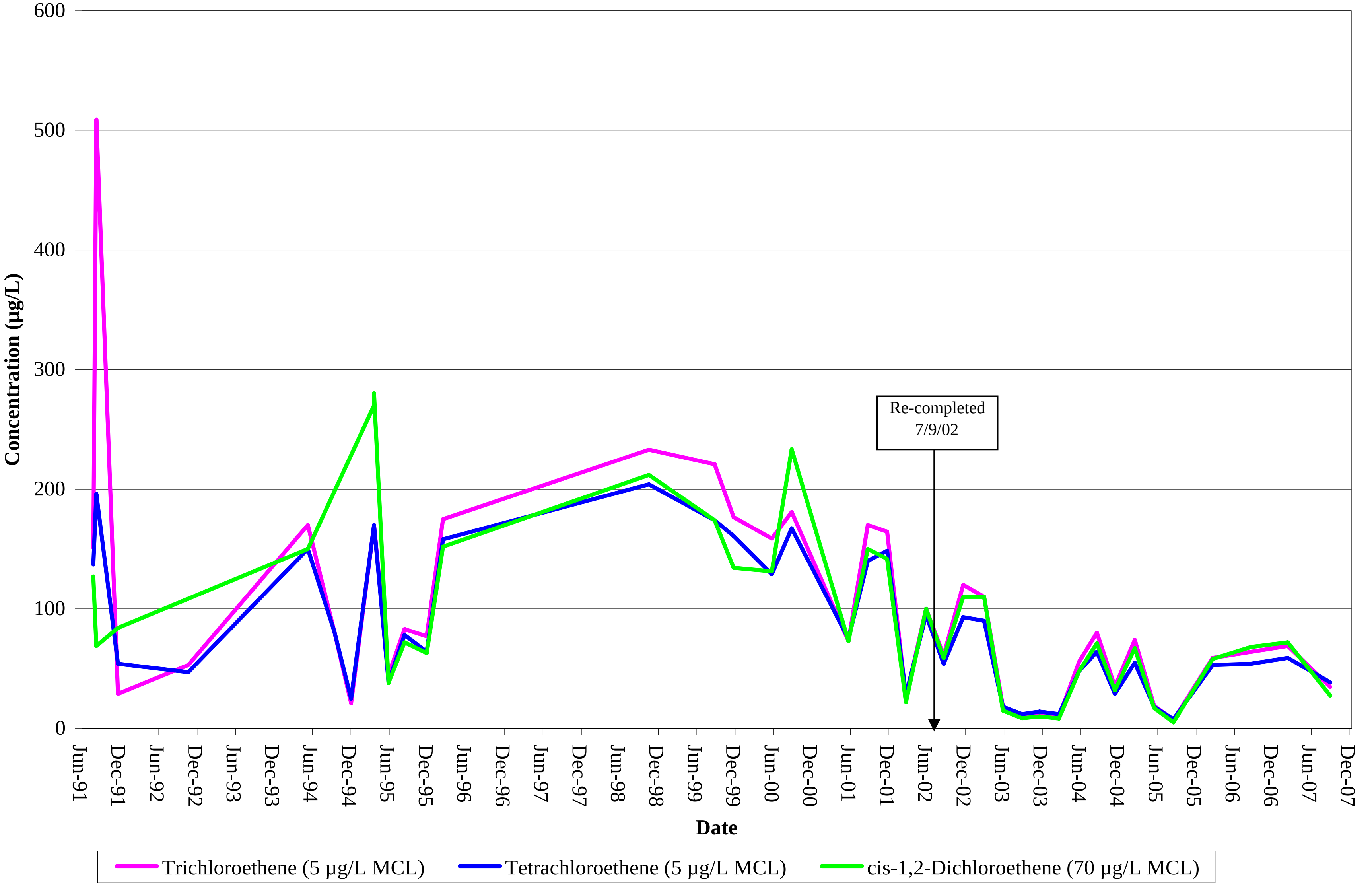
The open borehole well CS-16 was
re-completed on 7/9/02 as CS-16-LGR

Figure 5.3
VOC Concentrations at CS-16-LGR since 1991



The open borehole well CS-16 was
re-completed on 7/9/02 as CS-16-LGR

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The northern extent of Plume 1 within the LGR has been consistently defined by the lack of contamination at CS-G, CS-MWH-LGR, and CS-I. CS-MW9-LGR appears to be close to the plume margin, such that PCE concentrations just at the laboratory MDL have been reported (June 2003 through March 2006). The eastern and southeastern portion of Plume 1 has not been defined by wells free of contamination. New wells CS-MW21-LGR, -MW22-LGR, and -MW23-LGR have helped define the southern edge thus far with only two rounds of sampling since their inception. CS-MW3-LGR establishes a control point to the NE, otherwise PCE concentrations near the on-post laboratory MDL of 0.05 µg/L appear to extend into the East Pasture as shown by results of CS-MW5-LGR, CS-MW4-LGR, and CS-MW17-LGR. The lack of contaminant detections along the northern portion of Ralph Fair Road defines the plume to the NW. The data indicates that municipal and private wells close to Fair Oaks Ranch have not been impacted by CSSA. The only exception to this assertion is a single, F-flagged detection (below the RL) in off-post well RFR-3 in December 2003. The other 10 sampling events from this well between 1995 and 2007 have resulted in no detections of target VOCs.

The PCE component of Plume 1 appears to migrate southwesterly beneath Ralph Fair Road near Jackson Woods. The migration of the plume in this direction may be attributed to several factors, including the natural groundwater gradient with a southwesterly vector, migration induced by long-time groundwater production from the CSSA well field (CS-9, CS-10, and CS-11), wells within Jackson Woods, and structural controls related to faulting or karstic features. The odd geometry of the plume suggests that structural controls may be a dominating force. The southwesterly nose of Plume 1 is located beneath both residential and agricultural properties between Ralph Fair Road and Old Fredericksburg Road. The southwestern tip of Plume 1 is demarcated by the historical lack of detections at FO-17, I10-7, I10-8, OFR-4, RFR-9, and RFR-13. Off-post detections in Plume 1 typically range between the MDL of 0.06 µg/L and 1 µg/L. With the exception of the SW portion, the location and geometry of Plume 1 appears to be static. As seen in the figures presented in Appendix C, the overall shape and geometry of the VOC plumes is also governed by the introduction of new monitoring wells during this time period and the temporal detection/non-detection patterns established at wells near the plume margin.

RFR-9, CS-MW6-LGR, CS-MW22-LGR, and CS-MW23-LGR define the margins between the PCE fractions of Plume 1 and Plume 2. The total area of groundwater that appears to be impacted by PCE is 1,831 acres. Of this, 1,566 acres is on-post (including Camp Bullis), with the remaining 265 acres located off-post.

TCE

While it is postulated that TCE was used as solvent at the facility, TCE also occurs within the model area as a daughter product resulting from the reductive dehalogenation process of PCE (Appendix C). The distribution and occurrence of TCE readily mimics that of the PCE fraction of the plumes, and the total area of the plume is slightly less than the PCE fraction. As before, the TCE fraction of Plume 1 is centered around wells CS-D and CS-16-LGR (Figures 5.2 and 5.3). Wells with concentrations in excess of 1 µg/L include CS-4, CS-MW2-LGR, and CS-MW5-LGR, and cover approximately 386 acres of the post. CS-MW1-LGR consistently exceeds 20 µg/L, CS-16-LGR can exceed 100 µg/L, and CS-D is routinely between 250 and 300 µg/L. As with the PCE plume, the TCE plume is well defined to the north and west. However, the eastern and southern extents have not been completely defined by wells free of contamination. The plume has migrated southward onto Camp Bullis property, where trace TCE amounts have been seen in CS-1.

The TCE plume maps located in Appendix C indicate that most of the PCE degradation to TCE occurs along a line that roughly follows Salado Creek, which is also the direction of the groundwater gradient. Once again, the plume margins can be variable based upon isolated occurrences of detections the laboratory detection limit. As an example, the data from March 2003 (Figure C-5) has an expanded plume geometry in comparison to prior and subsequent quarterly events. In this particular case, the solitary low-level presence of TCE is reported in an off-post area where PCE has been detected at JW-30. The total area of groundwater that appears to be impacted by TCE is 1,331 acres. Of this, 1,233 acres is on-post, with the remaining 98 acres located off-post.

Cis-1,2-DCE

Cis-1,2-DCE occurs within the HCSM area as a degradation product resulting from the reductive dehalogenation process and dilution of parent compounds PCE and TCE. The presence of *cis*-1,2-DCE indicates that the anaerobic conditions of the subsurface are somewhat favorable, and that natural attenuation processes are occurring. The *cis*-1,2-DCE plume is co-located with the PCE and TCE fractions, but covers a significantly smaller area (Appendix C). Once again, the greatest concentration of *cis*-1,2-DCE is associated with CS-D and CS-16-LGR (Figures 5.2 and 5.3). The center of the plume is the only area that exceeds the federal MCL of 70 µg/L. *Cis*-1,2-DCE concentrations in excess of 10 µg/L routinely occur at CS-MW1-LGR, followed by detections above 1 µg/L at CS-MW2-LGR and CS-MW5-LGR. Detections less than 1 µg/L repeatedly occur at CS-4 and CS-MW4-LGR. Approximately 260 acres of the plume exceed 1 µg/L of *cis*-1,2-DCE. The margins of the on-post *cis*-1,2-DCE plume is confined by no detections in wells CS-MW9-LGR, CS-3, CS-2, CS-MW12-LGR, CS-MW19-LGR, CS-1, CS-MW17-LGR, and CS-MW3-LGR. An isolated off-post location associated with Plume 1 also occurs in Jackson Woods across Ralph Fair Road. Four wells, including Fair Oaks Ranch municipal well FO-J1 and private wells JW-8, JW-9, and JW-30, had sporadic detections of *cis*-1,2-DCE less than the RL since 2001. The total area of groundwater that appears to be impacted by *cis*-1,2-DCE is 648 acres.

Plume 2

PCE

PCE releases associated with past hazardous materials operations at Building 90 (AOC-65) have affected the LGR portion of the aquifer at the SW portion of CSSA and beyond (Appendix C). As stated previously, the plume appears to be distinct from Plume 1 as indicated by a line of wells free of PCE contamination. Geographically, the plume is smaller than Plume 1. The area of contamination extends from Building 90 southward beneath Leon Springs Villa and westward to Interstate 10. The southern and eastern extents of the plume have not been defined by wells free of contamination, and PCE is present in municipal wells LS-1, LS-2, LS-3, LS-4 and HS-2. Private well DOM-2 is the only southern well sampled that has not been impacted by groundwater contamination. The western extent is somewhat defined by lack of detections at I10-5 and I10-7.

The plume morphology has remained consistent between December 2002 and September 2007. The area of the LGR aquifer impacted by PCE concentrations above the MDL is approximately 612 acres. PCE groundwater contamination in excess of 1 µg/L extends westward from the CS-MW8 cluster to OFR-3, and southward within Leon Springs Villa beneath 236 acres of land. Within this area, PCE concentrations within the LGR exceed the federal MCL of 5 µg/L on a periodic basis. Wells consistently in excess of 10 µg/L occur 1,500 ft west-SW of Building 90 at RFR-10 and RFR-11.

TCE

In the SW corner of CSSA, the 365-acre TCE degradation plume is co-located within the main PCE plume body in the LGR (Appendix C). The degradation to TCE has not occurred at the plume margins, thus the overall area of impacted groundwater is somewhat less than for PCE. Most concentrations are below the CSSA RL, with only six wells (I10-4, OFR-3, RFR-10, RFR-11, LS-6, and LS-7) exhibiting concentrations in excess of 1 µg/L (50 acres). Between December 2002 and September 2007, the plume remained essentially static, with the exception of consistent TCE detections in I10-4 since September 2004. Because of the discontinuous nature of the occurrence of specific compounds in off-post wells, it is unclear if the occurrence of TCE in I10-4 is a result of Plume 1 or Plume 2 migration.

***Cis*-1,2-DCE**

In association with Plume 2, *cis*-1,2-DCE has been detected in four wells that range from CS-MW6-LGR (June 2001 only) and CS-MW8-LGR (March 2003 only) located on-post, westward towards RFR-10 and OFR-3 located off-post (Appendix C). As much as 35 of the 43 acres mapped for *cis*-1,2-DCE contamination are located off-post. The *cis*-1,2-DCE plume off-post is consistently reported in samples and is co-located with the highest occurrence of Plume 2 PCE concentrations known to exist within the LGR.

5.2.3 Bexar Shale (Layer 3)

<u>Plume 1</u>

To date, only four monitoring wells (CS-MW1-BS, CS-MW6-BS, CS-MW12-BS, and CS-MW9-BS) have been installed to exclusively monitor the BS. While many wells penetrate the unit within the HCSM area, they have been included with the discussions regarding the LGR (Section 5.3.2). As shown in various Appendix C figures, PCE, TCE, and *cis*-1,2-DCE are only detected within the BS at CS-MW1-LGR. With the exception of *cis*-1,2-DCE (1.3 µg/L) and toluene (26 µg/L) at CS-MW1-BS, the VOC concentrations were reported at trace levels between the MDL and RL. While the representations of a single-point plume likely do not represent the true distribution of trace contamination within the BS (Appendix C), the current subsurface studies thus far indicate that the BS has been minimally impacted. As an example, trace detections of VC have been consistently reported in CS-MW12-BS and less often in CS-MW9-BS. The occurrence of VC in the BS is notable considering the rarity of detections within the LGR and CC as compared to its occurrence in the BS.

<u>Plume 2</u>

Only one BS well (CS-MW6-BS) is located in the vicinity of AOC-65. During the monitoring period (December 2002 through September 2007), trace detections of toluene, naphthalene, methylene chloride and *cis*-1,2-DCE (Figure C-9) have been reported in groundwater samples from that well. The occurrence of these compounds is sporadic, and some compounds may be associated with laboratory contamination (methylene chloride). The same compounds at comparable concentrations have also been reported in the LGR and CC counterpart wells at the CS-MW6 monitoring cluster.

5.2.4 Cow Creek (Layer 4)

To date, a total of ten (10) wells completed exclusively within the CC Limestone. Both methylene chloride and toluene are the primary VOC analytes detected within the CC wells, usually at trace concentrations below the AFCEE RL. Infrequent and isolated detections PCE, TCE, and VC have been reported at trace concentrations within the CC portion of the Plumes 1 and 2 areal extents. The exception to this generalization is where long-term cross-connection between the LGR and CC has occurred within open borehole well completions (CS-MW16 area). Appendix C figures depict the occurrences of PCE, TCE, and *cis*-1,2-DCE within the Cow Creek.

Plume 1

Sampling results within the CC from December 2002 through September 2007 are presented in Appendix C depict the occurrences of PCE, TCE, and *cis*-1,2-DCE within the Cow Creek. Prior to September 2003, the CC wells were still being installed and are reflected as such in the maps. The plume delineation as it exists today was defined by the installation of well CS-MW16-CC.

Prior to September 2003, a solitary trace detection of *cis*-1,2-DCE was reported in CS-MW9-CC during the March 2003 event. While trace detections of methylene chloride and toluene have been reported in the CC wells, the lack of PCE, TCE, and *cis*-1,2-DCE in this unit was notable. By September 2003 well CS-MW16-CC had been incorporated into the monitoring network and changed the perception of on-post contamination within the CC unit.

Table 5.2 lists the results of grab samples collected during the installation and development of well CS-MW16-CC. This well is located 30 ft west of the original supply well, CS-16, which was an open borehole well extending from the LGR to the CC. Discrete interval packer samples were collected from the CC interval during coring in June 2003. Results indicated that significant levels of solvent contamination were in the CC groundwater (Table 5.2). PCE was detected to nearly 50 µg/L, while TCE and *cis*-1,2-DCE exceeded 100 µg/L. The borehole results were confirmed with a development sample collected in July 2003. After three weeks of additional well development pumping in August 2003, a post-development sample showed further reduced concentrations (as shown in Table 5.2). However, results from the June 2004 quarterly event indicate that CS-MW16-CC VOC concentrations have not remained reduced, and it would seems that relative concentration is a function of amount of recharge, or flushing of the vadose zone that has occurred prior to the sampling event.

Table 5.2 Sampling Results at Well CS-MW16-CC

		CS-MW16-CC Corehole Discrete Interval Groundwater Sampling		CS-MW16-CC Extraction		
Date		**June 2003**		**July 2003**	**August 2003**	**June 2004**
Depth (ft bgs)		**398-410'**	**411-423'**	**Pre-Development**	**Post-Development**	**Quarterly Sampling**
Concentration (*µg/L*)	PCE	8.58	48.4	46.2	25	55
	TCE	95	131	129	66.8	120
	cis-1,2-DCE	135	139	101	93.2	120
	trans-1,2-DCE	1.86	3.51	5.64	3.61	1.8

Using the TPDES-permitted outfall, CSSA began a pilot study to determine the effectiveness of groundwater extraction and treatment of CC water produced from CS-MW16-CC. The study implemented the permitted Outfall 002 treatment facility for treatment and discharge of the CC groundwater. The test began in February 2004, and continued nearly 15 months until June 2005. The well was operated at a constant rate of 12 gpm, and extracted groundwater was treated using granular activated carbon. During the course of the study, more than 8.2 million gallons of CC groundwater was extracted and treated. Based on the monthly sampling results, an estimated 16.6 pounds of VOC mass (PCE, TCE, *cis*-1,2-DCE, and *trans*-1,2-DCE) were removed during the pilot study. At the end of the study, contaminant concentrations were essentially equivalent, or slightly less, then their pre-test concentrations, One notable result of the pilot study was that significant drawdown (greater than seven feet) was measured in CC monitoring locations more than 2,000 feet from the pumping well. Another observed correlation was that temporal fluctuations in contaminant concentration were attributable to dilution effects corresponding to significant precipitation events.

Investigation data indicates that the CC has been impacted near Plume 1. However, current distribution data shows that the CC portion of Plume 1 is mostly confined to the area near the source, specifically near well CS-MW16-CC. At this time it is unclear whether contaminants have migrated downward through the BS, or whether inter-aquifer contamination has occurred as a result of open borehole completions in former water supply wells. The findings at CS-MW16-CC would seem to indicate that open borehole cross-contamination between units was a prime mechanism for the vertical migration of contaminants. This is supported by the hydraulic data that indicates that a downward vertical gradient exists over much of the year.

Plume 2

For the December 2002 through September 2007 groundwater monitoring events, Plume 2 within the CC is characterized by a sporadic occurrences of PCE, TCE, and *cis*-1,2-DCE at trace concentrations slightly in excess of the MDL. Since September 2004, PCE has been consistently detected in well CS-MW8-CC at trace concentrations below the RL. Routinely, trace concentrations of methylene chloride and toluene are also reported in the CC strata within the confines of Plume 2. While the detection within the CC is puzzling, it may be related to the occasional northward gradient that has been observed within CC wells around AOC-65 or to open borehole construction of former supply wells (such as CS-6, which was plugged in 1996) or active municipal and domestic supply wells in the area.

During the course of the environmental studies, a subject of interest has been the effect of well construction with respect to the occurrence of contamination. Thus far, the data has indicated that contamination is primarily regulated to the LGR portion of the Middle Trinity aquifer. Of concern is the long-term effect of potential cross contamination between the transmissive portions of the LGR and the CC.

Evidence of open borehole cross-contamination was found at off-post well RFR-10. This well was inspected and tested during July 2003 as part of the multi-port well investigation. During the inspection, discrete interval groundwater samples were collected from the private consumer well. Table 5.3 shows that nearly ten times the concentration of PCE is present in LGR than in the CC. It is suspected that the presence of VOCs in the CC is a localized phenomenon associated with the open borehole completion within a contaminated portion of the LGR. This hypothesis is supported by the lack of CC contamination concentration levels at, or near the AOC-65 source area.

Table 5.3 Results of RFR-10 Discrete Interval Groundwater Sampling

RFR-10	**Concentration (µg/L)**			
Depth (ft)	**Interval**	**PCE**	**TCE**	**DCE**
160-198'	LGR	**91.7**	**16.2**	**0.56 J**
201-265'	LGR	**54.4**	**19.9**	**0.79 J**
302-366'	LGR	**5.07**	<0.10 U	<0.20 U
360-424'	LGR/BS	**4.86**	<0.10 U	<0.20 U
413-477'	BS/CC	**9.02**	**1.29**	**0.37 J**

As part of this study, multi-port well CS-WB04 was installed less than 100 feet away the open borehole well shown in Table 5.3 (RFR-10) to assess the effect of cross contamination within a borehole. The well was designed to divide and isolate the aquifer into smaller hydrostratigraphic segments, thereby allowing long-term discrete samples to be collected from small segments of the aquifer. The results for 13 months of monitoring are presented in Table 5.4. The first four months of screening showed low levels of PCE, TCE, and *cis*-1,2-DCE in comparable groundwater intervals as sampled in Table 5.3. However, beyond the December 2003 sampling event, these concentrations have dissipated in most intervals. 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.

Since that time, only trace detections of *cis*-1,2-DCE (less than 0.34 µg/L) have been reported in interval CS-WB04-CC01 (441.5-471.5’). The results from the multi-port well indicate that the level of contamination in the base of RFR-10 is not present within the same

Table 5.4 Cumulative Results from the Selected Intervals within CS-WB04

Sampling Date	**BS-02 (414.5-436.5')**			**CC-01 (441.5-471.5')**			**CC-02 (476.5-492.5')**			**CC-03 (497.5-513')**		
	PCE	TCE	*cis* -1,2-DCE	PCE	TCE	*cis* -1,2-DCE	PCE	TCE	*cis* -1,2-DCE	PCE	TCE	*cis* -1,2-DCE
18-Sep-03	<0.70 U	**0.74**	<0.20 U	<0.70 U	**0.47**	<0.20 U	**1.3**	**0.81**	<0.20 U	<0.70 U	**0.49**	<0.20 U
16-Oct-03	**0.81**	**0.86**	<0.20 U	<0.70 U	**0.45**	<0.20 U	**0.92**	**0.73**	<0.20 U	<0.70 U	**0.52**	<0.20 U
20-Nov-03	<0.70 U	**0.62**	<0.20 U	<0.70 U	<0.10 U	<0.20 U	<0.70 U	**0.44**	<0.20 U	<0.70 U	<0.10 U	<0.20 U
18-Dec-03	<0.70 U	**0.53**	<0.20 U	<0.70 U	**0.34**	**0.35**	<0.70 U	**0.49**	**0.35**	<0.70 U	**0.31**	**0.35**
22-Jan-04	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U
25-Feb-04	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	**0.34**	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U
23-Mar-04	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	**0.25**	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U
7-Apr-04	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	**0.3**	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U
28-Apr-04	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	**0.26**	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U
26-May-04	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U
21-Jun-04	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U
27-Jul-04	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U
3-Sep-04	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U	<0.70 U	<0.70 U	<0.20 U

J:\743\743322 CSSA TO 08\11000 CSM Update\TO 008 HCSM\Figures&Tables\WB04 CC Results.xls stratigraphic intervals of CS-WB-04. In this case, it appears that inter-aquifer mixing of contaminants at the ranch supply well is limited to the immediate vicinity (less than 100 ft) of the open borehole.

5.3 VERTICAL DISTRIBUTION OF CONTAMINANTS WITHIN THE AQUIFER

5.3.1 Discrete Interval Groundwater Sampling

A total 102 discrete interval groundwater (DIGW) samples were collected at 24 well locations between April 2001 and January 2007 as documented in the CSSA Environmental Encyclopedia (**Volume 5, RL83, TO8, and TO42 Well Installation Reports)**. Using borehole packers, the discrete samples were used to vertically profile the contaminant characteristics of perched water intervals, the LGR Limestone, and the CC Limestone. The RL83 and TO42 samples were analyzed for target VOCs which included MEK, *cis*-1,2-DCE, *trans*-1,2-DCE, PCE, TCE, and toluene. In addition, acetone, isopropyl alcohol, and toluene, were identified early on in the drilling program as tentatively identified compounds (TIC), and were subsequently added to the target list. Isopropyl alcohol is the primary ingredient of the foaming agent occasionally used during the drilling, and acetone is a by-product of the isopropyl alcohol degradation. The TO8 target analyte list included 1,1-DCE, *cis*-1,2,-DCE, *trans*-1,2,-DCE, PCE, TCE, and VC. However, none of the 10 DIGW samples collected during the TO8 effort detected any of the target compounds in LGR groundwater.

The discrete interval packer test data strongly indicate that much of the residual contamination occurs in the upper 300 feet of the LGR Limestone. It was demonstrated consistently across the southwest portion of the facility that contaminant levels generally decreased to less than 1 µg/L below 300 feet bgs once the main production zone of the aquifer was penetrated (Figures 5.4 and 5.5). To better characterize the hydrologic profile in the vicinity of a known source area, DIGW samples were obtained from wells near AOC-65 (Building 90 and vicinity). These included wells CS-MW7-LGR, CS-MW7-CC, CS-MW8-LGR, and CS-MW8-CC. Results indicate that increased concentrations of PCE, TCE, *cis*-1,2-DCE, and toluene were present in upper portions and/or perched waters of the LGR Limestone. Concentrations up to 57 µg/L of PCE, 20.5 µg/L TCE, 0.57 µg/L of *cis*-1,2-DCE, and 14.2 µg/L of toluene were encountered at three or more intervals at the CS-MW8 cluster location. Lesser concentrations of the same compounds were also encountered at CS-MW10 and CS-MW7 locations. A single detection of MEK (15 µg/L) and two detections of acetone (50 µg/L) were also reported at the CS-MW8 location. Similar results were reported for the CS-WB wells that were installed at the same locality.

These results indicate that contaminants may be attenuated naturally by dilution and dispersion in the basal 60 feet of the LGR production zone. It is hypothesized that, regionally, within the LGR, the basal portion of the limestone yields most of the groundwater available from the formation. Depending on recharge conditions, upper water bearing zones in VOC source areas may also contribute significant well discharge at greater contaminant concentrations. Hence, well construction factors (e.g., casing depth) may play a critical role in the overall contaminant concentration present in a well.

Figure 5.4
CS-MW7 Cluster Discrete Interval Groundwater Sampling

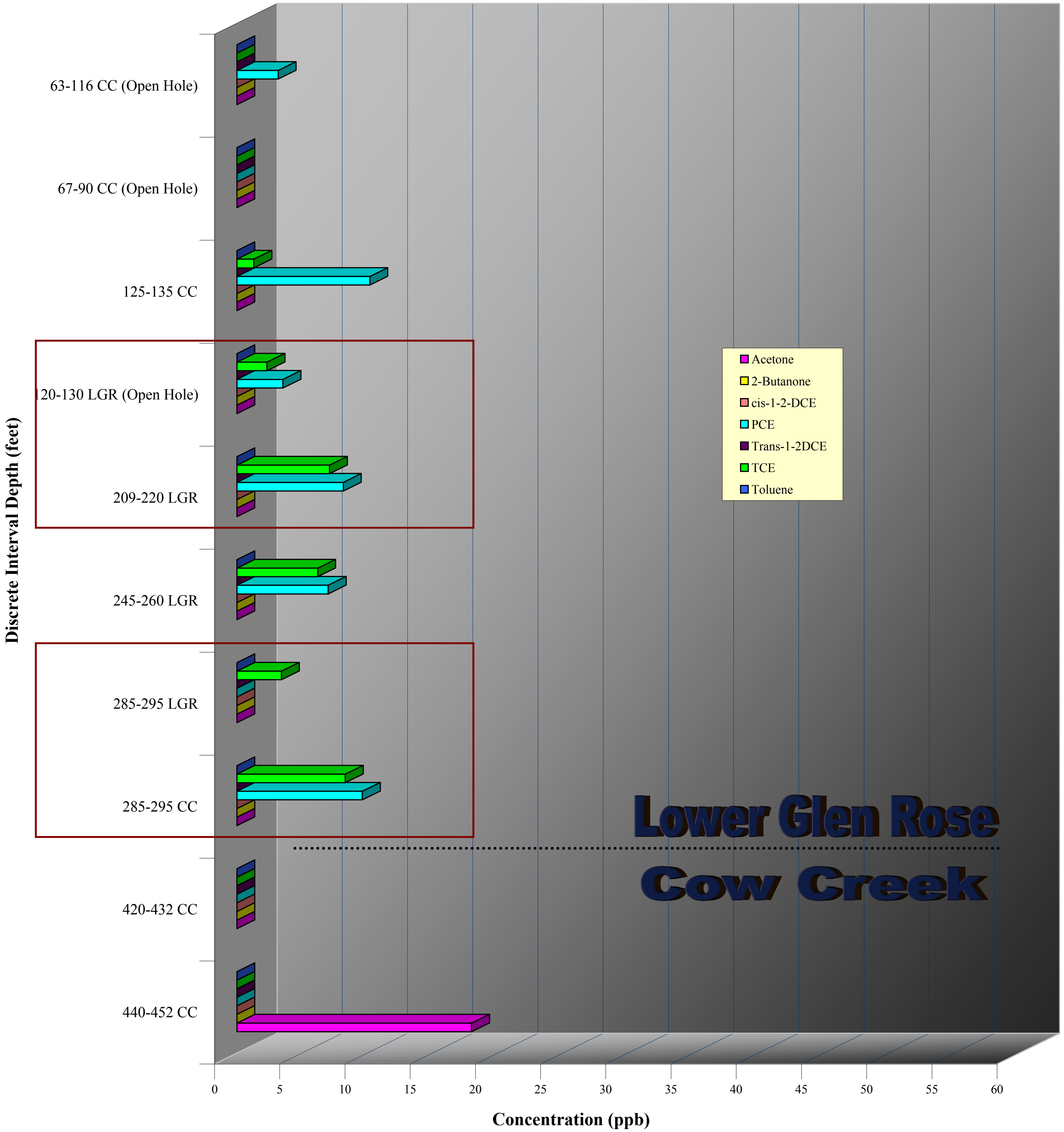
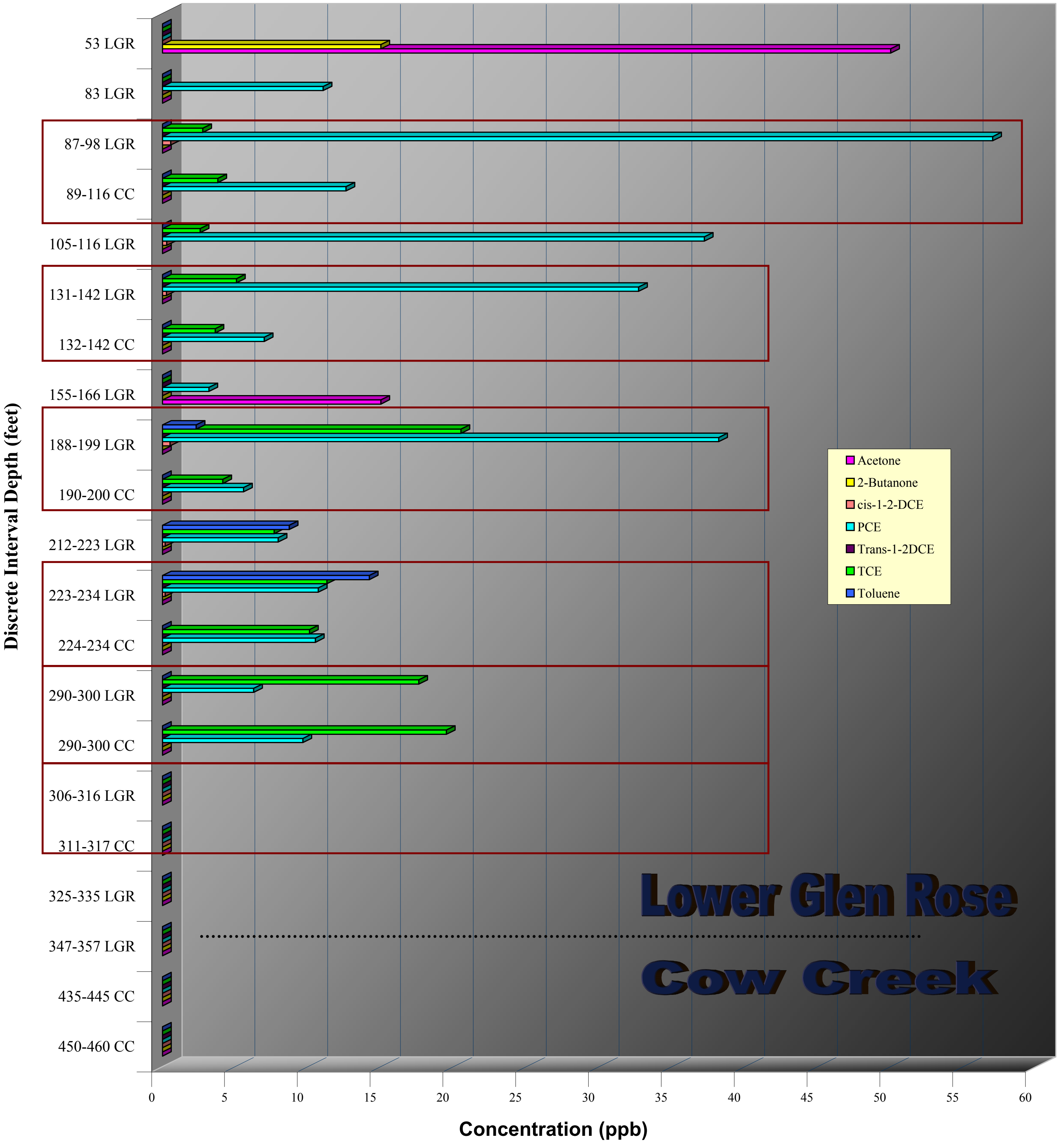


Figure 5.5
CS-MW8 Cluster Discrete Interval Groundwater Sampling



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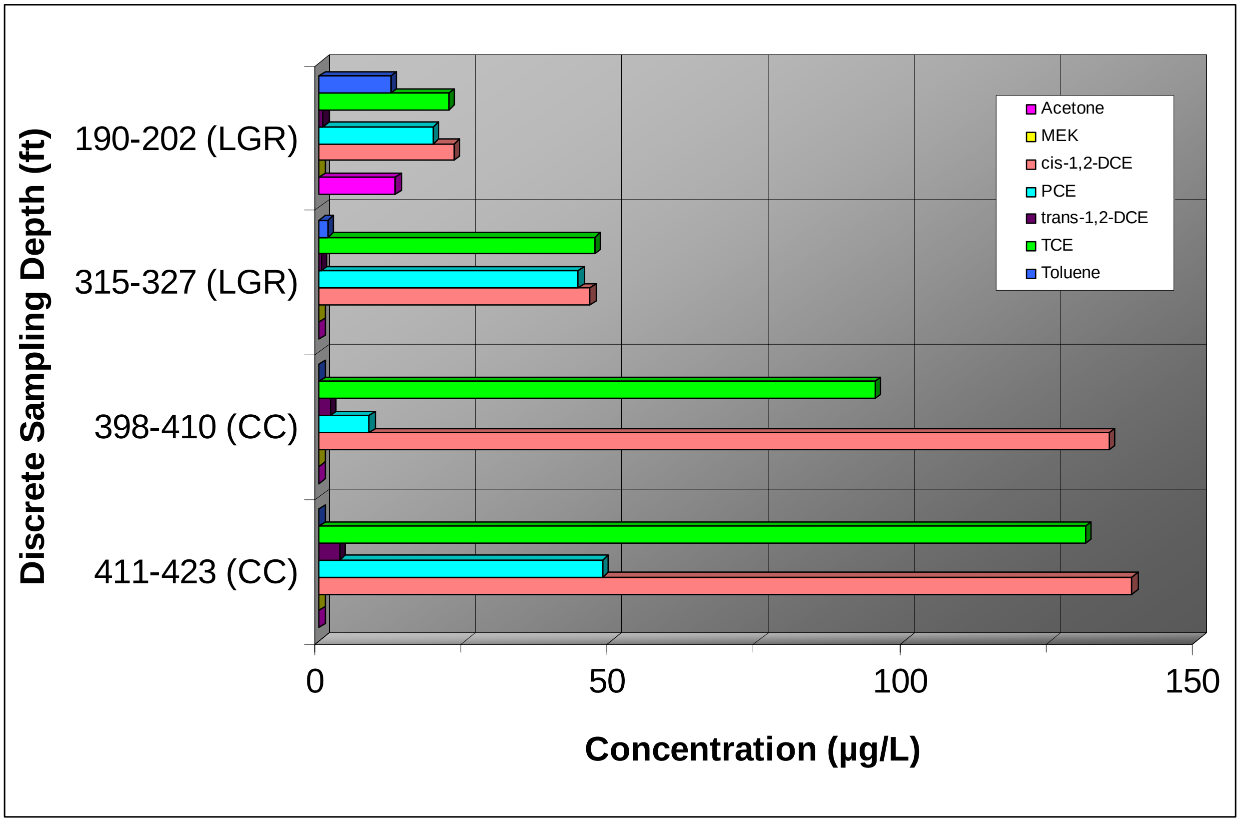
As an example, Figure 5.6 shows that contaminants have been detected throughout the entire thickness of the Middle Trinity aquifer near former well CS-16, and is located adjacent to the Plume 1 source area. Previously, well CS-16 was an open borehole completion for more than 50 years until 2002 when the BS and CC portions of the well were plugged to mitigate the downward migration of contaminants.

Figure 5.6 CS-MW16-CC Discrete Interval Groundwater Sampling



5.3.2 Multi-Port Wells

Methodology

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). For the most part, 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. At the time, 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.

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.

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.

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, the collected data from the drilling and testing phase was evaluated and integrated into a stratigraphic model. As shown in the Figure 5.7, the approach consisted of 17 unique monitoring zones with the Middle Trinity aquifer. The monitoring model 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.

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. Both absolute hydraulic pressure and temperature were obtained at each sampling port, in addition to retrieving as much as 1 liter of groundwater sample.

Results

Appendix D summarizes the analytical results for AOC-65 Westbay® samples collected between September 2003 and October 2007. Graphs of short list VOC concentrations from sampled monitoring zones in the Westbay® wells are presented in Figures 5.8 through Figure 5.11. The depths indicated for each monitoring zone represent the sampling interval open to the formation. Appendix E presents selected maps which depict the vertical distribution of the plume for the most pervasive contaminant, PCE.

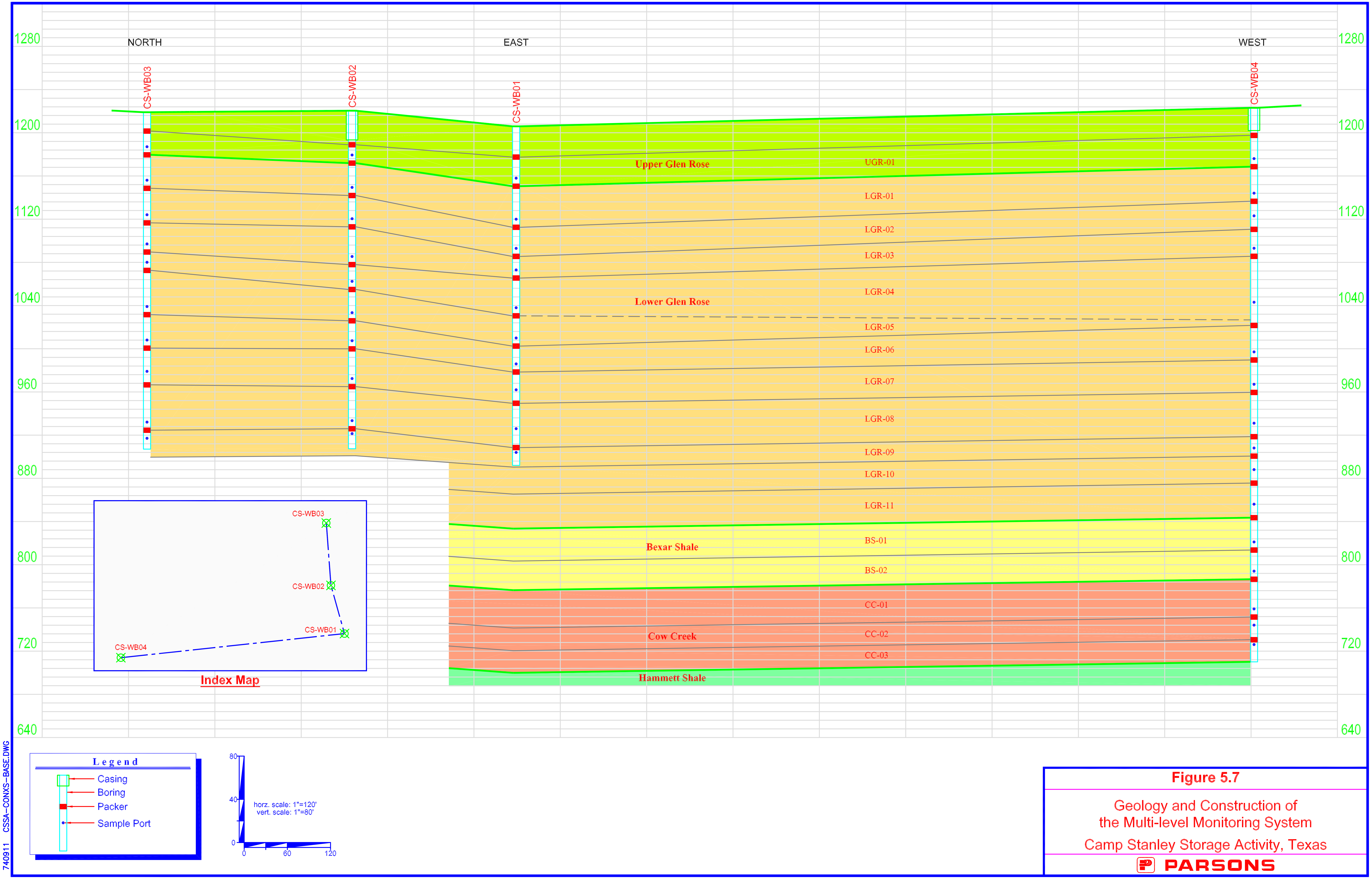


Figure 5.7

Geology and Construction of
the Multi-level Monitoring System

Camp Stanley Storage Activity, Texas

Figure 5.8
CS-WB01
Combined Concentration Data
Camp Stanley Storage Activity

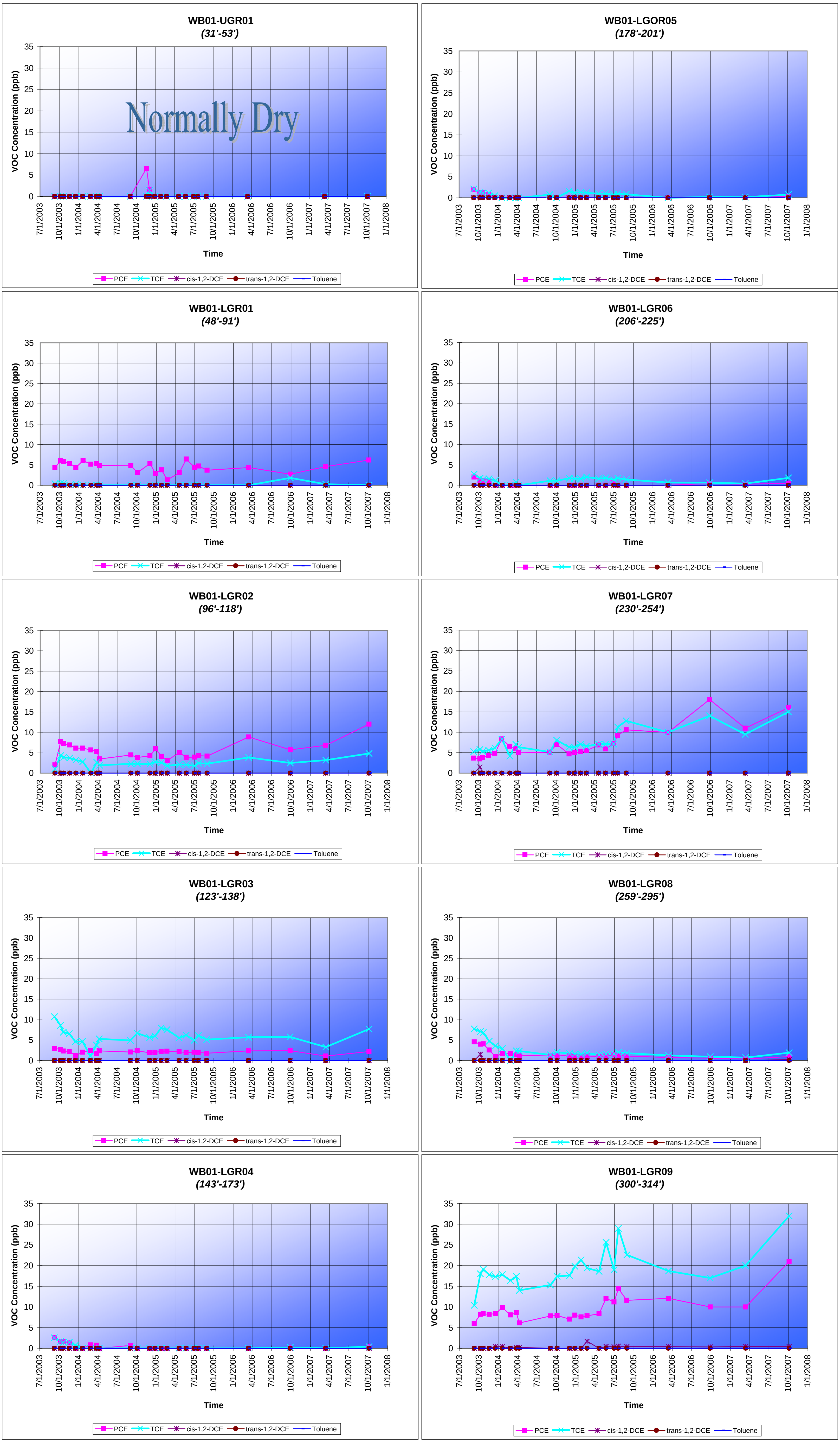


Figure 5.9
CS-WB02
Combined Concentration Data
Camp Stanley Storage Activity

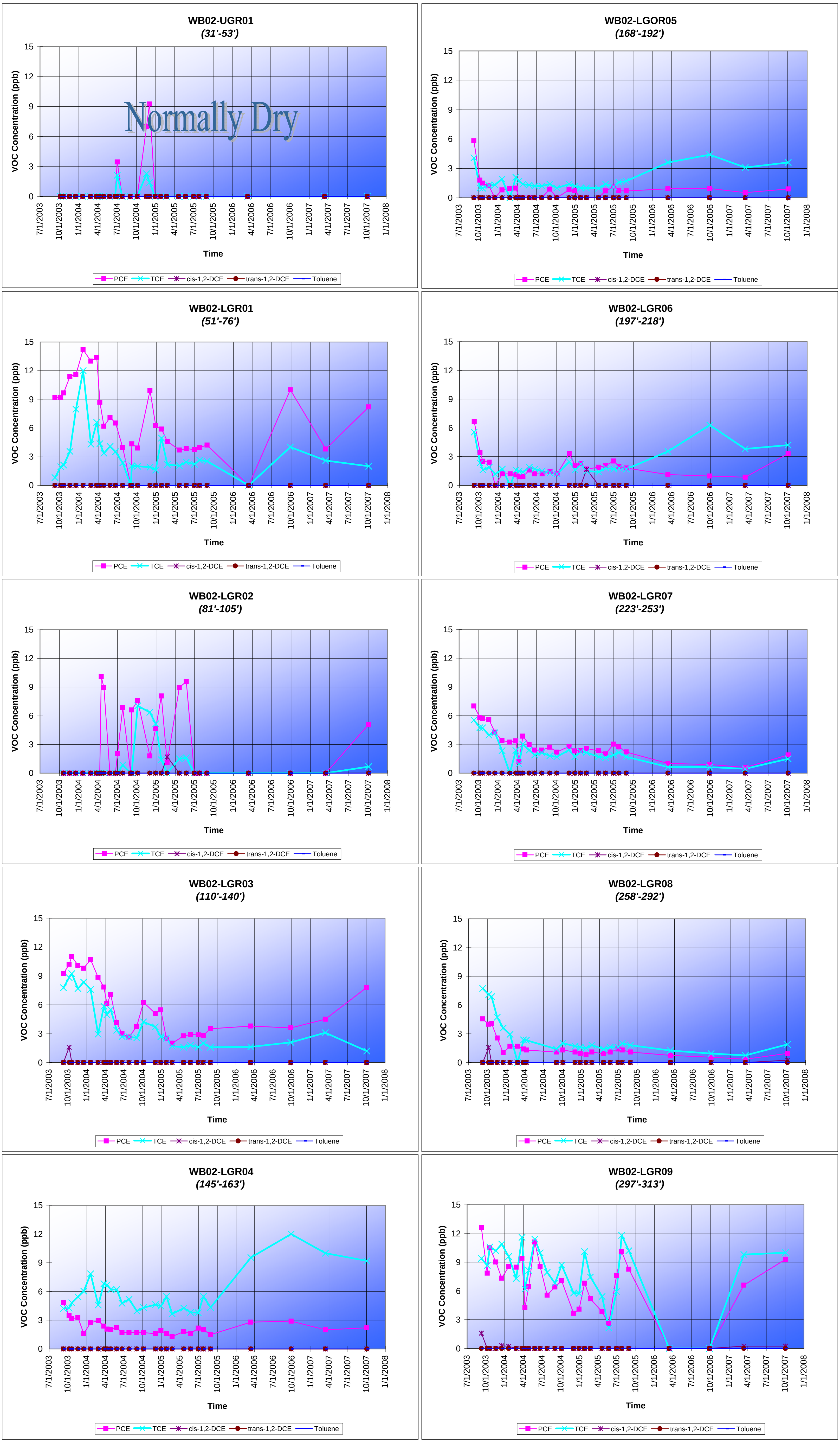
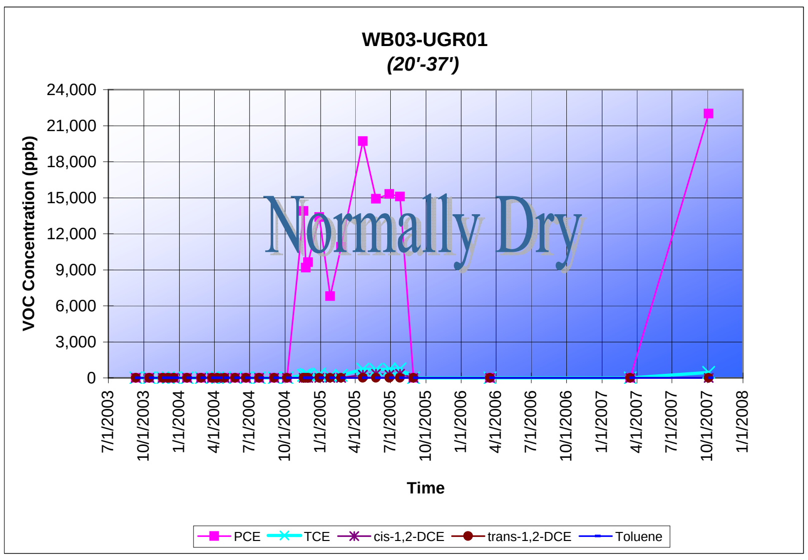
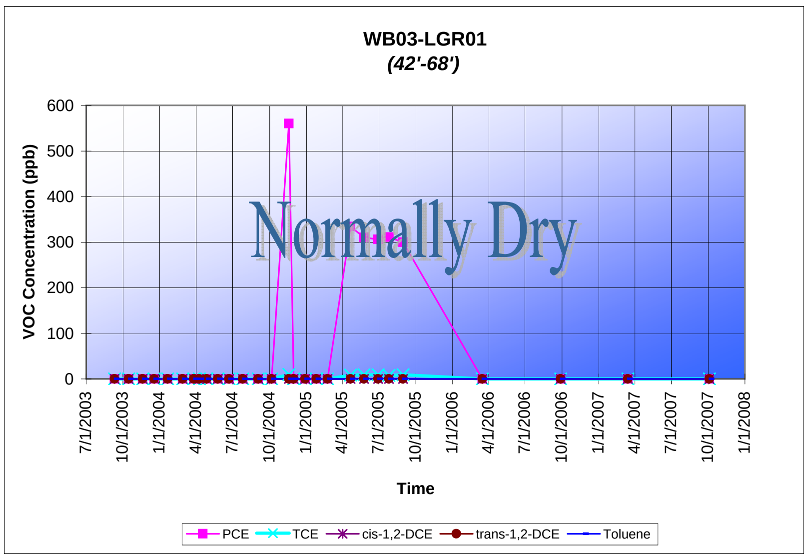
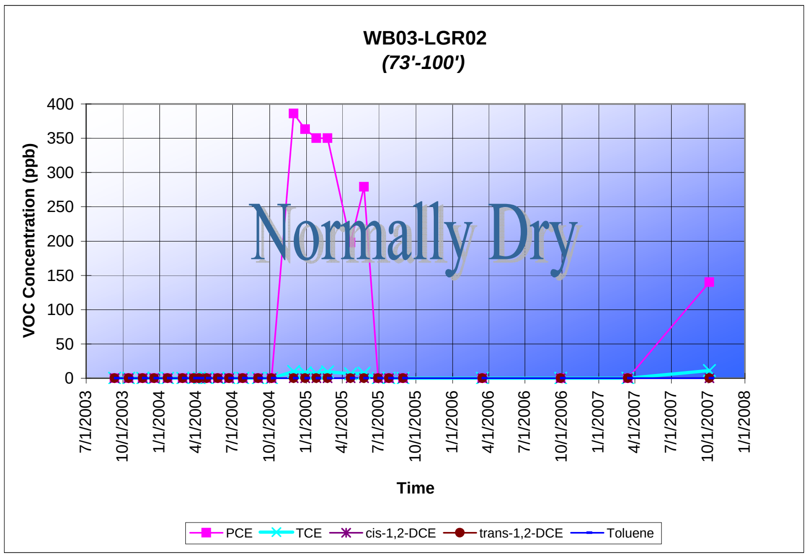
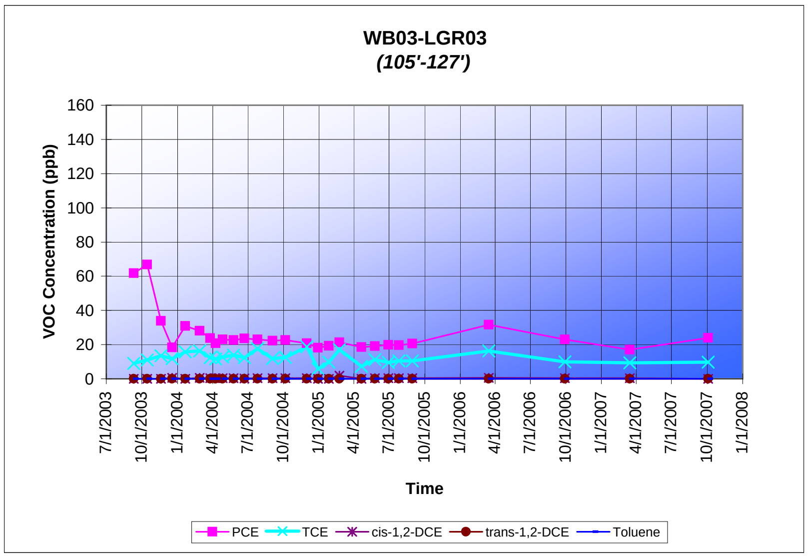


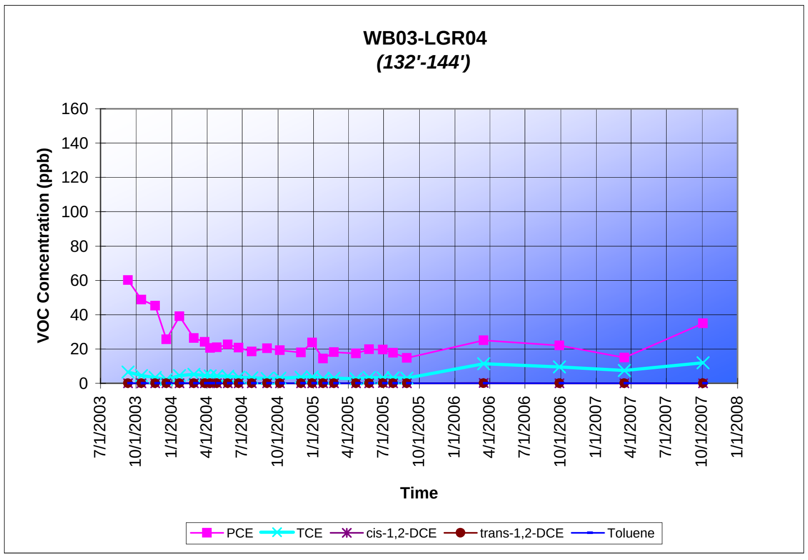
Figure 5.10
CS-WB03
Combined Concentration Data
Camp Stanley Storage Activity

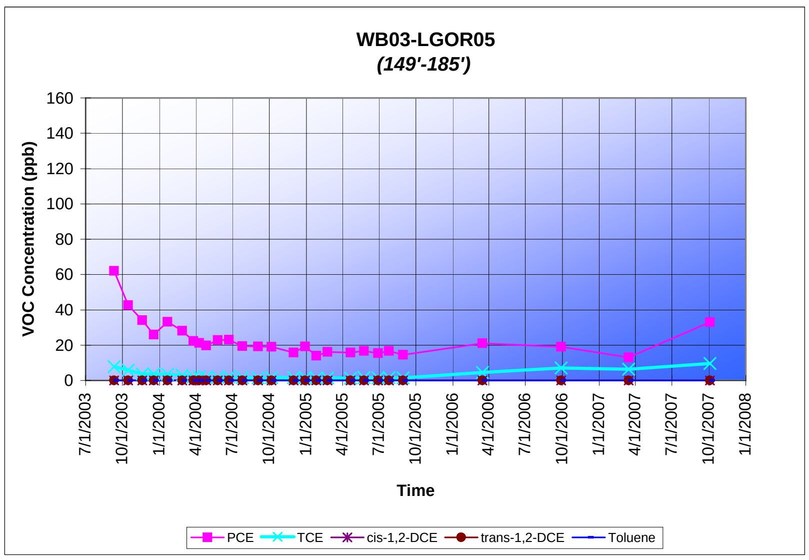


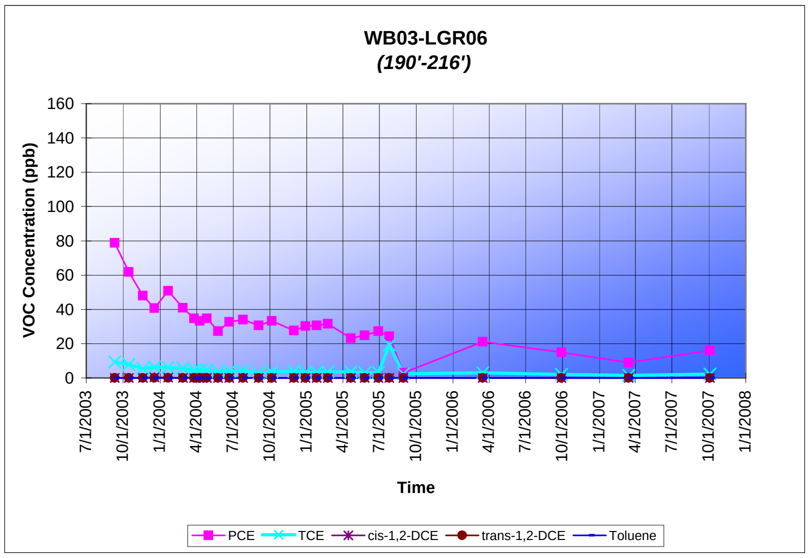


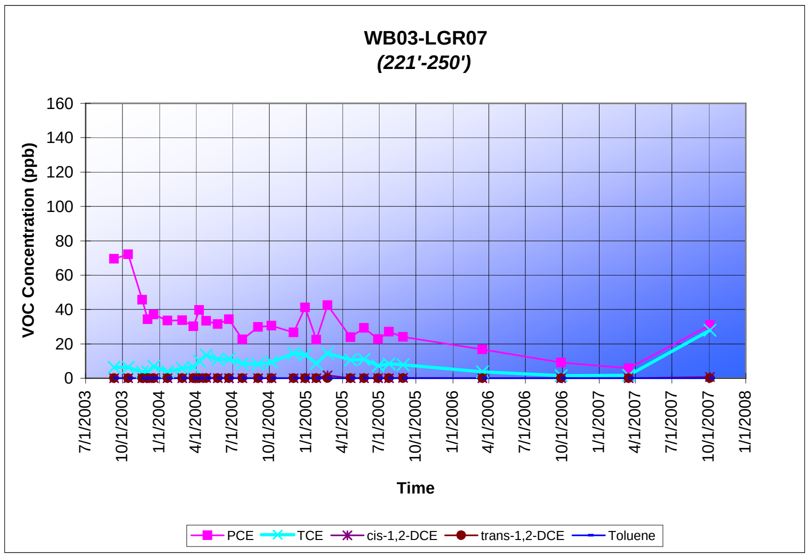


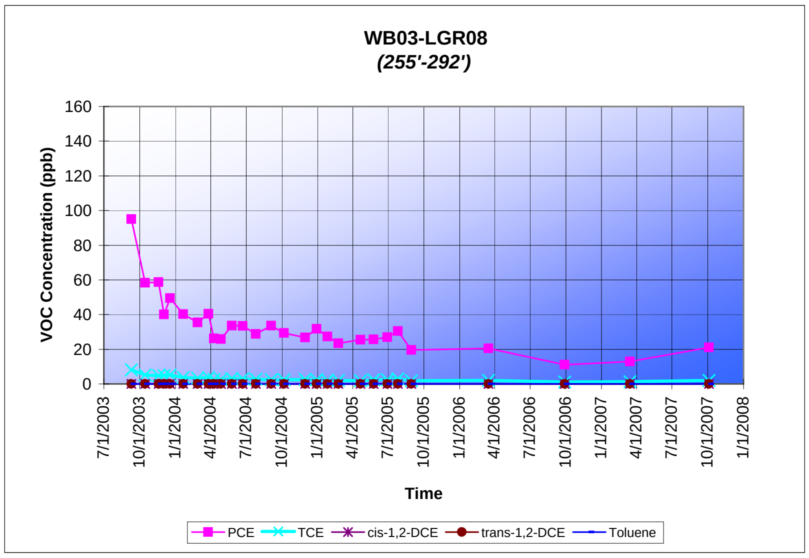












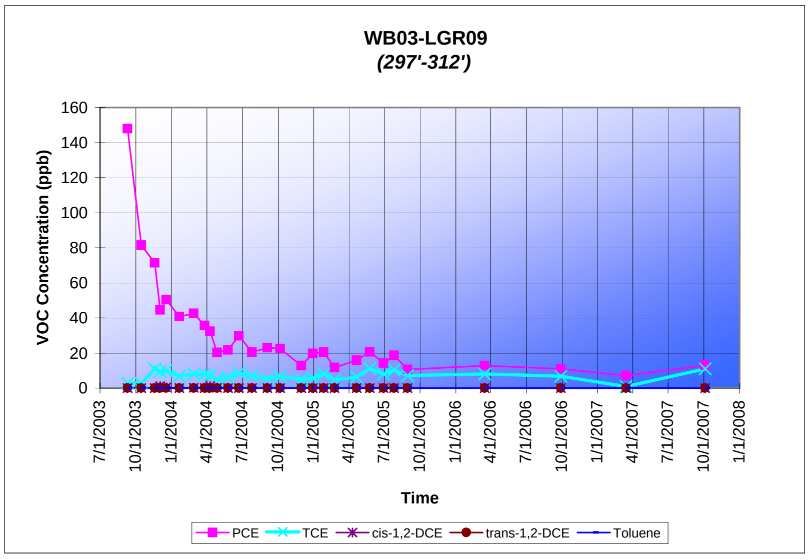


Figure 5.11
CS-WB04
Combined Concentration Data
Camp Stanley Storage Activity

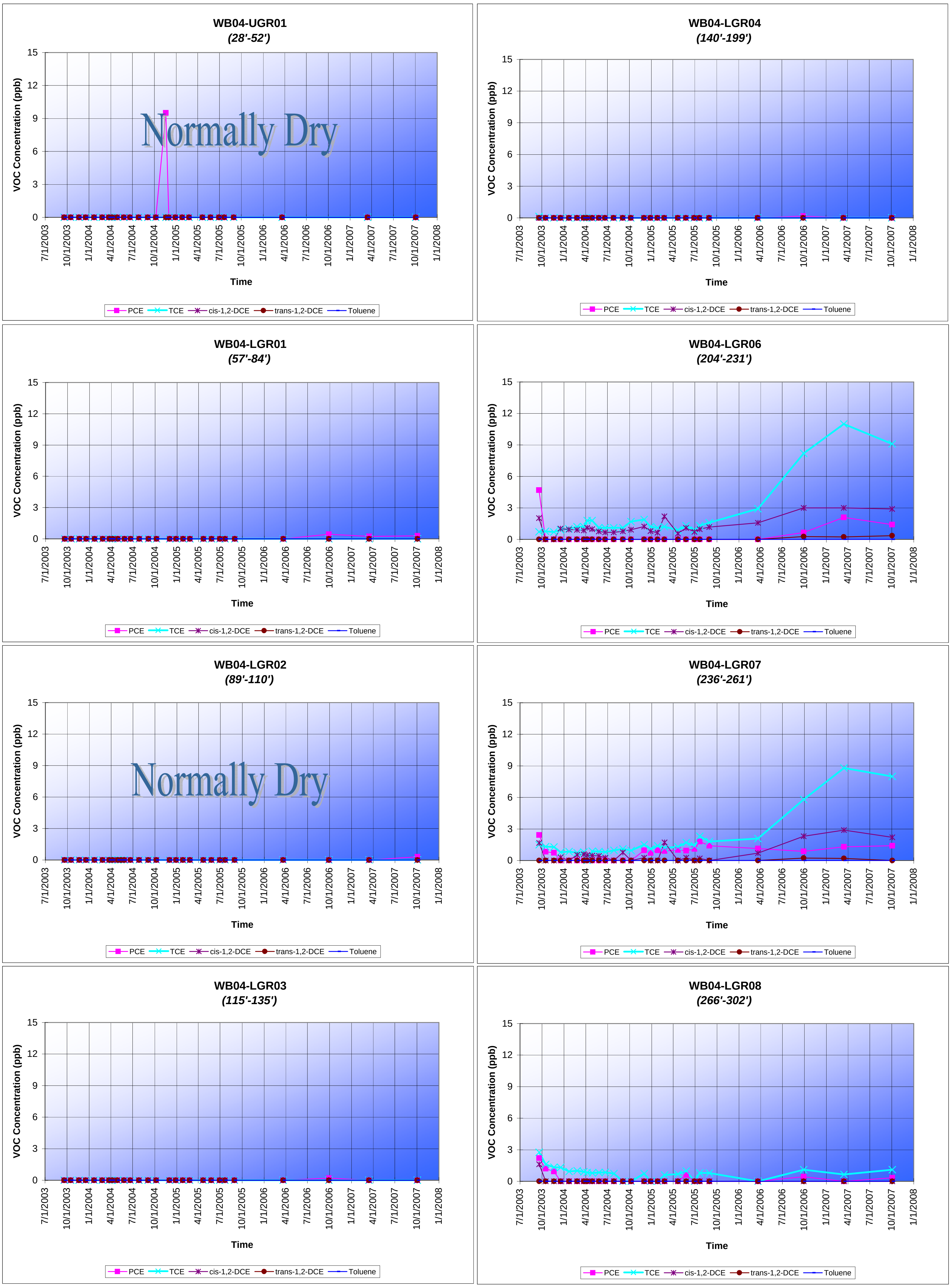


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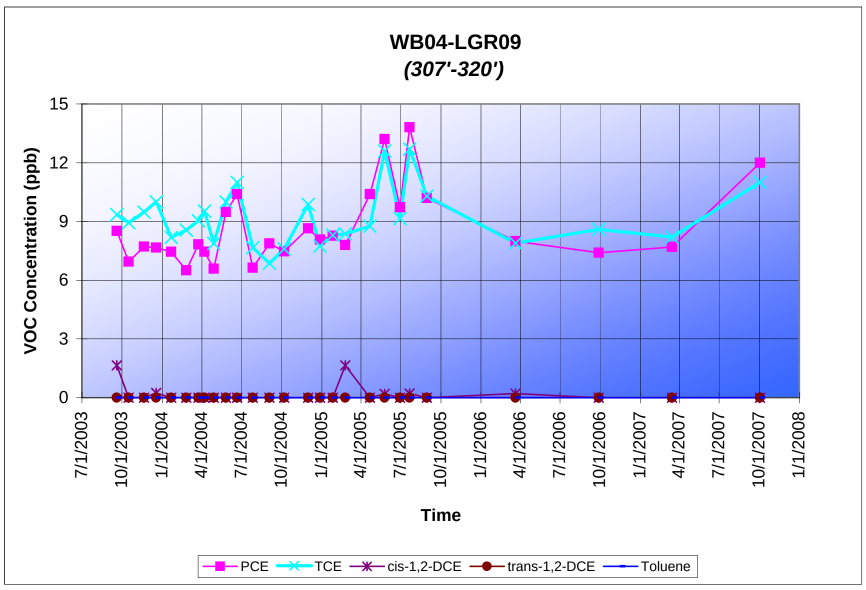
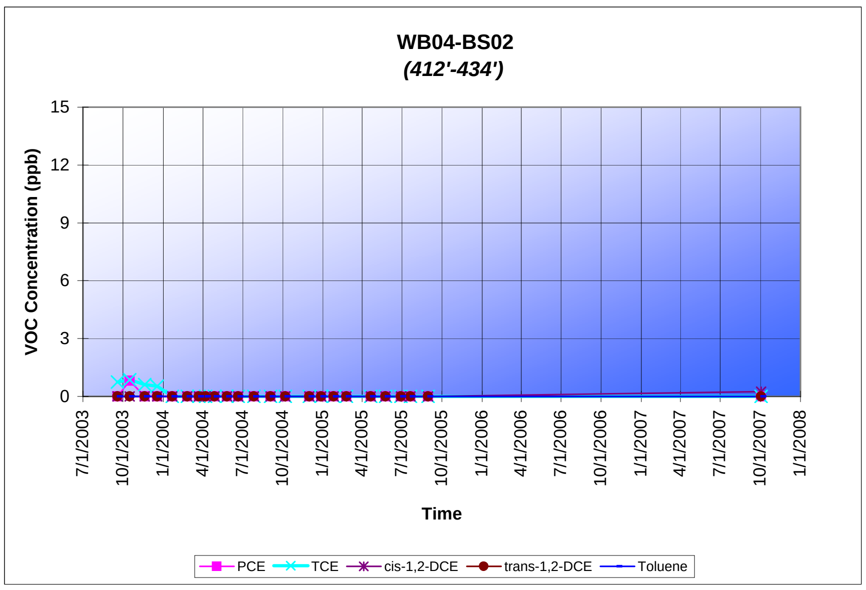
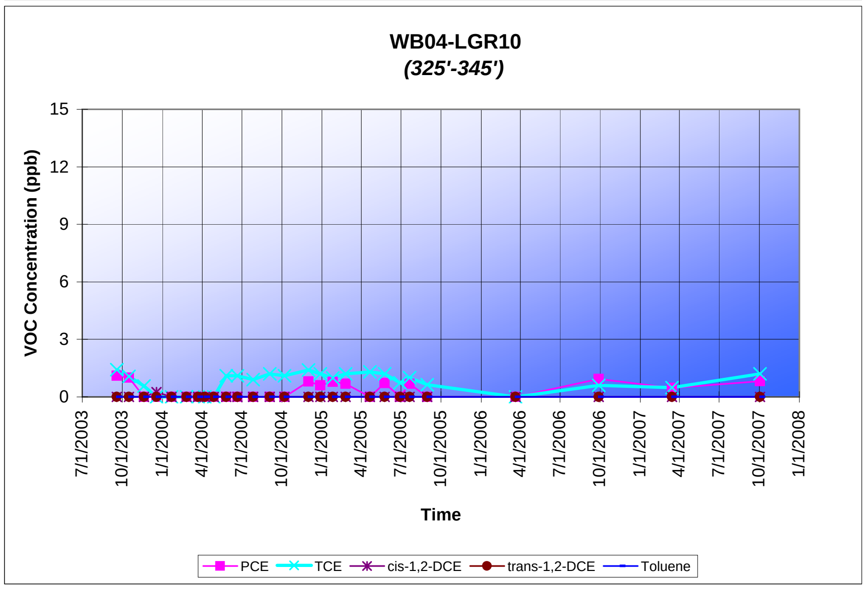
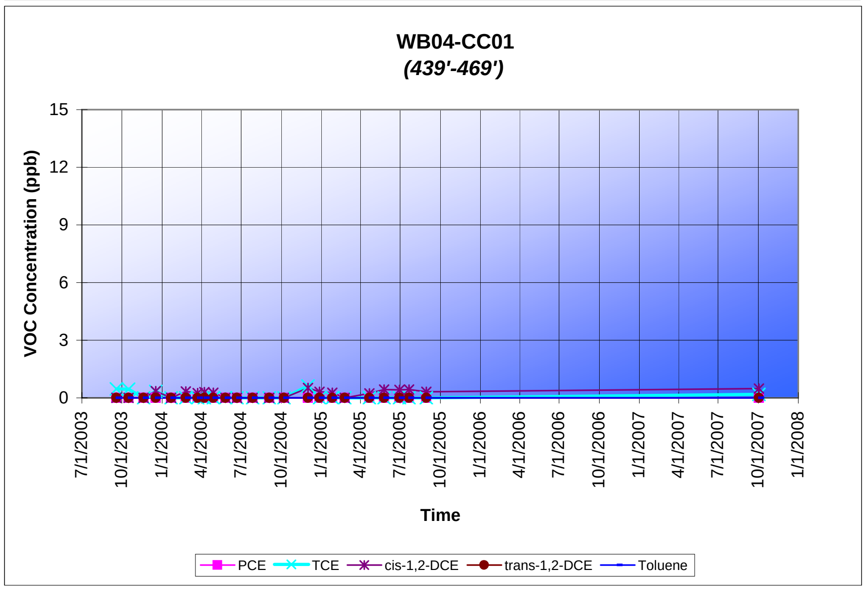
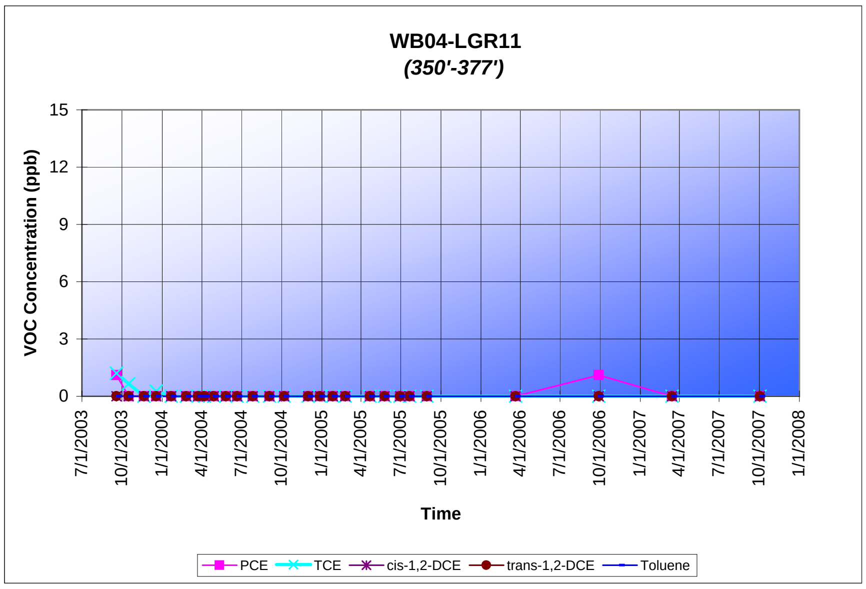
Figure 5.11
CS-WB04
Combined Concentration Data
Camp Stanley Storage Activity

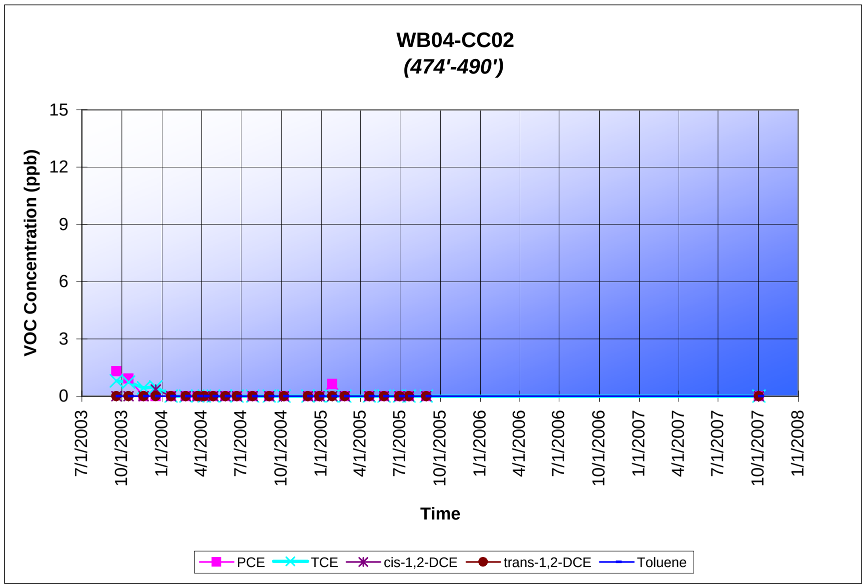


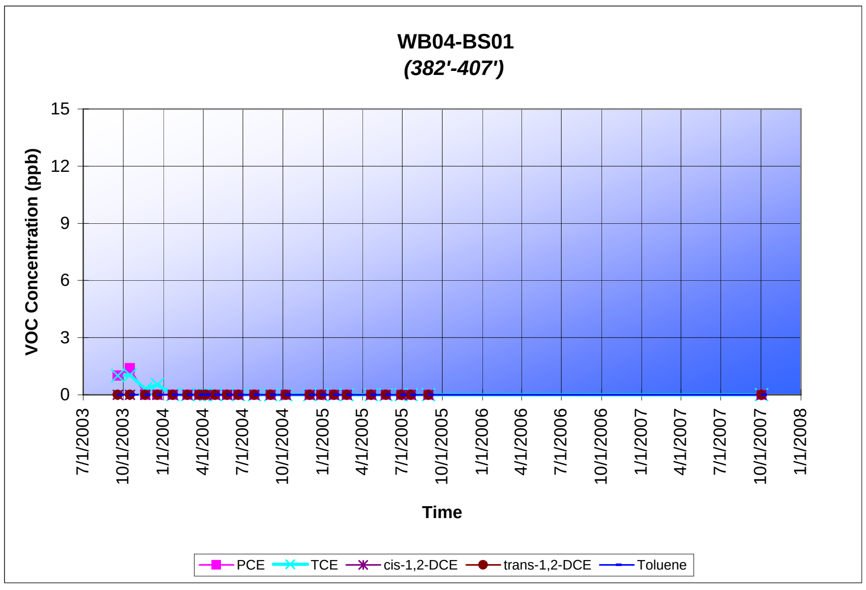


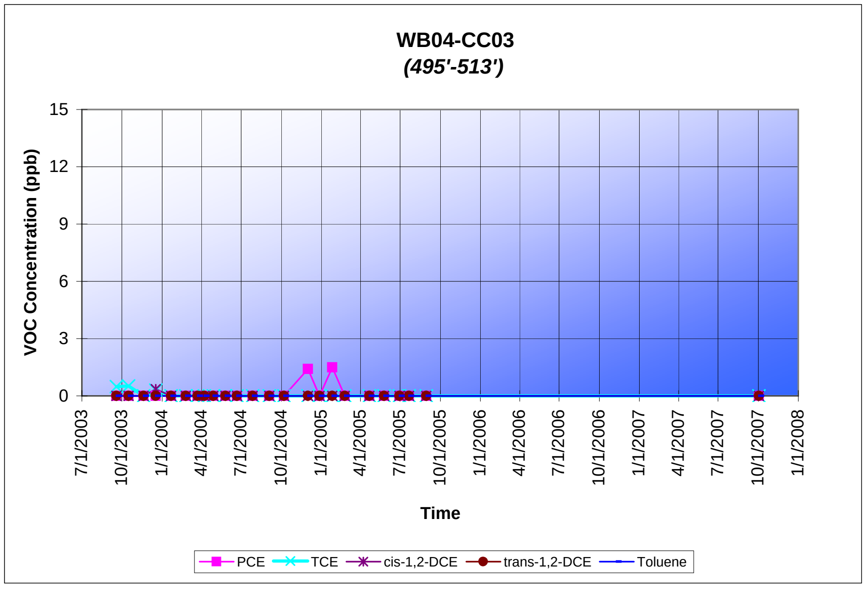












Detections of PCE, TCE, and *cis*-1,2-DCE have occurred in all four AOC-65 Westbay® wells since the inception of the monitoring program. Early on, a prominent feature of the multi-port data was the apparent decrease in concentration since the inception of monitoring in September 2003. This effect is most notable in Figure 5.10, where the bottom zone (CS-WB03-LGR09) had decreased in concentration by approximately 70 percent from 148 µg/L (September 2003) to 44 µg/L (January 2004). Similar trends were noted from the other multi-port devices as well during the initial months of monitoring.

For example, it is postulated that the initial concentrations measured in CS-WB03 were a result of the borehole development prior to the installation of the multi-port well. The reasoning stems from discrete interval groundwater samples collected after the borehole completion in July 2004. During that activity, groundwater screening samples yielded 767 µg/L (229 to 241 ft) and 380 µg/L (298 to 310 ft), respectively. The multi-port data does not indicate those concentrations at those intervals, therefore it is assumed that such groundwater concentrations are within the capture radius of the borehole under pumping stress. It is clear that the borehole development prior to well installation temporarily skewed the natural groundwater condition which required 4 months to be restored to an equilibrated state. Since the multi-port wells have re-established equilibrium within the aquifer, contaminant concentration trends decreased or remained stable in most Westbay zones through October 2007 Some exceptions include zones LGR06, LGR07, and LGR09 in CS-WB01 and CS-WB04, which have shown increasing trends in contaminant concentration. These multi-port wells are furtherest from the source area, and the results may indicate that the AOC-65 plume continues to migrate to the south-southwest. However, In general, overall contaminant concentrations in the Westbay zones decrease with distance away from AOC-65.

CS-WB03 is located closest to the Building 90 source area, and consistently records the highest concentrations of contaminants. The uppermost three zones (CS-WB03-UGR01, -LGR01, and –LGR02 are typically dry except during extreme precipitation events. However, when groundwater is present in these zones, PCE concentrations have ranged between 140 µg/L (CS-WB03-LGR02) and 22,000 µg/L (CS-WB03-UGR01). No less than 6,810 µg/L of PCE has been reported in –UGR01 when groundwater is present. These concentrations in the shallowmost zone is indicative of its close proximity to the plume source.

In lower zones at CS-WB03 typically range between 20 µg/L and 40 µg/L of PCE, with significantly lesser amounts of TCE being reported (Figure 5.10). For the zones that are normally saturated (LGR03 through LGR09), the contaminant concentrations are for the most part ubiquitous and consistent throughout the section (HCSM layers LGR[B-E]). As seen in quarterly groundwater monitoring, the contamination attenuates in layer LGR(F) to trace detections of PCE (less than 1.1 µg/L) and TCE (less than 0.42 µg/L) in nearby wells. These wells include CS-MW6-LGR (580 ft north), CS-MW7-LGR (725 ft west), and CS-MW8-LGR (430 ft south).

CS-WB02 was installed nearly 300 feet south of CS-WB03 and the Building 90 source area. Compared to CS-WB03 and CS-WB01, relatively equal levels of PCE and TCE are present throughout the CS-WB02 vertical profile. Zones CS-WB02-LGR03 through –LGR09 are normally saturated throughout the year. Intervals CS-WB02-UGR01 is almost always devoid of groundwater except after the heaviest of rains. While groundwater can normally be expected in

CS-WB02-LGR01, the same is not always true for the underlying zone, CS-WB02-LGR02. Like the other WB wells, CS-WB02 experienced an initial decline in concentrations once the re-establishment of natural groundwater flow following well development had been made. Although several zones (CS-WB02-LGR03, -LGR04, -LGR05, and -LGR06 have exhibited increases in contaminant concentration (TCE in particular) since mid-2005. Overall, PCE and TCE concentrations range between 15 µg/L to less than 5 µg/L in any given CS-WB02 monitoring interval.

Multi-port well CS-WB01 is located approximately 500 ft south of CS-WB03 and the Building 90 source area. Once again, for the zones that are normally saturated (LGR01 through LGR09) at CS-WB01, PCE and TCE are present at concentrations of less than 35 µg/L. Since mid-2005, there has been a steady trend of increasing contaminant concentrations in zones CS-WB02-LGR02, -LGR07, and -LGR09. These increases correspond with increases observed in several CS-WB02 zones, and may be associated with a "flushing" event in which a slug of contaminated groundwater is moving downgradient away from the source zone.

At CS-WB01, the trend has been that TCE concentrations generally exceed PCE for most zones. The zone with the relatively highest concentration is LGR09 (HCSM layer LGR[E]). Lesser concentrations appear to occur within HCSM layer LGR(C) with zones CS-WB04-LGR04, -LGR05, and –LGR06. Of interest is the fact that both the LGR01 and LGR02 zone yield water at this location, whereas these zones are dry at CS-WB03. While it is uncertain, it is postulated that the operation of the AOC-65 SVE system has played a role in drying out those zones with similar completion depths near the source area and CS-WB03. This location is less than 100 ft from the CS-MW8 well cluster. While the CS-MW8-LGR well screen is only separated from the CS-WB01-LGR09 monitoring interval by 32 ft, the dilution of chlorinated organic contamination has diluted nearly twenty-fold within the basal reef structure that is HCSM layer LGR(F).

In similar fashion to the other locations, the UGR01 and LGR02 zones at CS-WB04 tend to be devoid of water. Since September 2003, the UGR zone has only contained groundwater during one monitoring event. In November 2004, 9.51 µg/L of PCE was present in the UGR01 zone.. CS-WB04 sampling results through March 2006 had indicated that the upper zones (LGR01 through LGR04) in HCSM layers LGR(A), LGR(B), and LGR(C) are essentially without contamination. Although, more recent sampling events (September 2006 through October 2007) have resulted with PCE detections less than 0.5 µg/L in each of these zones.

Between intervals LGR06 and LGR08, detections of PCE, TCE, and *cis*-1,2,-DCE components were reported at generally in the range of 1 µg/L to 3 µg/L until March 2006. Beginning September 2006, concentrations of TCE profoundly increased upwards between 11 µg/L and 9 µg/L in the LGR06 and LGR07 zones, respectively.

At CS-WB04, the zone with the greatest contamination (CS-WB04-LGR09) occurs at the base of HCSM layer LGR(E). Nearly equivalent levels of PCE and TCE are found at concentrations that generally range above the MCL between 6 µg/L and 13 µg/L. Below this depth, any solvent contamination in the remainder of the LGR, BS, and CC are at concentrations less than 1.5 µg/L. Since the wellbore has stabilized, only isolated minimal detections of PCE have been reported in the LGR11 zone, and the BS zones have essentially been contaminant-free, except for a single occurrence of *cis*-1,2-DCE (0.25 µg/L). *Cis*-1,2-DCE is consistently reported in interval CC01, otherwise isolated PCE detections below 1.50 µg/L have detected in either CC02 or CC03. As stated previously, it appears that inter-aquifer mixing of contaminants at the RFR-10 ranch supply well is limited to the immediate vicinity of the open borehole as evidenced by the apparent lack of contamination detected in the BS and CC intervals of CS-WB04.

Between the September 2003 and September 2004 monitoring periods, the UGR(E) portion of the Westbay monitoring zones remained without groundwater except for on instance in July 2004 at CS-WB02-UGR01. At that time, 3.45 µg/L PCE and 2.12 µg/L TCE were detected in this portion of the stratigraphy. None of the UGR zones accumulated groundwater during this period, and CS-WB02-UGR01 immediately went dry after the sampling event.

Nearly 9 inches of rain fell at the facility over an 11-day period in November 2004 which was temporarily sufficient to saturate the uppermost UGR01 intervals in all the AOC-65 multi-port wells. For the period that the UGR was water-bearing, samples were collected from the uppermost interval to assess what had not been previously possible. Following that period, 10 samples were extracted from WB03-UGR01 over a 9-month period. However, only limited numbers of samples could be obtained from the other UGR01 zones at the other AOC-65 multi-port locations.

The results of those sampling events are presented in Table 5.5. As shown in the table, the VOC concentrations at CS-WB01 and CS–WB02 are generally consistent the results of lower zones within the aquifer, with results generally less than 10 µg/L for any given constituent. As indicated in the table, at those locations the UGR01 interval would drain between significant rain events such that intermediate samples could not be obtained. One sample was obtained from CS-WB04 at a PCE concentration of 9.51 µg/L. This is significant in the fact that routine samples from underlying intervals LGR01, -02, -03, and -04 have never resulted in any COC detections. The data indicates that the UGR01 interval has served as a perched conduit during periods of intense precipitation. For those open borehole wells with minimal surface casing, this contaminated perched groundwater is not impeded from entering the water supply that otherwise potentially yield uncontaminated LGR and CC groundwater.

Near the source area at CS-WB03, the UGR01 interval remained saturated for over seven months, and samples obtained revealed concentrations up to 19,700 µg/L, 746 µg/L, and 354 µg/L of PCE, TCE, and *cis*-1,2-DCE respectively. Again in October 2007, the CS-WB03-UGR01 was saturated, resulting in the highest AOC-65 detections to date (22,000 µg/L, 450 µg/L, and 7.60 µg/L of PCE, TCE, and *cis*-1,2-DCE respectively. The most recent results eclipse the concentrations previously detected in AOC65-MW2A by more than six-fold. The results indicate that a persistent source still exists, and that period flushing by intense rainfall can mobilize these perched contaminants that are probably otherwise bound to the matrix during the rest of the year.

Table 5.5
Results of Multi-Port Interval Saturation
November 2004 through October 2007

	7/2/04	**11/18/04**	**11/24/04**	**11/30/04 through 12/2/04**	**12/29/04 through 7/26/05 (Max)**	**10/4/07**
CS-WB01-UGR01						
PCE	*Dry*	6.58	*Dry*	1.5	*Dry*	*Dry*
TCE	*Dry*	<0.60	*Dry*	1.4	*Dry*	*Dry*
cis-1,2-DCE	*Dry*	<0.20	*Dry*	<0.20	*Dry*	*Dry*
CS-WB02 UGR01						
PCE	3.45	7.02	*Dry*	9.25	*Dry*	*Dry*
TCE	2.12	2.26	*Dry*	1.4	*Dry*	*Dry*
cis-1,2-DCE	<0.20	<0.20	*Dry*	<0.20	*Dry*	*Dry*
CS-WB03 UGR01						
PCE	*Dry*	13,900	9,170	9,640	19,700	22,000
TCE	*Dry*	215	294	227	746	450
cis-1,2-DCE	*Dry*	5.32	7.49	7.35	354	7.6
CS-WB04 UGR01						
PCE	*Dry*	9.51	*Dry*	*Dry*	*Dry*	*Dry*
TCE	*Dry*	<0.60	*Dry*	*Dry*	*Dry*	*Dry*
cis-1,2-DCE	*Dry*	<0.20	*Dry*	*Dry*	*Dry*	*Dry*

5.4 EXTENT OF INORGANIC CONTAMINATION

As previously discussed in Section 5.1, inorganic concentrations of arsenic, barium, cadmium, chromium, copper, lead, mercury, nickel, and zinc are routinely sampled from on-post wells. Although there have been some metals exceedances above the MCL on-post, they have been sporadic and limited largely to wells located in the interior areas of the post. Table 5.6 summarizes the detections of inorganic compounds above either the MCL or action level (lead). Figure 5.12 illustrates the wells with historical inorganic concentrations above the MCL.

Historically prior to 2007, lead was the only inorganic compound reported in any on-post well above the MCL. The nine wells that contained lead above the action level of 0.015 mg/L are typically the older agricultural or domestic water supply wells that have open borehole completions. Concentrations above the MCL have ranged from 0.015 mg/L (CS-1) to 0.25 mg/L (CS-2). In one instance (CS-2), cadmium was also reported above the MCL in December 1995.

It would seem that the open borehole wells with minimal surface casing are most prone to the lead detections at CSSA. Materials issues associated with well casing, piping, or the pumping apparatus may also play a role in the detection of lead in these wells. The inactive agricultural wells are now used for environmental groundwater monitoring, while most of the production wells (CS-1, CS-9, and CS-10) are still actively utilized.

Table 5.6
Historical Occurrence of Inorganics above the MCL (1995-2007)

Historic Metals Exceedances						
Well ID	**Sample Date**	**Pb (mg/L)**	**Well ID**	**Sample Date**	**Pb (mg/L)**	**Cd (mg/L)**
	MCL	**0.015**		**MCL**	**0.015**	**0.005**
CS-1	11-Dec-95	**0.023**	**CS-2**	12-Dec-95	**0.25**	**0.008**
	19-Jan-96	**0.015**	**CS-3**	12-Dec-95	**0.029**	
	1-Mar-96	**0.015**		27-Feb-96	**0.028**	
	20-Mar-00	**0.0172**		13-Jun-06	**0.018**	
CS-9	13-Dec-07	**0.0362**		13-Sep-06	**0.028**	
CS-10	12-Dec-95	**0.06**		13-Dec-07	**0.0362**	
CS-11	17-Jun-02	**0.0154**	**CS-MWG-LGR**	19-Jan-96	**0.048**	
	13-Dec-07	**0.0359**		28-Feb-96	**0.094**	
CS-I	12-Dec-95	**0.019**		12-Sep-01	**0.0369**	
	19-Jan-96	**0.022**	**CS-MWH-LGR**	12-Dec-96	**0.045**	
	28-Feb-96	**0.018**		12-Jun-01	**0.0459**	
	12-Jun-01	**0.0349**		12-Sep-01	**0.047**	
	12-Sep-01	**0.0193**	**CS-MW2-CC**	25-Sep-07		**0.0073**
	17-Dec-01	**0.0827**	**CS-MW9-BS**	25-Sep-07	**0.1065**	
	13-Mar-02	**0.087**				

New Monitoring Well Exceedances				
Well ID	**Sample Date**	**Pb (mg/L)**	**Cr (mg/L)**	**Hg (mg/L)**
	MCL	**0.015**	**0.1**	**0.002**
CS-MW22-LGR	7-Jun-07	**0.091**		
	1-Oct-07	**0.086**		
	13-Mar-08	**0.04**		
Duplicate	13-Mar-08	**0.038**		
CS-MW23-LGR	5-Jun-07			**0.0078**
CS-MW25-LGR	5-Jun-07	**0.017**		
	1-Oct-07	**0.032**	**0.24**	
	11-Dec-07	**0.023**	**0.22**	

MCL = Maximum Contaminant Level

Note = Lead criteria is an Action Level, not a MCL

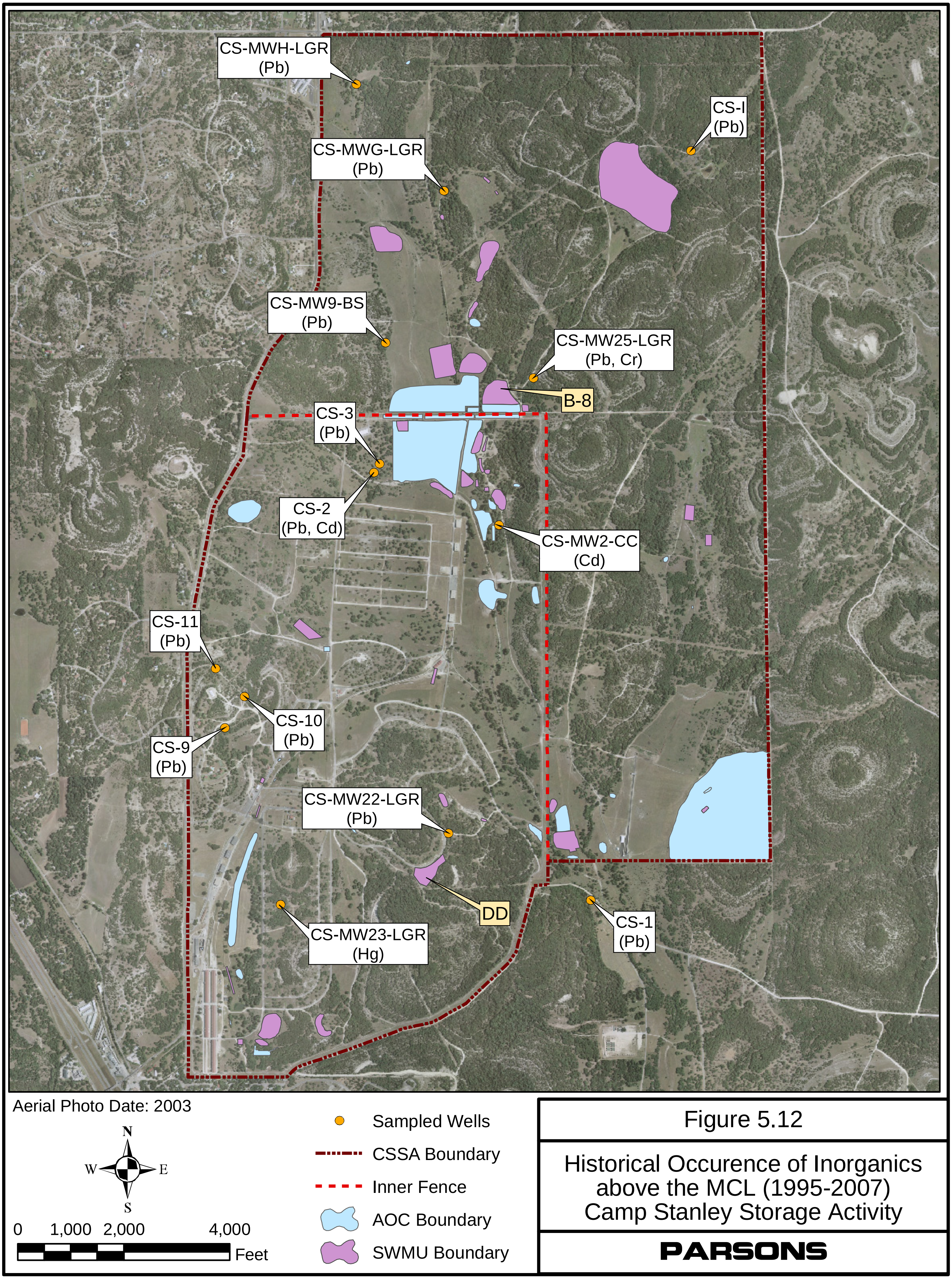


Figure 5.12

Historical Occurence of Inorganics above the MCL (1995-2007)
Camp Stanley Storage Activity

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In 2007, six new LGR wells were drilled at CSSA. Of these, 3 wells have resulted in concentrations above the MCL for lead, chromium, and mercury, or the non-enforceable secondary standards for iron, manganese, and zinc. Lead concentrations have ranged between 0.023 mg/L to 0.091 mg/L in wells CS-MW22-LGR and CS-MW25-LGR. Coincidently, these wells are located near former munitions SWMUs DD and B-8, respectively. Both of these sites have soils impacted by inorganic contamination, including lead.

With the exception of lead, two or less detections of the remaining inorganics listed on Table 5.6 have been reported in on-post wells. The occurrence of chromium and mercury above the MCLs is a new phenomenon that has been reported in new that were installed in 2007. Chromium has been detected above the MCL (0.1 mg/L) at well CS-MW25-LGR, near SWMU B-8. Concentrations have ranged between 0.22 and 0.24 mg/L. One instance of mercury has been reported above the MCL (0.002 mg/L) at CS-MW23-LGR in June 2007 (0.0078 mg/L). Thus far, the detection has been an isolated occurrence and non-repeatable.

Currently metals are not sampled at off-post locations due to the minimal or lack of on-post metals detections exceeding MCLs. With the exception of one location, historical samples obtained for off-post wells between 1995 and 2001 did not yield any metals concentrations above the MCLs. For the one well that exceeded the lead MCL, the 1996 follow-up sample resulted with no lead detection. Additional data from local water utility purveyors demonstrated that no public water wells exceed the MCLs for metals constituents.

5.5 CONTAMINANT FATE AND TRANSPORT CONCEPTS

The fate of a contaminant in the environment is the length of time it is present in an unsafe form. The environmental fate considers whether a contaminant is persistent in environmental media, and into which media a contaminant will partition. Specific properties of the media and the contaminants determine which mechanism will have the dominant effect on the length of time a contaminant remains in the environment. Factors that affect the fate of a contaminant in the environment include mass transport and chemical degradation. These concepts are discussed in the following sections.

5.5.1 Mass Transport

Mass transport is the movement of hazardous constituents within a medium, or from one medium to another. Media that act as migration pathways include soil/rock in the unsaturated zone, groundwater, surface water, or air. Soil and rock properties such as chemistry and organic content, air temperature and pressure, and soil and water quality affect migration of contaminants. The characteristics of the contaminants also affect the potential for contaminant migration.

Primary transport mechanisms that may occur in the CSSA study area are volatilization, dispersion, dissolution, advection, and adsorption. Adsorption refers to the binding of metals or organic compounds to the soil, sediment, or rock. Some compounds adsorb more strongly to the clay fraction of a soil or sediment, while many organic compounds and some metals adsorb more strongly to the organic fraction. In these cases, the higher the organic content in the soil, the less mobile these constituents will be. Sorption is defined as the accumulation of a chemical in the boundary region of the soil-water system. Factors affecting sorption include the physical makeup of the geologic media through which the contaminants are moving. The clay content, the specific surface area, and the cation exchange capacity of the media affect the sorption of a contaminant.

Advection, sorption, dispersion, and diffusion are processes that are more descriptive of contaminant migration in groundwater than soils. As mass transport process, advection contributes to the physical spreading of contaminated groundwater by carrying it with the inherent groundwater flow. The groundwater flow velocity depends on physical characteristics of the medium such as hydraulic conductivity, gradient, and effective porosity. Contaminants undergoing adsorption during advection will move at a rate less than the groundwater velocity. The retardation factor, R, describes the proportion of a contaminant undergoing adsorption during advection. For example, if the retardation factor is 2, the pollutant will move half as fast as the water.

Dispersion is also a mass transport process. Mechanically, dispersion is the spreading out of a contaminant plume caused by differences in water velocities in larger or smaller pores of the soil or rock. Typically, the effects of advection are much greater than the effects of dispersion in most cases. However, if groundwater velocity is very low, dispersion may be the dominant transport mechanism. Finally, diffusion is the molecular movement from areas of high concentration to areas of low concentration within a single medium. Diffusion is the dominant mechanism only when velocity and retardation factors are negligible.

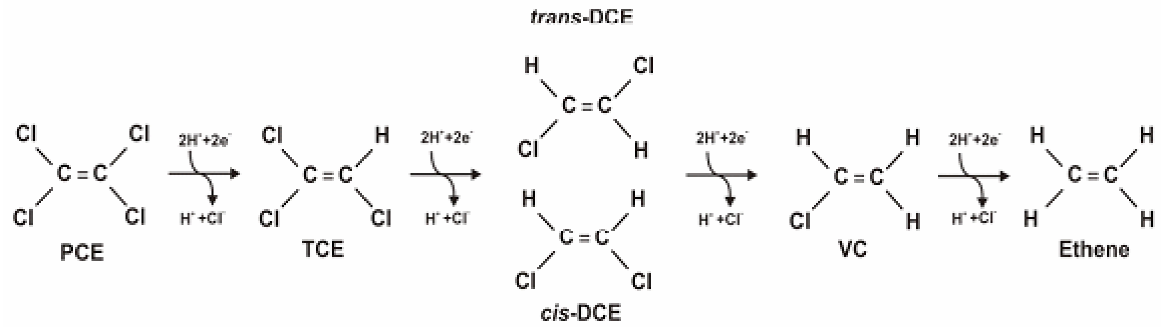
5.5.2 Contaminant Degradation

Degradation is likely to be the primary mechanism affecting the fate of contaminants in the HCSM. Properties of organic compounds that are used to assess degradation include the degradation rate, the solubility, and the toxicity of the compound to bacteria in soil. The fate of metals is controlled by other properties. Metals may be converted into more innocuous forms by complexation and precipitation. Complexation is the mechanism by which metal ions are bound by larger molecules present in the aqueous fraction of the system. Precipitation is the formation of an insoluble metal compound.

PCE was the primary solvent used at CSSA, with some records indicating that TCE may have also been used for a period. Typically, TCE and *cis*-1,2-DCE are natural degradation products of PCE. These compounds result from of dehalogenation (dechlorination) processes that occur in aerobic or anaerobic metabolic environments. The degradation of PCE can lead to the production of seven chlorinated volatile hydrocarbons. The transformation pathway for various chlorinated volatile hydrocarbons in environment is shown in Figure 5.13.

Research has shown that there are several mechanisms, which result in the dehalogenation (e.g., dechlorination) of some classes of organic contaminants. These include stimulation of metabolic sequences through introduction of electron donor and acceptor combinations; addition of nutrients to meet the needs of dehalogenating micro-organisms, possible use of engineered micro-organisms, and use of enzyme systems capable of catalyzing reductive dehalogenation (EPA, 1991).

Figure 5.13 Transformation Pathways for PCE within Environmental Systems



An organic chemical is said to be reduced if it undergoes a net gain of electrons as the result of a chemical reaction (electron acceptor). Conversely, an organic compound is said to be oxidized if it undergoes a net loss of electrons (electron donor). Under aerobic environmental conditions, oxygen commonly acts as the electron acceptor when present. However, when oxygen is not present or has been depleted, microorganisms can use organic chemicals or inorganic anions as alternate electron acceptors under metabolic conditions referred to as fermentative, denitrifying, sulfate-reducing, or methanogenic. Generally, organic compounds present at a contaminated site represent potential electron donors to support microbial metabolism. However, halogenated compounds can act as electron acceptors, and thus become reduced in the reductive dehalogenation process, which is the replacement of a halogen on an organic molecule by a hydrogen atom (EPA, 1991).

The process listed in Figure 5.13 shows PCE converting to TCE via reductive dehalogenation. Likewise, TCE is reductively dehalogenated to either 1,1-DCE, *cis*-1,2-DCE, or *trans*-1,2,-DCE with hydrogen (H_2) and hydrochloric acid (HCl) by-products. In general, reductive dehalogenation of tetra- and tri-halogenated carbon atoms (PCE and TCE, respectively) is easier than di- or monohalogenated molecules, which is why many metabolic reactions appear to stall at the generation of DCE isomers. In the presence of favorable conditions, the DCE isomers can reductively dehalogenate to vinyl chloride, which is then easily converted to ethane via further reductive dehalogenation.

The environmental conditions in the subsurface at CSSA have favored the reductive dehalogenation processes that convert PCE to TCE, then DCE. The generation of *trans*-1,2-DCE is less common, and is specifically limited to wells within the Plume 1 vicinity (CS-16-LGR, CS-D, CS-MW1-LGR, and CS-MW2-LGR). Trace concentrations slightly greater than the laboratory method detection limits (MDL) of vinyl chloride have been reported in as many as nine wells. Many of these occurrences were single detections at a well location, but do indicate that a minor amount of DCE is being reduced to vinyl chloride by dehalogenation. However, for the most part, the degradation process at CSSA appears to stall after the generation of *cis*- and/or *trans*-1,2-DCE. Concentrations of PCE, TCE, and DCE exceed MCLs within the HCSM area.

5.6 CONTAMINANT FATE AND TRANSPORT AT CSSA

This section conceptualizes the fate and transport mechanisms that are active at CSSA, and have ultimately dictated the distribution of contaminants within the Middle Trinity aquifer. The contamination will be addressed by source area and plume to help tie together the observations and measurements that have been collected during the course of the investigations. Figures 5.14 thru 5.17 conceptualizes the horizontal and vertical extent of the PCE plume within the Middle Trinity aquifer based upon the maximum extent of contaminants observed in June 2004. As described in previous sections, the occurrence of VOCs seems primarily limited to the LGR section of the Middle Trinity aquifer, and is reflected as such in the graphics. The occurrence of significant CC contamination is associated with well CS-MW16-CC as a result of the long-term open borehole completion of former CS-16 next to the SWMU B-3 source area. The occurrence of PCE contamination above the MCL of 5 µg/L within Plume 1 is contained within the facility. Plume 2 has migrated off post which has resulted with off-post MCL exceedances at the southwest corner of CSSA.

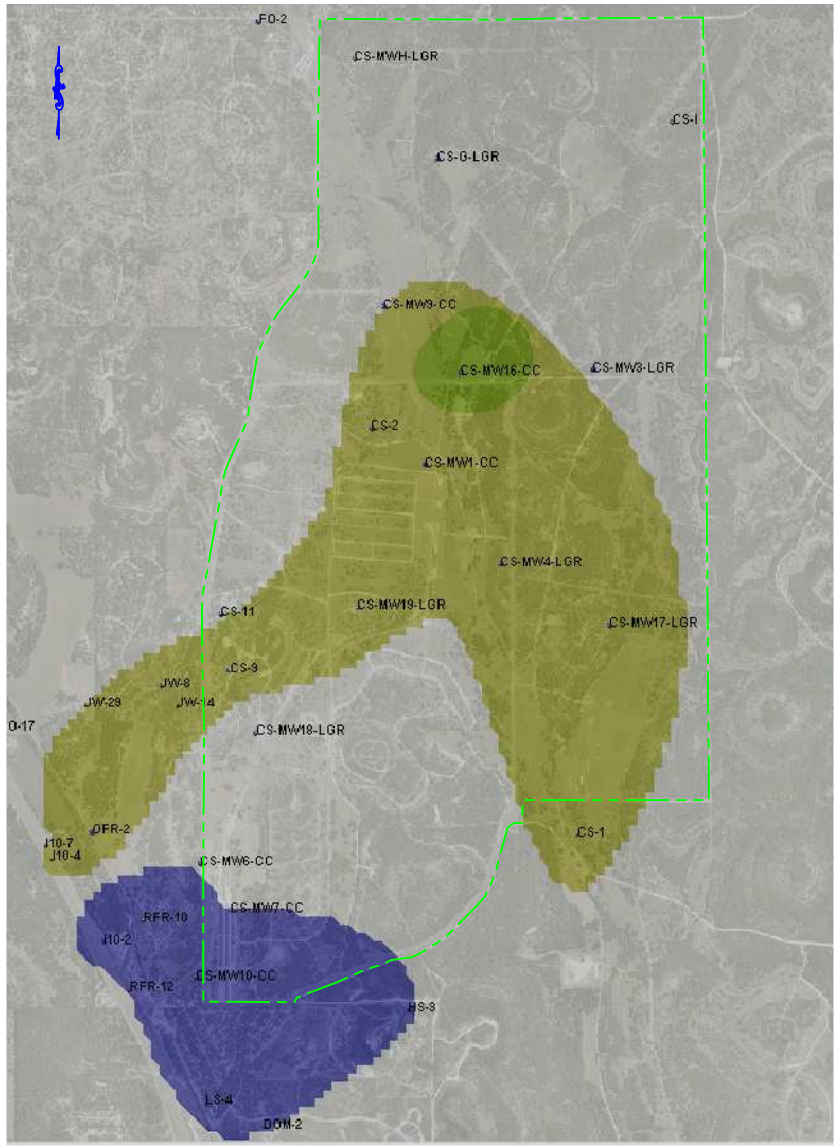
5.6.1 Source Area

Since 1996, extensive investigations have been completed to identify and define the potential source areas responsible for the occurrence of Plume 1 in CSSA groundwater. A series of geophysical surveys, soil-gas surveys, soil characterizations, and source removal investigations has led to the conclusion that SWMUs B-3 and O-1 were responsible for the VOC contaminants detected in well CS-16 and elsewhere since 1991. The actual contaminant source included solvents that were either disposed into an oxidation pond (O-1 or used as an accelerant for refuse burning within landfill cells (B-3). Likewise, beginning in 1999, investigations were completed to identify and define the potential source areas responsible for the occurrence of Plume 2 in CSSA groundwater. The actual contaminant source included solvents that were used and stored in vats within the building, or associated with discharges from a drain line to the nearby drainage ditch.

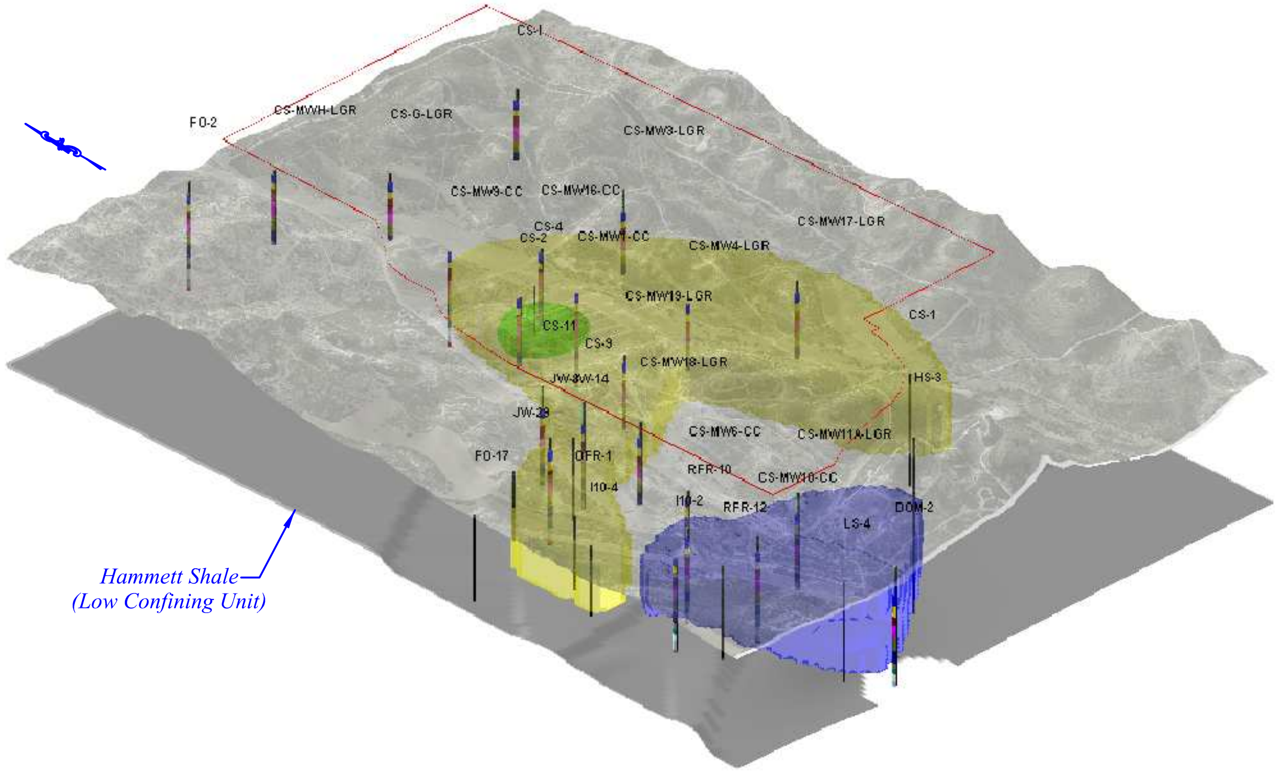
Regardless of the site, once the solvents were introduced to the environment, it was subjected to volatilization, and sorption to organic fractions of the soil and/or rock, or it migrated deeper into the stratigraphic profile by gravity, flushing, or meteoric waters. For the portion of contamination that remained within the source area, that fraction proved to be susceptible to volatilization and degradation. Soil-gas surveys and near-surface sampling has demonstrated that significant quantities of solvents remain within the disposal units, and that the degradation process of PCE is occurring, primarily due to large concentrations of DCE isomers now measured within the subsurface. For these portions of the solvent release, CSSA has implemented source removal via vapor extraction and waste removal by excavation and disposal at both plume source areas. In addition, CSSA constructed a Bioreactor at SWMU B-3 (Plume 1) in 2007 to stimulate biologic processes metabolically degrade the solvent contamination by metabolic processes.

5.6.2 Vadose Zone

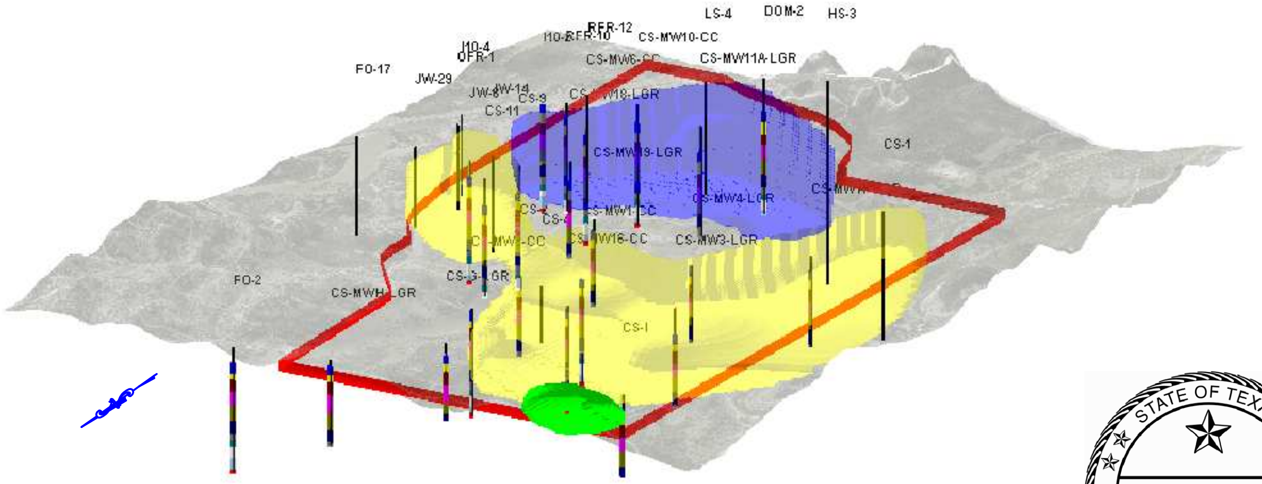
For the fraction of contaminants that mobilized beyond the source area, the solvents may migrate as a dense, non-aqueous phase liquid (DNAPL), and/or it may partition to the groundwater and soil-gas phases of the environment. Of particular interest is the determination if DNAPL still is present in the subsurface, providing a continual source for groundwater contamination. Its presence can be determined by direct observation in soil or groundwater, or



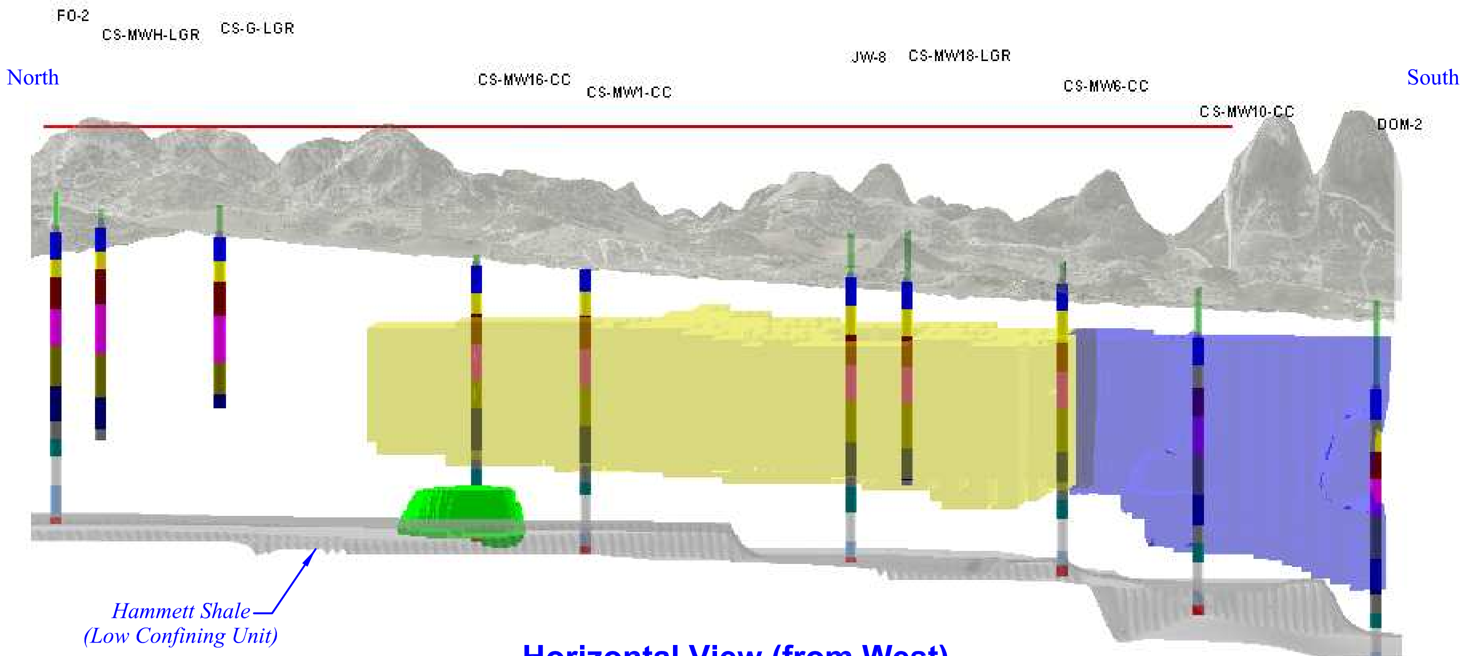
Plan View



Oblique View (above from Southwest)



Oblique View (below from Southwest)



Horizontal View (from West)

Legend

🟩	Plume 1 - CC
🟨	Plume 1 - LGR
🟦	Plume 2 - LGR

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Figure 5.14

Horizontal and Vertical Extent of PCE within the Middle Trinity Aquifer Above 0.05 μg/L

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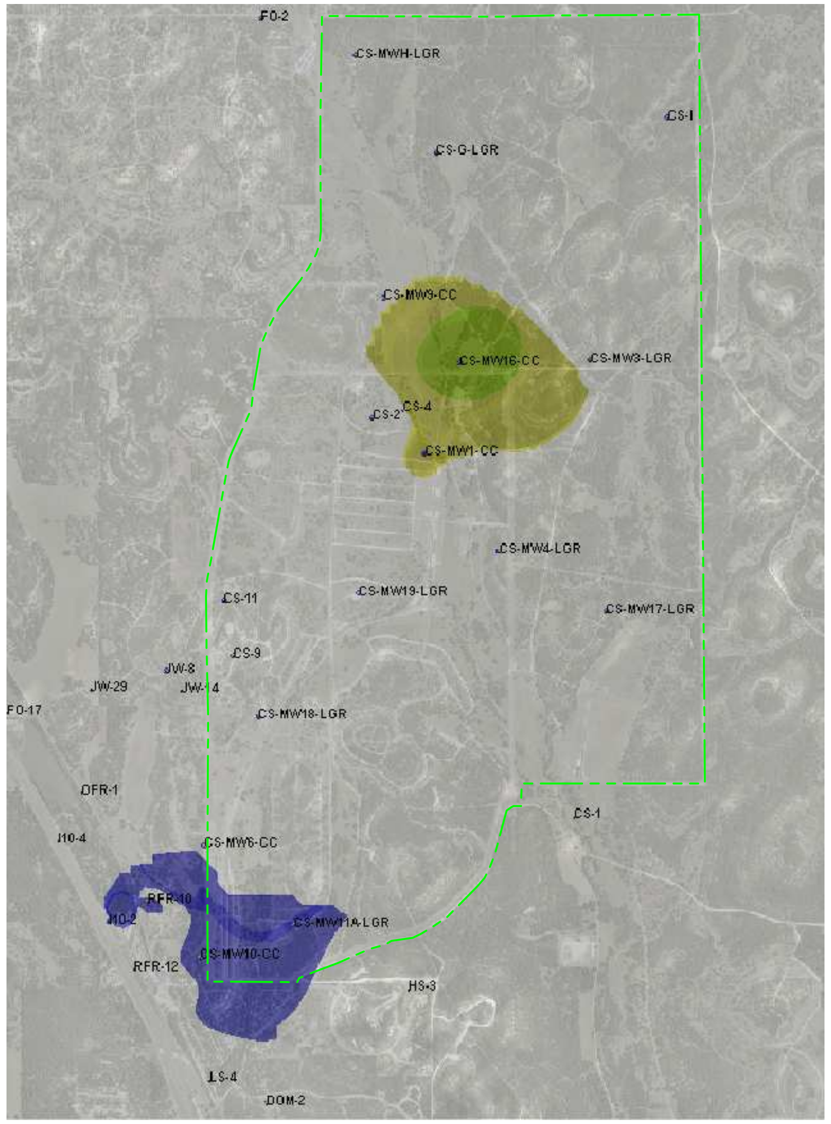
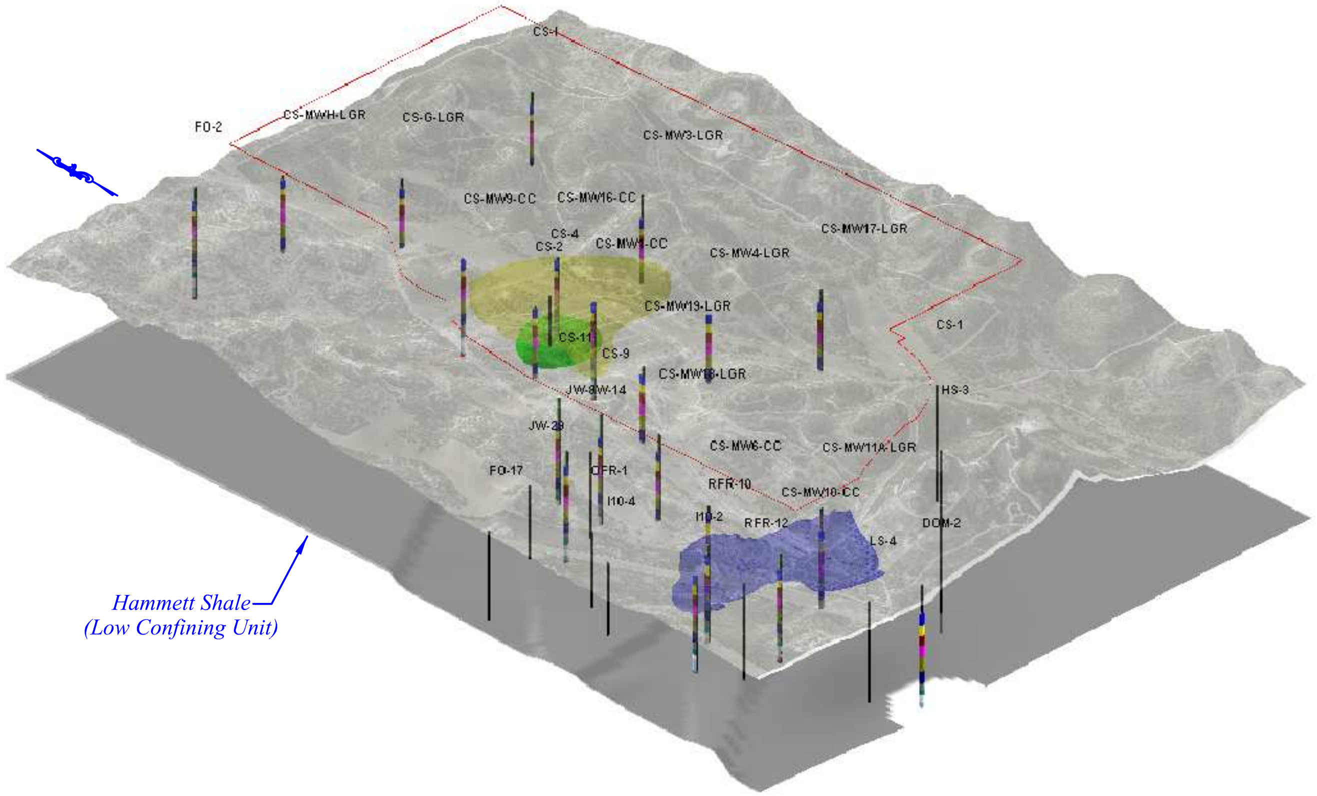
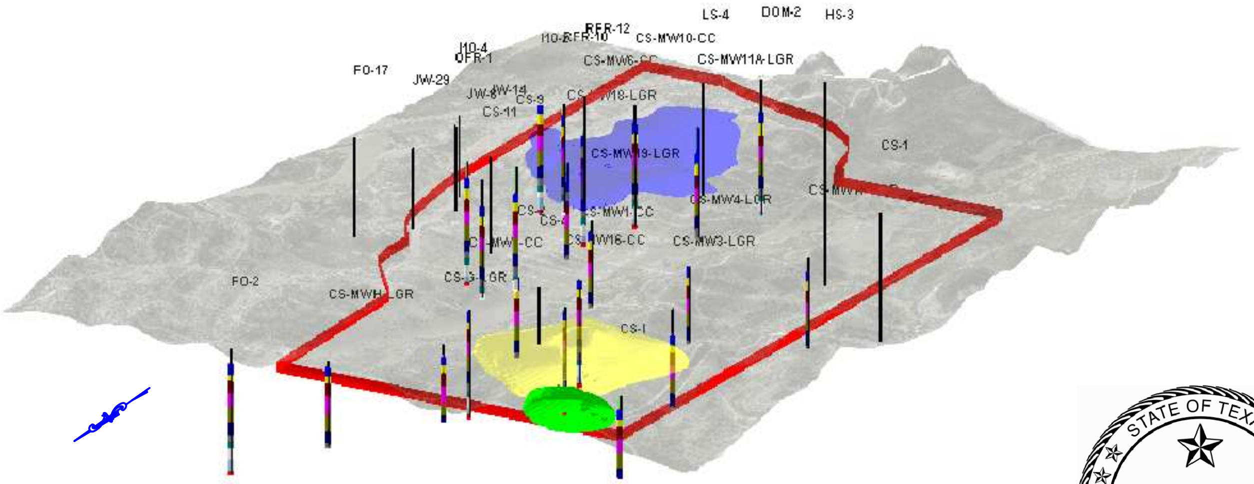


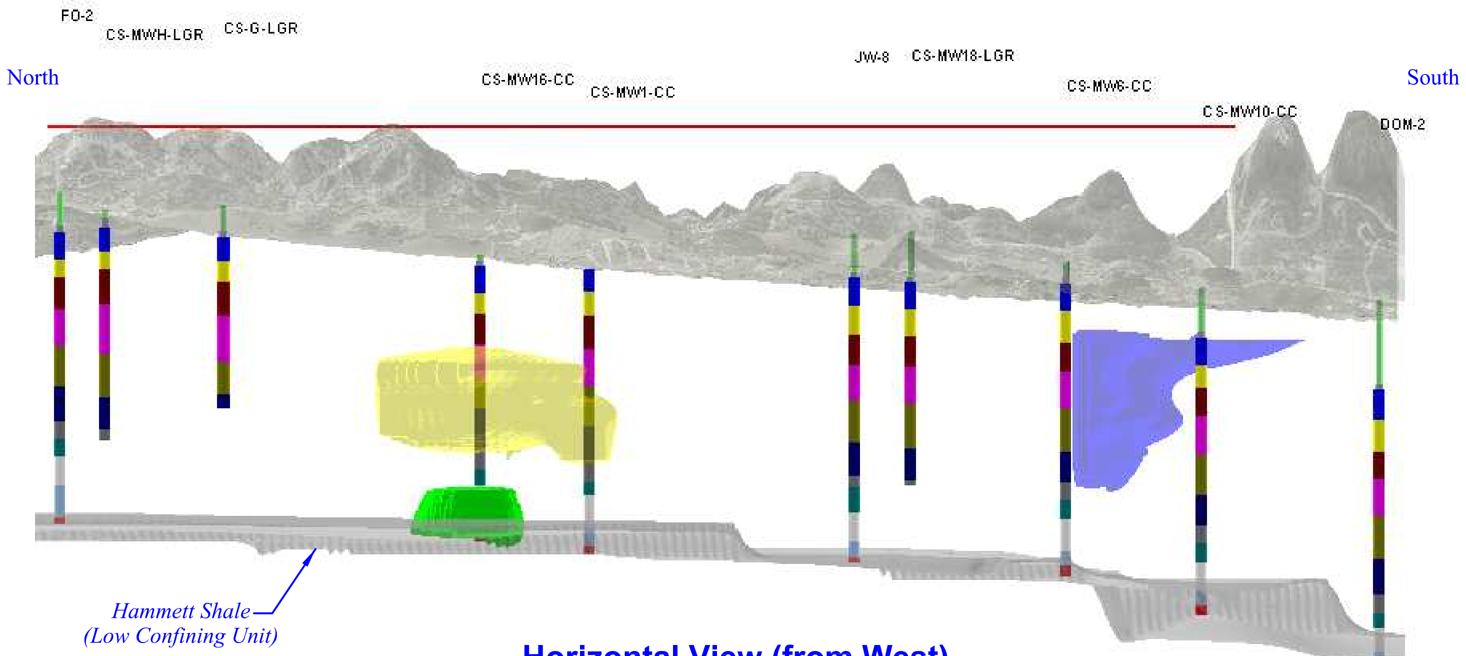
Plan View



Oblique View (above from Southwest)



Oblique View (below from Southwest)



Horizontal View (from West)

Legend

🟩	Plume 1 - CC
🟨	Plume 1 - LGR
🟦	Plume 2 - LGR

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Figure 5.15

Horizontal and Vertical Extent of PCE within the Middle Trinity Aquifer Above 1.0 µg/L

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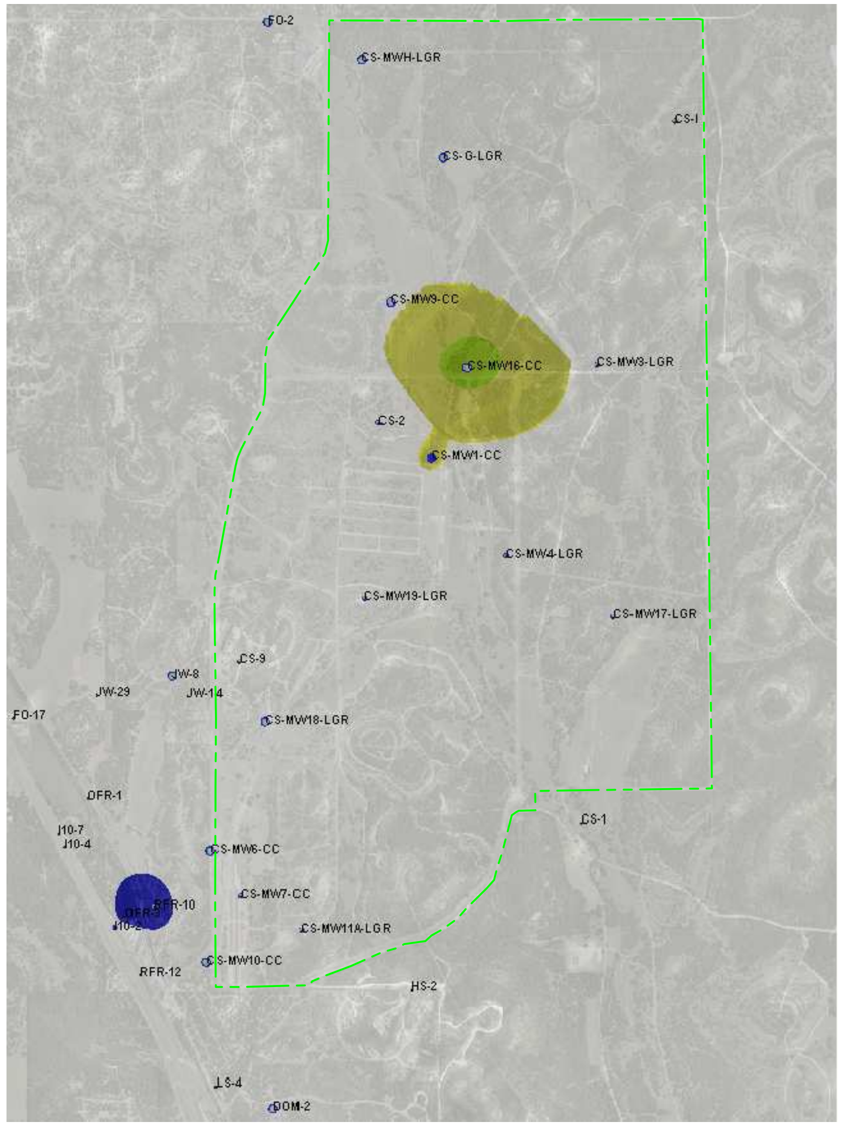
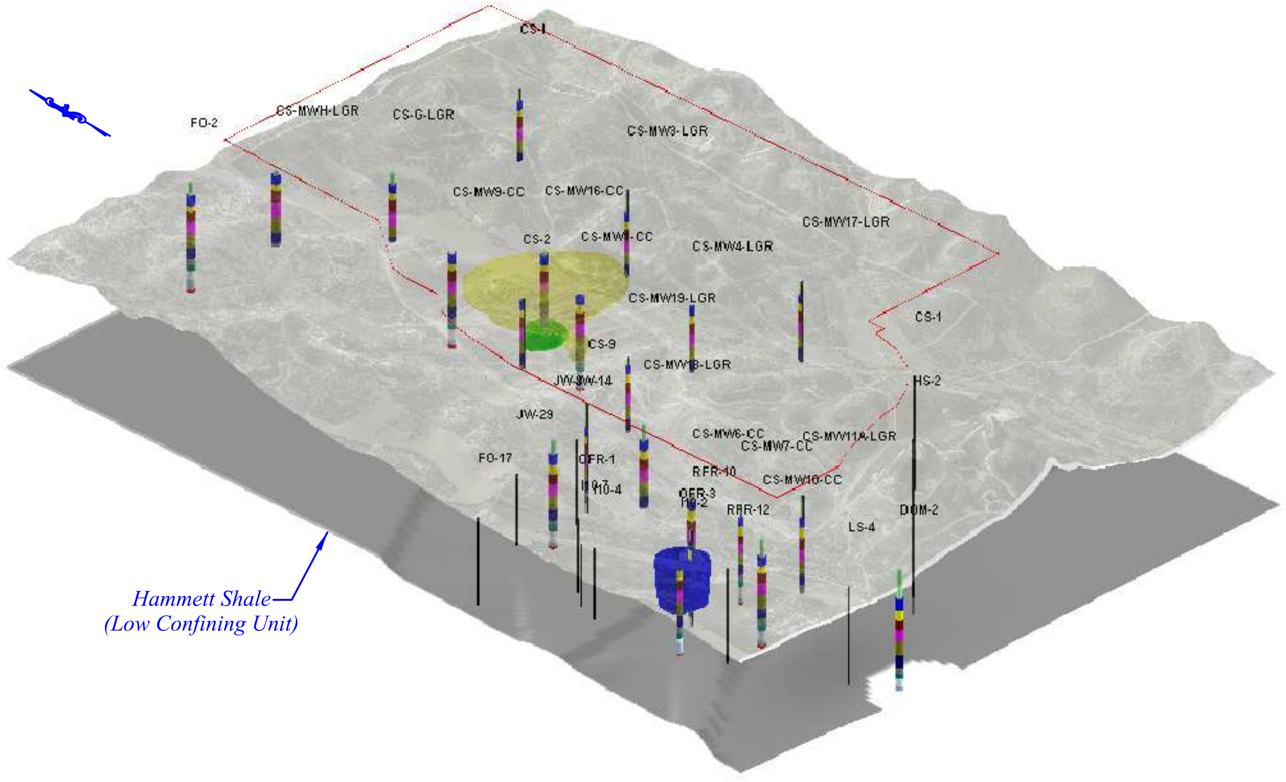
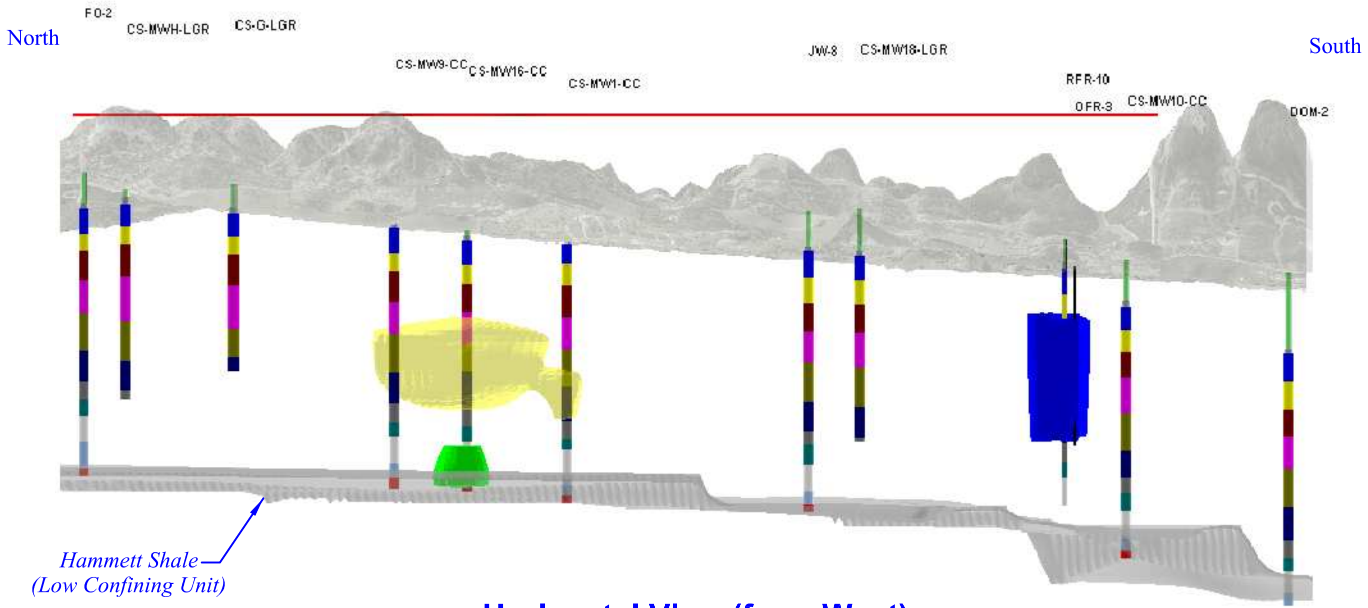
740911 CSSA-HVPCE-B.DWG



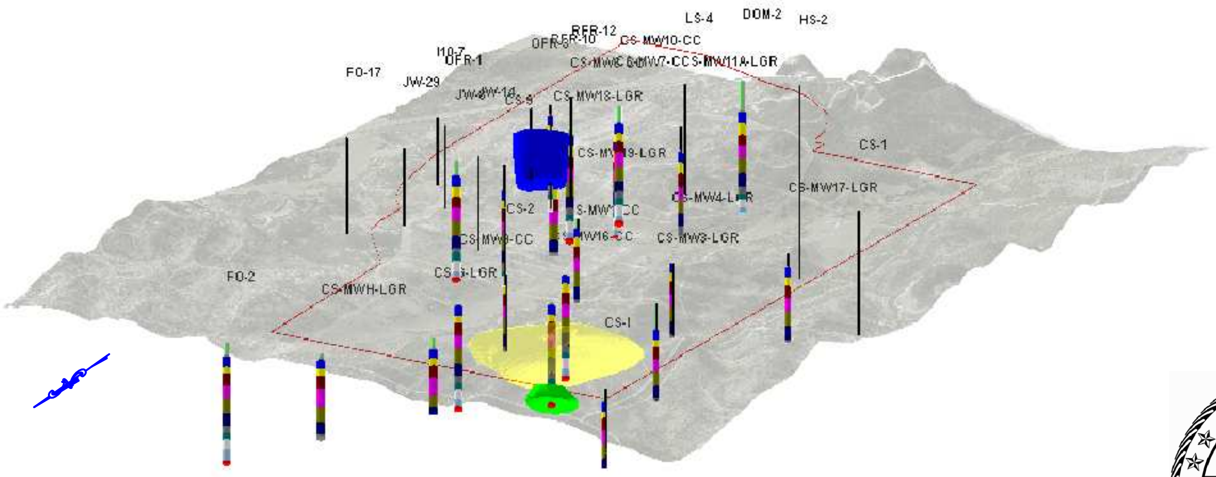
Plan View



Oblique View (above from Southwest)



Horizontal View (from West)



Oblique View (below from Southwest)

Legend

🟩 Plume 1 - CC
🟨 Plume 1 - LGR
🟦 Plume 2 - LGR

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Figure 5.16

Horizontal and Vertical Extent of PCE within the Middle Trinity Aquifier Above MCL (5.0 μg/L)

Camp Stanley Storage Activity, Texas

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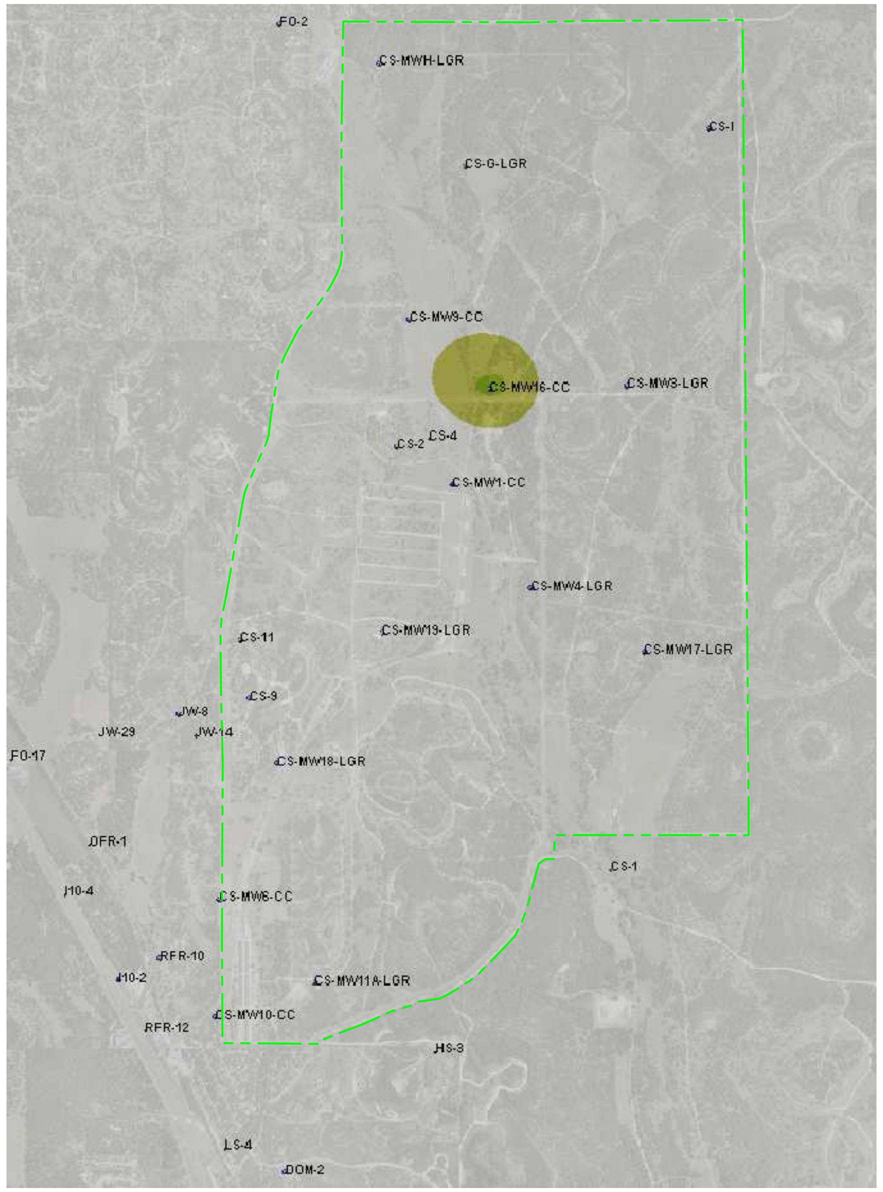
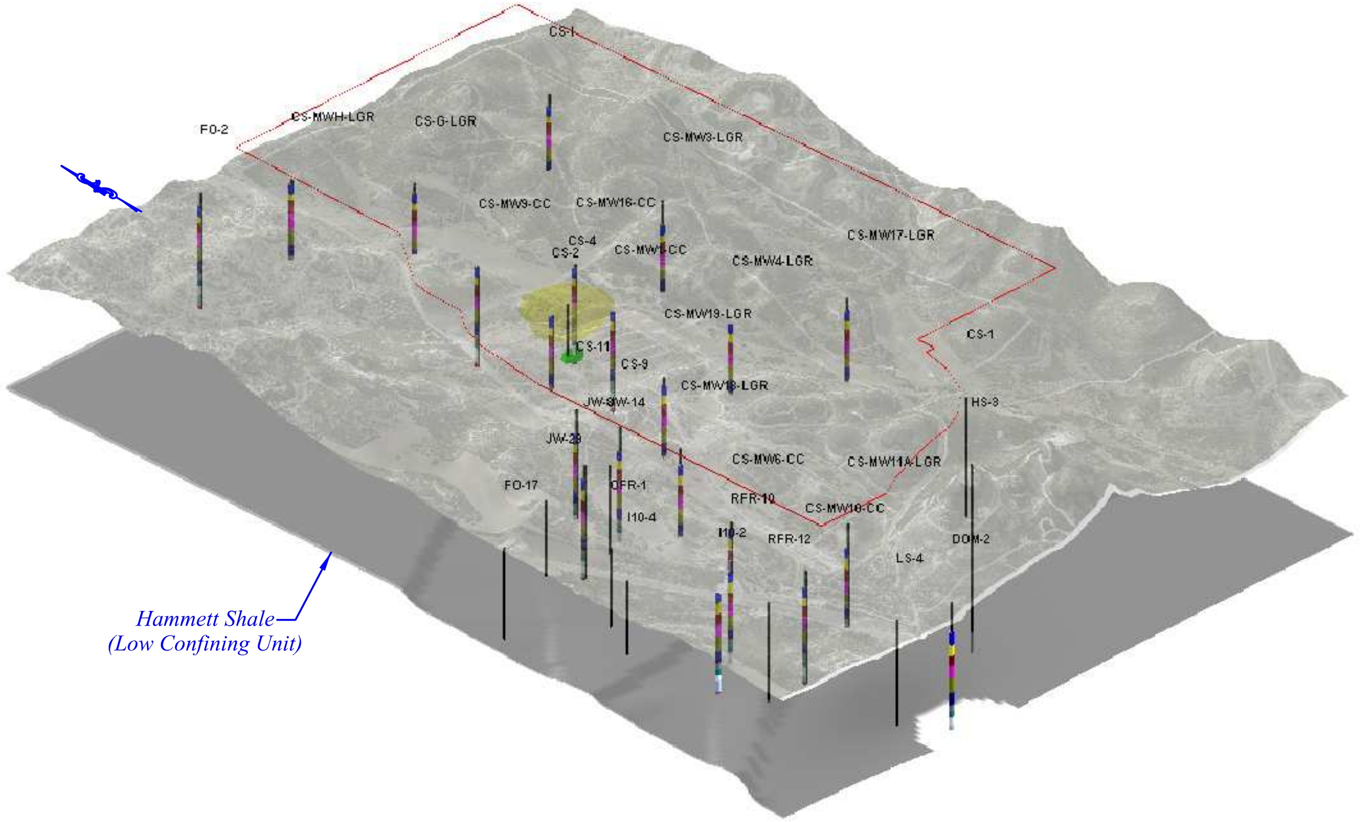
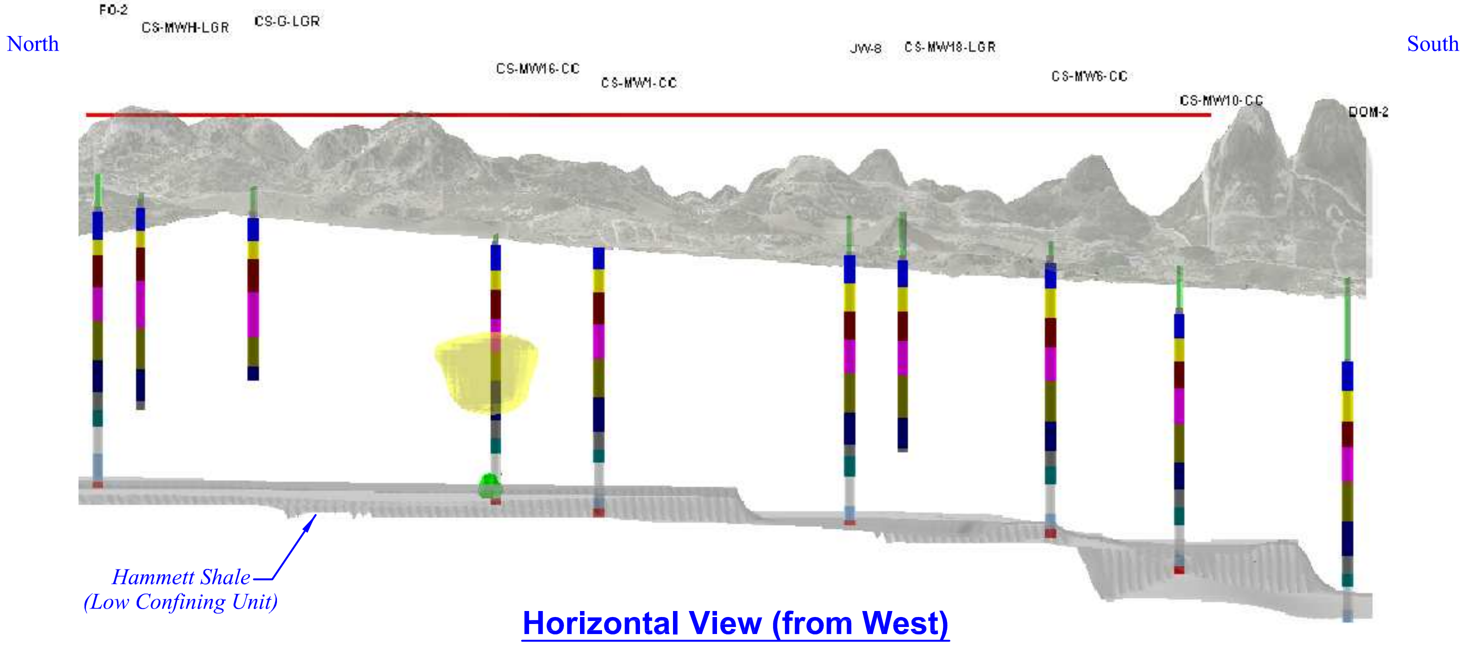
740911 CSSA-HVPCE-C.DWG



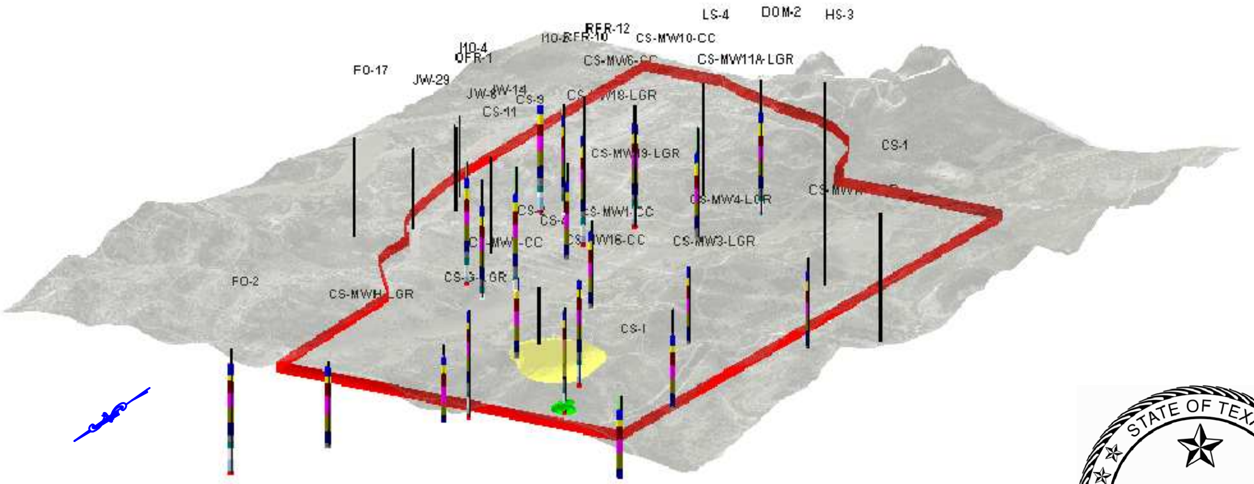
Plan View



Oblique View (above from Southwest)



Horizontal View (from West)



Oblique View (below from Southwest)

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Legend

🟩	Plume 1 - CC
🟨	Plume 1 - LGR
🟪	Plume 2 - LGR

Figure 5.17

Horizontal and Vertical Extent of PCE within the Middle Trinity Aquifier Above 25.0 µg/L

Camp Stanley Storage Activity, Texas

PARSONS

740911 CSSA-HVPCE-D.DWG

by inference based upon contaminant concentration within an affected media. Current guidelines suggest that DNAPL may be present when contaminant concentrations are found in excess of one percent of their solubility in water.

For PCE, TCE, and *cis*-1,2-DCE, a one percent concentration of their solubility in water corresponds to 1,500 µg/L, 11,000 µg/L, 35,000 µg/L, respectively. Thus far, only PCE has been consistently encountered in the vadose zone above the one percent solubility guideline. At AOC-65, concentrations up to 22,000 µg/L have been reported at CS-WB03-UGR01. Likewise, PCE concentrations above 1,500 µg/L have also been reported in SWMU B-3 vadose monitoring zones which occasionally yield groundwater after prolific precipitation events. The occurrence of contamination in groundwater above this one percent threshold are indicators that DNAPLs do persist in the near-surface soils/rock, and that continual flushing of DNAPL is occurring from the contaminant source areas.

Because DNAPLs have a specific gravity greater than water, they are able to penetrate through and below perched groundwater bodies and fractured strata that may otherwise be relatively impervious to groundwater. Within the vadose zone, a DNAPL will migrate downward, while succumbing to the mechanisms of dispersion and diffusion. Within fractured bedrock, these processes can be complicated by the erratic network or fractures and karstic features that act as preferred migration pathways. The chaotic nature of fracture and karst patterns are not well understood, but are expected to be the primary mechanism that allowed contaminants to seemingly migrate upgradient to CS-16 where it was detected in 1991. The long-term pumping of CS-16 as a supply well likely provided enough capture gradient to assist the northward migration of contaminants.

Along these pathways, DNAPLs can pool, where they may either enter the actual matrix of the rock, or be flushed by infiltrating water. The flushing effect is crucial for the solvent contamination to reach the main body of the aquifer. During precipitation events, infiltrating groundwater picks up and pushes the solvent advectively in the path of least resistance downward. In the instance of B-3, the disturbed nature of the overlying source area can exacerbate the recharge effect because of higher porosity backfill can accumulate and transmit greater quantities of groundwater downward than what may be expected within the natural stratigraphic horizon. For this reason, CSSA placed an impermeable cap on O-1 prior to closure in an effort to reduce, if not eliminate those recharge pathways.

5.6.3 Phreatic Zone

Dispersion of the solvent occurs as it migrates downward through faults, fractures, and karstic voids. The depth that groundwater occurs can fluctuate drastically with seasonal rainfall. For this report, the main body of the LGR aquifer is considered to be the basal 60 ft of the unit. However, groundwater does occur as much as 200 ft above the main body of the aquifer. Water-bearing strata and structure perched above the basal aquifer tends to be low-yielding, and its presence directly correlates to the recent environmental conditions.

Discrete interval groundwater sampling around AOC-65 indicates that the higher concentrations of solvent contamination are often associated with the lower yielding units that are stratigraphically higher than the main aquifer body. While the contamination dilutes and attenuates in the basal unit around AOC-65, this is clearly not the case within Plume 1. Wells CS-16-LGR, CS-MW1-LGR, CS-MW2-LGR, and CS-MW5-LGR have demonstrated that groundwater contamination in excess of the MCLs exists within the main body of the aquifer. This would indicate that the source of contamination was either large enough to allow DNAPL to penetrate deep to this depth, or sufficient time has elapsed to carry the bulk of contamination downward into the LGR. However, concentrations within the Middle Trinity Aquifer do not indicate that DNAPL is present in the main body of the aquifer.

5.6.4 Plume 1 Groundwater

While the concentrations detected in groundwater do not strongly suggest that DNAPL is present within the aquifer (less than 1 percent of the solvent solubility), significant residual contamination must persist near the source area. Slugs of contaminated percolating recharge continue to diffuse into the main body of the aquifer, where it is advectively transported in down gradient vectors. Along the main gradient path, sampling results indicate that a dilution/attenuation factor of roughly 10 is occurring over the 2,300-foot distance between the plume center (CS-D at 180 µg/L) and southward (CS-MW1-LGR at 17 µg/L). With the exception of the interior of plume centered around CS-D, CS-MS16-LGR, CS-MW1-LGR, and CS-MW2-LGR most of the remaining detections are below MCLs.

Advectively transported groundwater plumes in granular media tend to be long and narrow, which does not describe the PCE plume shown in Appendix C. Dispersion of the contaminants is occurring within Plume 1 by multiple paths of advection, likely due to structural features within the rock. Flow through these structural features, such as karst or fractures, may be controlling factors during abnormally high and low precipitation cycles, and may account for the multiple directions of plume migration. Notable is the SW migration of Plume 1 from the source area. It is hypothesized that the continual long-term pumping of the CSSA well field (CS-9, CS-10, and CS-11) and residential wells in Jackson Woods subdivision have resulted in migration of a portion of the plume southwestward along the fractures associated with faulting. The collective pumping of the communities and residences west of Ralph Fair Road has likely facilitated the migration of the contaminant plume along preferential pathways.

The geometry of the plume is also probably a function of the types of well construction used in the area. Most of the CSSA monitoring wells are constructed to monitor relatively short segments of the aquifer. The design is appropriate in reducing the possibility of further cross-contamination between strata, but also limits the amount of detections that may be measured at a location. This point has been well demonstrated at CS-MW8 where significant contamination was encountered in the upper 300 ft of strata, yet the final 25 ft monitoring point within the main aquifer body is essentially free of contamination. Given that most off-post wells are open borehole completions with minimal surface casing, these wells are more susceptible to detections of contaminants that occur within upper strata of the Glen Rose.

The presence of open borehole completions is also suspected to result in the minimal contamination of the underlying BS and CC. Within an open borehole, the predominant downward vertical component of flow allows for the co-mingling and loss of LGR groundwater into the CC Limestone. Conceptually, this draining effect through fully penetrating small diameter boreholes is minimal given the large area of the HCSM.

The natural attenuation of the PCE and TCE solvents appears to be occurring within the aquifer. The presence of *cis*-1,2-DCE within the Middle Trinity aquifer is attributable to the reductive dehalogenation of PCE and TCE. Those fractions of the plumes appear to coincide with the location of Salado Creek. As a recharge feature with potentially increased porosity, Salado Creek may facilitate the favorable conditions required for the metabolic reduction of the solvents. To date, only very few instances of vinyl chloride have been detected in groundwater samples, indicating that the natural attenuation of PCE is stalling at *cis*-1,2-DCE. This can occur within a plume as the available electron donors are consumed during the biodegradation process.

5.6.5 Plume 2 Groundwater

Plume 2 appears to quite smaller than Plume 1. Drilling at the AOC-65 source area has shown that significant impact to the upper strata of the LGR has occurred. The results of discrete interval groundwater sampling from those locations are shown in Figures 5.4, 5.5, 5.8, 5.9, 5.10, and 5.11 clearly depict how contaminant concentrations attenuate with depth. The multi-port data seem to indicate that on post near AOC-65, the contamination for the most part equally distributed throughout layers LGR(A) through LGR(D). Recent multi-port evidence (Table 5.5) has demonstrated that significant residual contamination appears to be flushed from the UGR matrix during the heaviest of precipitation events. Likewise, the downgradient multi-port well (CS-WB04) seems to indicate that contaminants are preferentially transported in layers UGR(F) and LGR(D). The premise that contaminants are attenuated within the main body of the aquifer (LGR[F] and CC[A]) is supported by the results of CS-WB04.

A series of investigations which included seismic, direct current resistivity, AEMs, and ground truthing by drilling has indicated that a series of stepwise normal faults occur within the Plume 2 vicinity. Given the location of the source area at Building 90, the contaminant plume has spread in all directions southward of the source area. Within the LGR unit, the center of the plume has appeared to have moved westward towards RFR-10. Normally, the drift of plume center indicates that the source area has diminished and the plume is migrating by advection. However, the attributes of Plume 2 are potentially skewed by the co-mapping of cased and un-cased wells. Conceptually, the greatest concentration of plume still resides within CSSA (near AOC-65-MW2A and CS-WB03), and the bulk of the plume resides in upper unscreened strata of the LGR.

Several faults inferred by the USGS (Figure 5.1) are located in the same area as Plume 2, and the distribution of contaminants is suspected to be related these fault locations. Wells with more elevated concentrations (RFR-10, RFR-11, LS-6, and LS-7) are positioned very close to the known faults. The orientation of the faults line up favorably between the Building 90 source area and wells with known contamination above the MCLs. The measured concentrations of contaminants within Leon Springs Villa and Hidden Springs probably resulted from the advective forces associated with the overall regional gradient towards the south and enhanced by groundwater pumping for potable water systems. Contaminated groundwater, which has migrated southward across fault planes, is notably lower in overall concentrations, and are diluting as they are dispersed.

As with Plume 1, the shape of the plume is also probably a function of the types of well construction used in the area. Most of the CSSA monitoring wells are constructed in such a fashion to observe relatively short segments of the aquifer. The design is appropriate in reducing the possibility of further cross-contamination between strata, but also limits the amount of detections that may be measured at a location. Given that most off-post wells are open borehole completions with minimal surface casing, these wells are more susceptible to detections of contaminants that occur within upper strata of the Glen Rose.

The presence of open borehole completions is also suspected to result in the minimal contamination of the underlying BS and CC in the vicinity of Plume 2. Within an open borehole, the predominant downward vertical component of flow allows for the co-mingling and loss of LGR groundwater into the CC limestone. Conceptually, this draining effect is minimal given the large area of the HCSM. The results from RFR-10 (Table 5.3) lend credence to this hypothesis. Those results also indicate that the upper strata of a minimally-cased well is the most contaminated, and co-mingling of these waters within the well bore result in groundwater exceeding MCLs. CSSA has demonstrated that wells with adequate casing are far less susceptible to producing contaminated water that resides in the upper strata of the LGR.

Natural attenuation processes presumably are in effect given the presence of TCE and *cis*-1,2-DCE within Plume 2. Data indicates that dehalogenation is occurring within the interior of the plume where favorable anaerobic conditions are present. As with Plume 1, there seems to be insufficient electron donors to continue the degradation beyond *cis*-1,2-DCE. As would be expected, the relative contaminant concentrations in groundwater are inversely proportional to distance from the source area.

Table 5.7 lists the average concentration of PCE and TCE within the multi-port monitoring zones at Plume 2. The data reflects the dates between January 2004 and October 2007, and represent data collected after the timeframe at which natural groundwater conditions had been restored following installation activities. As seen in Table 5.7, relative contaminant concentration decreases away from the source area (near CS-WB03) towards the south (CS-WB01) and southwest (CS-WB04). The table also indicates that the degradation of PCE to TCE is occurring as the plume migrates downgradient. In monitoring zones were both PCE and TCE are present, the average ratio of PCE to TCE decreases from 9.13 at the source area (CS-WB03) to 0.89 at the furthest downgradient position (CS-WB04). These relationships indicate that within 500 feet, the contaminant plume has degraded such that TCE has become the major constituent within select intervals.

Other generalized conclusions based on the ratio analysis in Table 5.7 is that PCE is the predominant component of contamination in the upper zones (UGR[E], LGR[A], and LGR[B]), whereas TCE becomes the primary constituent in the lower portion of the aquifer (LGR[C] through LGR[F]). The data suggests that less biodegradation is happening in the upper strata that is only periodically saturated, and the solvent contamination persists in its original chemical form of PCE. It would also appear that undegraded PCE can travel some distance from the source area to CS-WB04 (>1,200 feet) with minor degradation in the uppermost intervals. This may suggest that the PCE is highly mobile during flood (flushing) events through preferential pathways, covering large distances quickly before degradation mechanisms can occur. However, this premise is based upon a single occurrence of PCE (9.51 µg/L) in CS-WB04-UGR after extreme precipitation events in November 2004.

Table 5.7
Ratio of PCE and TCE in AOC-65 Multi-port Zones
January 2004 through October 2007

HCSM Model Layer	Approx. Distance from Source Area		CS-WB03 *90 feet*			CS-WB02 *350 feet*			CS-WB01 *575 feet*			CS-WB04 *1200 feet*		
	Multi-port Zone	Contaminant	*Avg. Conc. Jan-04 to Oct-07*	*Number or occurrences*	*Ratio PCE:TCE*	*Avg. Conc. Jan-04 to Oct-07*	*Number or occurrences*	*Ratio PCE:TCE*	*Avg. Conc. Jan-04 to Oct-07*	*Number or occurrences*	*Ratio PCE:TCE*	*Avg. Conc.*[1] *Jan-04 to Oct-07*	*Number or occurrences*	*Ratio PCE:TCE*
UGR(E)	**UGR01**	**PCE**	13710.91	11	31.76	6.57	3	3.41	4.04	2	3.85	9.51	1	15.85
		TCE	431.73			1.93			1.05			**0.60**		
LGR(A)	**LGR01**	**PCE**	353.50	6	40.43	6.80	22	1.97	4.35	19	6.66	0.32	6	2.67
		TCE	8.74			3.44			0.65			**0.12**		
LGR(B)	**LGR02**	**PCE**	295.14	7	34.49	6.26	13	2.91	5.32	19	2.14	0.30	1	1.88
		TCE	8.56			2.15			2.48			**0.16**		
	LGR03	**PCE**	22.32	23	1.82	4.78	23	1.58	2.08	19	0.38	0.20	1	2.00
		TCE	12.29			3.03			5.48			**0.10**		
LGR(C)	**LGR04**	**PCE**	21.43	23	4.56	2.02	23	0.34	0.56	5	1.03	0.17	1	1.70
		TCE	4.71			5.96			0.54			**0.10**		
	LGR05	**PCE**	19.93	23	7.41	0.71	23	0.41	0.29	13	0.32			-
		TCE	2.69			1.74			0.90					
LGR(D)	**LGR06**	**PCE**	27.63	23	6.51	1.64	23	0.78	0.40	16	0.30	0.55	23	0.23
		TCE	4.25			2.11			1.32			2.42		
	LGR07	**PCE**	27.88	23	2.94	2.37	23	1.36	8.06	19	0.96	0.95	22	0.45
		TCE	9.49			1.74			8.38			2.11		
LGR(E)	**LGR08**	**PCE**	27.35	23	11.07	2.85	23	1.24	1.10	19	0.66	0.46	17	0.55
		TCE	2.47			2.30			1.66			0.84		
	LGR09	**PCE**	20.74	23	2.95	6.85	21	0.84	9.98	19	0.50	8.82	23	0.97
		TCE	7.04			8.19			19.95			9.12		
LGR(F)	**LGR10**	**PCE**										0.61	17	0.60
		TCE										1.02		
	LGR11	**PCE**										1.10	1	11.00
		TCE										**0.10**		
Formation Average (Weighted)[2]:					**9.13**			**1.22**			**1.58**			**0.89**

BS(A)	**BS01**	**PCE**										-	0	-
		TCE										-		
BS(B)	**BS02**	**PCE**										-	0	-
		TCE										-		
Formation Average (Weighted)[2]:														**-**

CC(A)	**CC01**	**PCE**										**0.15**	2	0.38
		TCE										0.40		
	CC02	**PCE**										0.63	1	1.05
		TCE										**0.60**		
CC(B)	**CC03**	**PCE**										1.45	2	2.42
		TCE										**0.60**		
Formation Average (Weighted)[2]:														**1.33**

[1] Bolded analyte concentrations at CS-WB04 were technically not reported above the Method Detection Limit (MDL). For the purposes of this ratio analysis, the particular compound was asssumed to be at a concentration equivilent to the MDL so that a PCE:TCE ratio could be calculated. This assumption will bias the actual PCE:TCE ratio somewhat low for a particular interval. In fact, the compound may not be present within the interval. This process was not required at the other multi-port locations.

[2] The PCE:TCE ratio by Formation is weighted by a percentage occurrence per interval so that a single detection with an abnormal ratio cannot adversely skew the formation average.

SECTION 6
SUMMARY AND CONCLUSIONS

6.1 SUMMARY AND CONCLUSIONS

CSSA is located in northwestern Bexar County approximately 19 miles NW of downtown San Antonio. At one time located in a rural setting, sprawling development of the San Antonio metroplex has encroached upon the facility, placing it adjacent to residential and commercial properties. The CSSA mission, receipt, storage and issuance of ordnance, materiels, as well as, quality assurance testing and maintenance of military weapons and ammunition, is associated with the maintenance of ordnance materiel, the use of industrial solvents as a degreasing agent was implemented from the 1950's through 1990. Citrus-based solvents have now replaced chlorinated solvents. As a result of past operations, releases of PCE to the environment have occurred from multiple source areas within CSSA.

The release of contamination to the environment occurred at several locations, including leaks, spills, and discharges from Building 90 (AOC-65) were degreasing operations occurred, and at landfill/surface impoundments (SWMUs B-3 and O-1) where solvents were discharged. SWMU O-1 was a lined oxidation pond that received waste fluids from the Building 90 operations. Nearby at B-3, spent solvents would be utilized as an accelerant for burning refuse within landfill cells.

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. The Middle Trinity aquifer is composed of calcareous mudstones and limestones of the LGR Limestone, BS, and CC Limestone. Locally, the BS serves as a confining unit between the water-bearing LGR and CC limestones. The site is located within the BFZ, which structurally influences and re-directs the groundwater flow paths.

The detection of solvent contamination (PCE and daughter products TCE and *cis*-1,2-DCE) was first reported by the TDH in 1991. Beginning in 1992, CSSA undertook a series of investigations to identify potential source areas for the groundwater contamination, which identified B-3 and O-1 as likely candidates. Starting in 1996, the first of 56 monitoring wells were installed. Well installation has continued through September 2003. Off-post contamination was first reported by CSSA in 1999 at private well LS-7. Since that time, solvent contamination has been detected in 30 off-post private and public water supplies. The U.S. Army has installed point-of-use treatment systems at six off-post well locations where concentrations exceed 80 percent of the federal MCL (5 µg/L) for PCE and TCE.

For the HCSM, horizontal and vertical boundaries were established to define the model area. Horizontal boundaries were based upon the watersheds units that bound the contamination area between Cibolo, Leon, and Salado Creeks. The vertical limits of the model include the lower portion of the UGR Limestone (Upper Trinity aquifer) and all of the Middle Trinity aquifer, which is bounded below by the Hammett Shale. The strata of the model area were divided into five layers based upon lithologic formation, and then further divided into 13 subunits based upon hydraulic and stratigraphic character. Of the subunits, two intervals stand out as groundwater producers: the basal 60 ft of the LGR (LGR[F]) and the upper 30 ft of the CC (CC[A]). While other portions of the stratigraphic profile contain groundwater, their yield is low, except locally where structural or karstic features prevail.

Most water production wells are completed as open boreholes to maximize groundwater yield, and they include varying lengths of surface casing to facilitate borehole stability or isolate less desirable groundwater strata. Observation wells at CSSA consist of cased and screened wells that discretely monitor 25-foot segments of the LGR, BS, or CC Limestone. Often, these wells are arranged in clusters at a single location. By monitoring the individual members of the aquifer, an assessment regarding the occurrence and distribution of contaminants within the Middle Trinity aquifer can be ascertained.

Information regarding the subsurface was compiled from borehole data, geophysics, and surface mapping to create a conceptual stratigraphic model. Data indicates that the LGR is typically an average thickness of 320 ft, and is overlain by a thin layer UGR normally 50 ft in thickness, but the thickness depends on the local topography. However, the UGR comprises nearly 90 percent of the surface outcrop, while exposures of the LGR only typically occur in the lowlands and creek beds. The underlying BS is normally 60 ft in thickness, and, the facies does not outcrop anywhere in the Hill Country. The underlying CC unit is typically 75 ft in thickness, and is known only to outcrop along the Guadalupe River to the NE. Drilling operations typically only penetrated the upper 15 ft of the Hammett Shale for logging purposes only, and was not further addressed in this study.

Extensive drilling indicated that the bulk of the main groundwater body occurred within the basal portion of the LGR and the upper portion of the CC. The occurrence of groundwater within these units was implicitly related to the massive moldic porosity and karstic features associated with reef-building events and fossiliferous biostromes capable of storing large quantities of water. Occasionally, large volumes of groundwater could also be produced from well-developed reefs above the basal unit, or from significant perched fracture or karstic features. Otherwise, groundwater yields in the UGR and the top 250 ft of the LGR are minimal. Likewise, groundwater production from the BS is minimal at best. According to the injection packer testing, the CC was found to have the potential of transmitting the greatest amount of groundwater, but its natural water quality is less desirable than that of the LGR.

Additional testing of aquifer properties employed the use of Hydrophysical logging. A good relative measure of hydrophysical properties was conducted at CS-WB04 where the well extends through the entire thickness of the Middle Trinity aquifer. The HpL interpretation estimates that 100 percent of the measured groundwater flow originates from only a total of 23 feet of permeable strata or fractures within the Lower Glen Rose and Cow Creek. According to the testing, only five zones of groundwater flow were interpreted between HCSM layers LGR(D and E). Conversely, significant increases in groundwater flow were measured in the reefal portion of layer LGR(F), where the average hydraulic conductivity was nearly 3.5 times greater than the average conductivity of LGR(D and E). The amount of total estimated flow from the LGR during the HpL testing resulted with 85 percent of the groundwater production originated from LGR(F). When considering the entire thickness of the Middle Trinity aquifer, the Lower Glen Rose accounted for 92 percent of the entire production at CS-WB-04 and the Cow Creek accounted for the remaining 8 percent. No measurable flow was reported from the Bexar Shale interval. The HpL logging provides a characterization of ambient flow occurring during July

2003. At that time, water levels overall were decreasing in elevation at CSSA. The hydraulic conditions observed will be consistent with flow behavior during a period of declining water levels.

Based upon measurements at observation wells, the regional groundwater flow is generally to the south-SE. The LGR typically has a southward gradient that is deviated around mounding which occurs at CS-MW4-LGR and CS-G. The BS has exhibited the potential for either northward or southward flow, depending upon the season. Likewise, the CC has exhibited erratic flow paths with seasonally radial flow from mounded areas, to a northeastward flow possibly related to off-post pumping along Ralph Fair Road.

Long-term monitoring shows that groundwater response to precipitation events can be swift and dramatic. Depending on the severity of a precipitation event, the groundwater response will occur within several days, or even hours. Average precipitation events do not invoke much response from shallow PZs within the LGR, yet main aquifer body wells will respond within a week. Such observations seem to indicate that the preponderance of recharge observed occurs elsewhere upon the outcrop, and not necessarily within CSSA.

Using continuous datalogging devices within a multi-port well, a significant increase in the resolution of recharge mechanics were observed. As measured in the LGR multi-port well, aquifer response to significant recharge typically occurs as an increased pressure gradient that emanates from the lower zones upwards. The mechanism by which the aquifer appears to be bottom filling is either that the recharge to the lower zones occurs elsewhere on a regional scale (perhaps at outcrop areas), or that well-developed structural conduits convey the recharge downward quickly to the bottom of the LGR. Recharge to the upper LGR strata occurs more slowly, and appears to be less of a function of direct infiltration at the site in comparison to effects of vertical and lateral leakage. The data recorders indicated that under intense precipitation events that an inter-aquifer gradient reversal occurs, providing the mechanism by which lower strata seemingly can recharge the upper strata through a network of fractures inherent to the bedrock. Once the recharge event has subsided, the aquifer resumes to its natural state of typically downward inter-aquifer gradient.

For the entire Middle Trinity aquifer, data obtained from the on-post well clusters indicate that for most of the year, a downward vertical gradient exists within the Middle Trinity aquifer. Differences in drainage rates often leave the head of the BS well above the head of the LGR and CC. The large differences in head suggest that the BS locally acts a confining barrier between the LGR and CC.

The average precipitation at CSSA is typically above 32 inches per year. The 30-year record (1971-2000) results in a mean annual rainfall average of 37.36 inches in Boerne, Texas. The CSSA weather station reported a 31.46 annual average between 1999 and 2006. As little as 17 inches and as much as 52 inches of precipitation have been reported within an individual calendar year. In an attempt to estimate an annual water balance, approximately 67 percent of the annual precipitation is expected to be lost to evapotranspiration. Another 29 percent is assumed to be lost to surface runoff annually, while the remaining 4 percent recharges the Middle Trinity aquifer (based upon published literature values). Assuming these estimates are valid, CSSA can be expected to consume between 8 percent and 25 percent of its annual recharge. Likewise, within the model area between 31 percent and 95 percent of the estimated recharge volume can be consumed by the collective groundwater consumers. These values are likely biased low since groundwater is obviously removed from storage during periods of drought, meaning the discharge will exceed recharge. CSSA implements a drought management plan to better manage its groundwater resources during times of reduce precipitation.

At CSSA, the VOC COCs are PCE, TCE, and *cis*-1,2-DCE. These COCs exceed federal MCLs in relatively small areas. In terms of contamination, PCE and to a lesser extent TCE are the parent products while TCE and *cis*-1,2-DCE are by-products resulting from biodegradation processes. Thus far, only sporadic trace detections of vinyl chloride have been reported. The lack of widespread vinyl chloride detections indicate that the reductive chlorination processes may have stalled with the production of *cis*-1,2-DCE, which is indicative to lack of potential electron donors within the system. Or, the other plausible explanation is that the notable lack of VC is due a process that rapidly degrades the VC to ethene, especially along the aerobic margins of the plumes.

VOC contamination from the past disposal activities as resulted in multiple groundwater units, referred to as Plume 1 (B-3 and O-1) and Plume 2 (AOC-65). Contamination is most widespread within the LGR water-bearing unit. Environmental studies have demonstrated that most of the contamination resides within the LGR, therefore the open borehole completions are considered to represent that unit.

At Plume 1, areas in excess of the MCL occur around wells CS-D, CS-MW1-LGR, CS-MW2-LGR, and the CS-MW16 cluster. Concentrations in excess of 200 µg/L have been reported at CS-D, CS-16-LGR, and CS-MW16-CC near the source area. This plume has advectively migrated southward to CS-1 at Camp Bullis, and west-SW toward CSSA well field (CS-9, CS-10, and CS-11) and several to off-post public and private wells. Over most of the plume area, contaminant concentrations are below 1 µg/L. In contrast, little to no contamination within the BS and CC has been consistently identified within Plume 1.

Contamination at Plume 2 originated at or near Building 90, 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 (22,000 µg/L at CS-WB03-UGR01). Within the post, concentrations in excess of 100 µg/L have been reported in perched intervals above the main aquifer body. However, as evidenced by the multi-port wells, once the main aquifer body is penetrated, the concentrations are diluted to trace levels. Off-post, concentrations in excess of the MCLs has been detected in private and public wells with open borehole completions. Concentrations exceeding 25 µg/L have been reported 1,200 ft west-SW of CSSA at RFR-10. 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 BS and CC wells within Plume 2.

The style of well completion can affect the concentration detected at a location. At CSSA, monitoring wells have been purposely designed to case off contamination present within upper strata in an effort to reduce cross-contamination between water-bearing units. This style of well has typically resulted in a groundwater sample from the main portion of the aquifer that has little to no contamination present. In contrast, most off-post wells are designed to maximize yield from all portions of the aquifer, resulting in the co-mingling of stratified groundwater with varying degrees of contamination. Within an open wellbore, the net effect is that perched waters with high concentrations of solvents are contaminating relatively pristine groundwater held within the main body of the aquifer. This scenario, coupled with the tendency of downward vertical flow, has potentially created pockets of cross contamination into the basal unit of the LGR, BS, and CC members of the Middle Trinity aquifer.

Results from the AOC-65 study seem to indicate that the bulk of contamination is locked within the upper 300 ft of strata, and may have a tendency to move laterally rather than vertically. This is supported by the elevated concentrations detected in the upper portions of the RFR-10 borehole. The method by which the contamination is transmitted horizontally is unconfirmed, but is likely related to the extensive NE-SW faulting in the area, possibly secondary dissolutioning along these preferential planes, and pumping of off-post wells.

From the onset, contaminant levels were detected in most of the CS-WB04 monitoring zones, including the BS and CC. The HCSM layers with the most prolific concentrations were LGR(D) an LGR(E), with significantly lesser amounts reported in LGR(F) and BS and CC layers. At CS-WB04 within the BS and CC layers, these concentrations have dissipated in most intervals beyond the December 2003 sampling event (Figure 5.11). The first four months of monitoring indicated decreasing concentration trends in most zones, presumably since the natural groundwater flow through the borehole has been re-established. These results indicate that some crosshole contamination occurred during the short time it took to install the multi-port well (8 hours), but has been restored to its natural condition over time.

Historical sampling activities had shown sporadic detections of lead above the action level of 0.015 mg/L in mostly older open borehole wells, such as former agricultural and potable supply wells. It would seem that the open borehole wells with minimal surface casing are most prone to the lead detections at CSSA. Materials issues associated with well casing, piping, or the pumping apparatus may also play a role in the detection of lead in these legacy wells. However, through 2006 the network of monitoring wells specifically installed for groundwater characterization had not indicated any persistent inorganic concerns in the aquifer. The fundamental difference between the monitoring wells and the legacy wells is there constructed design. Newer wells are comprised of PVC casing and stainless steel screens that monitor 25-foot segments of the Middle Trinity aquifer. In comparison, the legacy wells are open borehole completions that have the capacity to be influenced by perched zones above the main aquifer body.

New wells drilled in 2007 indicated potential problems with inorganics in the LGR groundwater may exist near former munitions disposal sites. Wells CS-MW23-LGR and CS-MW25-LGR are located in the vicinity of SWMU DD and B-8, respectively. Since their inception, both have had repeatable detections of lead above the 0.015 mg/L action level. This is significant since these are the first wells to exclusively monitor the basal portion of the LGR to have repeatable detections from the major water-bearing strata of the aquifer. In addition, chromium has been reported in CS-MW25-LGR on multiple occasions above the 0.1 mg/L MCL. Finally, a single detection of mercury has been reported in CS-MW23-LGR above the 0.002 mg/L MCL. No explanation for this instance is known at this time.

6.2 RECOMMENDATIONS

Ultimately, the migration of contaminants in groundwater is dictated by flowpaths inherent to the stratigraphy and structure of the subsurface. The flowpaths can also be affected by external forces such as prolific water development (pumping) or even extremes in the hydrologic cycle (droughts and floods). The next big step into understanding contaminant migration at CSSA would be to quantitatively measure groundwater flow direction and velocity. The shape and location of the plumes indicates that multiple advective directional forces are occurring, and possibly at different velocities.

The geometry of Plume 1 suggests a primary flow direction to the south that follows the overall regional groundwater gradient, and the path of Salado Creek. However, Plume 1 also has a "leg" emanating to the southwest, which is presumably dictated by the structural alignment of faults. In contrast, the primary migration path of Plume 2 appears to be to the west-southwest. This is contradictory to the apparent regional groundwater gradient, and indicates that the structural features (faulting or karst) are a significant mechanism in the migration of contaminants.

The following are recommendations for satisfying data gaps within the HCSM and CSSA groundwater program in general.

6.2.1 Tracer Studies

Traditionally, quantitative groundwater flow and direction is characterized by "tracer" studies in which a detectable concentration of a "tracer" compound is introduced the aquifer. Frequent monitoring of surrounding observation wells are routinely conducted to determine the travel time from point of introduction to an observation point at a known distance and direction. The groundwater velocity is simply stated as the distance traveled divided by amount of time between the tracer injection point and detection point (e.g., feet per day). Tracer studies will help quantify the velocity and direction of the plumes and qualify underlying controlling features such as karst, faults, and fractures. The result of the study will also provide a predictive basis for estimating release dates and how far the plume has traveled.

6.2.2 Isotope Studies

To the southwest of CSSA it appears that Plumes 1 and 2 may be co-mingling. With respect to PCE, separate and distinct plumes are not discernable with the current off-post monitoring network in the vicinity of Interstate IH-10 and Old Fredricksburg Road. However, the sequential and progressive mapping of TCE does suggest that some of this contamination does originate from Plume 1. To help differentiate the plumes in this vicinity, isotope studies may be performed to chemically "fingerprint" the contaminants in the groundwater. In theory, the isotope analysis would find chemical distinctions between the presumed sources of Plume 1 and Plume 2, and thereby correlate and associate the contaminants detected in off-post wells with one of the known source areas. Isotope comparison and analysis is also useful in understanding the reductive dehalogenation processes that are ultimately degrading the plumes from PCE to other chlorinated compounds (TCE, DCE, and VC).

6.2.3 Plume 2 Delineation

To the southwest of CSSA, there have been indications that the plume is still mobile and dynamic. In particular, the data has shown that off-post well I10-4 has gone from historically being contaminant-free until March 2004 (2.22 µg/L PCE), and has been as high as 3.47 µg/L of PCE in June 2005. The immediate and significant appear of contamination may suggest that contaminants can be rapidly flushed in "slugs" during significant precipitation events. Since this well is near what has been considered to be the leading edge of the plume, these observations should be addressed.

It is recommended that additional groundwater monitoring locations to the southwest of Interstate IH-10 be indentified and characterized. This may included utilizing existing wells (public or domestic), or securing access agreements for the installation of monitoring wells.

6.2.4 Other Considerations

The inspection and sampling of off-post wells has demonstrated that the style of well completion can likely play a role in the quality of groundwater that can be produced from a well seemingly within the margins of the plume. A sufficient length of cemented surface casing through most of LGR is considered to be a proactive approach in minimizing the amount of contamination that would be available to enter an open borehole. Specifically, surface casing that isolates the UGR and layers LGR(A-E) would be a protective step in ensuring that groundwater is extracted from zones of lesser contamination, namely LGR(F) and CC(A).

The Trinity-Glen Rose Groundwater Conservation District (TGRGCD) has been established for northern Bexar County, and has invoked requirements regarding casing installations and geophysical logging. The current District policies mandate that the newly-installed wells provide enough surface casing to prevent the commingling of UGR and LGR groundwater. CSSA has compiled enough compelling evidence that additional surface casing within the vicinity of the facility can be beneficial the groundwater end user with negligible impact to overall well yield. Consideration should be given to provide these findings to the TGRGCD such that they may amend their well construction requirements for those wells located proximal to CSSA.

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SECTION 7
GLOSSARY OF TERMS

Advection: The process by which solutes are transported by the bulk motion of the flowing groundwater.

Allochem: Sediment formed by chemical or biochemical precipitation within a depositional basin; includes intraclasts, oolites, fossils, and pellets.

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

Anion: A negatively charged ion that migrates to an anode, as in electrolysis.

Anisotropy: Condition where one or more of an aquifer's hydraulic properties vary according to the direction of groundwater flow.

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.

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

Bedding plane: A plane that divides two distinct bedrock layers.

Bioherm: A mound-like unit of rock of different character than the surrounding rock, which was created by the dense growth and later fossilization and lithification of sedentary organisms such as corals.

Biomicrite: A limestone consisting of a variable proportion of fossil skeletal debris and carbonate mud.

Biostrome: A bedded, laterally extensive unit of rock created by the dense growth and later fossilization and lithification of sedentary organisms such as corals and shelled animals.

Bioturbation: The churning and stirring of a sediment by organisms.

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

Borrow pit: A small quarry, often in poorly or unconsolidated materials. The term is common on U.S. Geological Survey topographic maps.

Boxwork: Mineral structure which originally formed as blades or plates along cleavage or fracture planes and then the intervening material dissolved leaving the intersecting blades or plates as a network.

Breccia: A rock made up of highly angular coarse fragments. May be sedimentary or formed by crushing or grinding along faults.

Calcarenite: A deposit composed of cemented sand-sized grains of calcium carbonate, usually a biosparite or grainstone.

Calcareous: Containing calcium carbonate.

Calcite: The predominant mineral in limestone. It is relatively soluble compared to other common minerals, and allows for the dissolution of limestone and the precipitation of calcite speleothems.

Caliche: Gravel, sand, or desert debris cemented by porous calcium carbonate. A soil formed by the near-surface crystallization of calcite and/or other soluble minerals by upward-moving solutions.

Cation: An ion that bears a positive charge.

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).

Cavern Porosity: Measure of the volume of cave space in rocks or sediments as a percentage of the total rock or sediment volume. Cavern porosity implies a large storage capacity for groundwater, and a sometimes tortuous flow path associated with the cave development.

Colluvium: Loose, poorly sorted deposits of sediment moved down-slope by gravity and sheetwash; includes talus and cliff-fall deposits.

Complexation: When polar interaction occurs between a solute molecule and a molecule of stationary phase, an associate (complex) is assumed to occur which actually removes the solute from the migration process.

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

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.

Confined: Pertaining to aquifers with groundwater restricted to permeable strata that are situated between impermeable strata.

Confining Layer: One which, because of its position because of its impermeability or low permeability relative to that of the aquifer, gives the water in the aquifer artesian head.

Conformable: A contact between strata that reflects a period of continuous deposit of material, typically a smooth surface without evidence of the erosion in the underlying older strata; see unconformity.

Corbula: A small, bivalved clam that occurs in both the upper and lower Glen Rose Limestone and forms an important marker bed that distinguishes the boundary of the Upper and Lower members of the Glen Rose Formation.

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

Crossbedded: The arrangement of laminations of strata transverse or oblique to the main planes of stratification of the strata concerned; inclined, often lenticular beds between main bedding planes.

Dehalogenation: Dehalogenation is the process of removing the chlorine molecules from an organic molecule. Generally an anaerobic process that is often referred to as reductive dechlorination.

Dehydrohalogenation: Reaction in which an alkyl halide, on being treated with a base such as sodium ethoxide, is converted to an alkene by loss of a proton from one carbon and the halogen from the adjacent carbon**.**

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.

Diagenesis: Process involving physical and chemical changes in sediment after deposition that converts into consolidated rock; includes compaction, cementation, recrystallization, and perhaps replacement as in the development of dolomite.

Diffuse flow: Laminar and very slow groundwater movement within small voids of primary and

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.

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

Dolomite: A term applied to a carbonate rock that approximate the mineral dolomite ($CaMg(CO_3)^2$) in composition. Commonly associated with a process whereby limestone becomes dolomite by the substitution of magnesium carbonate for a portion of the original calcium carbonate.

Dolostone: A term proposed for a sedimentary rock composed of fragmental, concretionary, or precipitated dolomite of organic or inorganic origin.

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.

Electrokenitics: **R**emediation process in which a low-voltage direct-current electric field is applied across a section of contaminated soil to move contaminants. The principle of electrokinetics remediation is similar to a battery. After electrodes (a cathode and anode) are introduced and charged, particles (e.g., ions) are mobilized by the electric current. Ions and water move toward the electrodes.

Electromigration: The transport of ions and ion complexes to the electrode of opposite charge.

Electron Acceptor: A compound that receives or accepts an electron during cellular respiration. The microorganism through its cellular machinery collects the energy for its use. The process starts with the transfer of an electron from an electron donor. During this process) the electron acceptor is reduced and the electron donor is oxidized.

Electron Donor: A compound that gives up or donates an electron during cellular respiration, resulting in the release of energy. The microorganism through its cellular machinery collects the energy for its use. The final result is the electron is donated to an electron acceptor. During this process the electron donor is oxidized and the electron acceptor is reduced.

Electroosmosis: The movement of soil moisture or groundwater from the anode to the cathode of an electrolytic cell.

Electrophoresis: The transport of charged particles or colloids under the influence of an electric field; contaminants bound to mobile particulate matter can be transported and separated on the basis of their tendency to migrate to a positively or negatively charged electrode at a particular pH.

En echelon: Typically refers to faults or other structures that occur in an overlapping but collectively linear arrangement, such as to form a fault zone.

Epikarst: The highly solutioned zone in karst areas between the land surface and the predominantly unweathered bedrock.

Estavelle: A feature that either recharges or discharges groundwater, depending on the level of the water table or potentiometric surface.

Evaporite: One of the sediments deposited from aqueous solution as a result of extensive or total evaporation of the solvent.

Evapotranspiration: A term embracing that portion of the precipitation returned to the air through direct evaporation or by transpiration by vegetation.

Fabric-Selective: Classification of carbonate porosity based on pore types as proposed by Choquette and Pray (1970). Porosity under this classification includes interparticle, intraparticle, intercrystal, moldic, fenestral, shelter, and framework porosities, as opposed to non-fabric selective such as vug and channel, cavern, and fracture porosities.

Facies: The characteristic appearance or aspect of a rock unit; often subclassified or described based on stratigraphy, fossils, mineralogy, lithology, and other similar factors; a stratigraphic body as distinguished from other bodies of different appearance or composition or a lateral subdivision of a stratigraphic unit.

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

Fenestral Porosity: Fenestrae are small pores which are common in carbonates and typically form because of desiccation and gas generation. While local porosities may be high, fenestrae form in a very narrow range of environments and occur in thin, discontinuous horizons. They are prone to early cementation and often contain geopetal sediments. They are, at best, only a minor porosity type complementing the more typical porosity types in peritidal sequences, such as intercrystalline and moldic porosity.

Fissure 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.

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.

Fossiliferous: Bearing or containing fossils. In stratigraphy, the term usually implies the rock has a high percentage of fossilized material bound within the matrix.

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

Geomorphology: The branch of geology that studies the shape and origin of landforms.

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.

Grainstone: A limestone description based upon the Dunham Mudstone Classification (1062). Grainstones are grain-supported carbonate rocks with no mud, and are not originally bound together during deposition. Often the interstices of these rocks are filled with a sparry cement.

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

Heterogeneous: Condition where an aquifer's hydraulic properties vary in different locations.

Homogeneous: Condition where an aquifer's hydraulic properties are the same in all locations.

Honeycomb: An interconnected series of small voids in rock, commonly formed in karst by near surface (epikarstic) solution, or by phreatic groundwater flow.

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

Hydrograph: A graph illustrating changes in water level or discharge over time.

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

Hydrostratigraphy: A geologic framework consisting of a body of rock having considerable lateral extent and composing a reasonably distinct hydrologic system.

Impermeable: Does not allow the significant transmission of fluids.

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

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: 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.

Lag time: The time between aquifer recharge or discharge and the initial resulting response of the aquifer, usually measured as the rise or fall of the hydrograph.

Laminar flow: Smooth water movement along relatively straight paths, parallel to the channel walls.

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.

Lenticular: Bedding feature that is shaped approximately like a double convex lens. When a mass of rock thins out from the center to a thin edge all around, it is said to be lenticular in form.

Limestone: A bedded sedimentary deposit consisting chiefly of calcium carbonate ($CaCO_3$). A general term for that class of rocks which contain at least 80 percent of the carbonates of calcium or magnesium.

Lineament: A linear feature, usually observed in aerial photographs, which likely represents a geologic feature such as a fault, joint, or lithologic contact.

Lineation: A linear alignment of features that may indicate control by fractures or other geologic features o processes.

Lithic: Refers to sediments and rocks in which rock fragments are more important proportionally than matrix.

Lithology: The description or physical characteristics of a rock.

Marl: Rock composed of a predominant mixture of clay and limestone.

Mesozoic: The era of the geologic time scale that extended from about 245 million years ago to 65 million years ago; it begins with the Triassic Period, continues through the Jurassic Period, and ends with the Cretaceous Period.

Metabolism: The chemical changes in living cells, by which the energy is provided for the vital processes and activities, and new material is assimilated to repair the waste.

Methanogenisis: The microbial generation of methane as a result of anaerobic decomposition of organic matter.

Moldic Porosity: A type of secondary porosity created through the dissolution of a preexisting constituent of a rock, such as a shell, rock fragment or grain. The pore space preserves the shape, or mold, of the dissolved material.

Mudstone: A limestone description based upon the Dunham Mudstone Classification (1062). Lime mudstones are composed of clay sized carbonate particles with less than 10 percent grains.

Nodular: Composed of nodules (rounded mineral aggregates).

Normal fault: A fault where strata underlying the fault plane are higher in elevation than the same strata on the other side of the fault plane.

Not-Fabric Selective: Classification of carbonate porosity based on pore types as proposed by Choquette and Pray (1970). Porosity under this classification includes vug and channel, cavern, and fracture porosities, as opposed to fabric selective such as. interparticle, intraparticle, intercrystal, moldic, fenestral, shelter, and framework porosities.

Onlapping: The extension of successive stratigraphic units beyond the marginal limits of their predecessors onto older rocks as in the deposits of a transgressing sea.

Packstone: A limestone description based upon the Dunham Mudstone Classification (1062). Packstones are grain-supported carbonate rocks; (i.e., there is less clay size matrix than allochems).

Pelecypod: A division(class) of the phylum Mollusca.

Perched groundwater: Relatively small body of groundwater at a level above the water table; downward flow is impeded within the area, usually by impermeable strata.

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

Permeable: Allows the significant transmission of fluids.

Phreatic Zone: Designation of groundwater in the zone of saturation.

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

Physiography: The study of the genesis and evolution of land forms.

Piezometer: An instrument for measuring the pressure head of liquids. A nonpumping well, generally of small diameter and short screen length, for measuring the elevation of a water table.

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.

Quaternary: A period of the geologic time scale that began 2 million years ago and continues to the present.

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.

Reverse fault: A fault where strata underlying the fault plane are lower in elevation than the same strata on the other side of the fault plane.

Rudist: A group of bivalves which evolved during the Late Jurassic to Cretaceous and lived in warm, shallow oceans of low latitudes. They became extinct at the Cretaceous/Tertiary boundary. Most rudists have not much in common with 'normal' bivalves and developed bizarre, occasionally large shells. Different to other bivalves, one or both valves are uncoiled which allowed for accretion of the shell along the complete mantle margin and the construction of tubular shells.

Schist: A medium or coarse-grained metamorphic rock with sub-parallel orientation of the micaceous minerals which dominate its composition.

Seep: A spring that discharges a relatively minute amount of groundwater to the surface at a relatively slow rate; typically a "trickle."

Shale: A laminated sediment in which the constituent particles are predominantly of the clay-sized grade.

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.

Slickensides: Polished and striated (scratched) surface that results from friction along a fault plane.

Solution: The process of dissolving; dissolution.

Specific capacity: The productivity of a well, expressed as the rate of discharge divided by the drawdown of the water level.

Specific yield: The storage term for unconfined aquifers; see storativity.

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.

Stage: The water level elevation or height measured in a stream or a well.

Storativity: The volume of water released from or taken into an aquifer for each unit of aquifer surface area per unit of change in head; usually refers to storage within confined aquifers. See specific yield.

Strata: Layers of sedimentary rocks; usually visually distinguishable. Often called beds. The plural of , stratum.

Stratigraphic: Pertaining to the characteristics of a unit of rock or sediment.

Stratigraphy: Pertaining to or the study of rock and sediment strata, their composition and sequence of deposition.

Strike: The direction of a horizontal line on a fracture surface or on a bed of rock; perpendicular to dip.

Structure: The study of and pertaining to the attitude and deformation of rock masses. Attitude is commonly measured by strike and dip; deformational features commonly include folds, joints, and faults.

Stylolite: A term applied to parts of certain limestones which have a column-like development; the ‘columns’ being generally at right angles or highly inclined to the bedding planes, having grooved, sutured, or striated sides, and irregular cross sections.

Syndepositional: A process or mechanism occurring at the same time that sediment is being deposited.

Terrace: A relatively narrow, flat topographic surface; with reference to streams it usually marks the elevation of a former, higher, water level, and is composed of and formed by the deposition of unconsolidated sand, gravel, and related alluvial material.

Transmissivity: The rate at which water moves through a unit width of an aquifer under a unit hydraulic gradient.

Trend: The azimuthal direction of a linear geologic feature, such as the axis of a fold or the orientation of a fracture; commonly used to denote average or general orientations rather than specific orientations.

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

Unconformity: A break in the sequence of stratigraphic deposition that is often recognized by an erosional surface overlain by younger strata; see conformable.

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

Vug: A small cavity in rock, often lined with crystals, and generally not significantly related to groundwater movement.

Wackestone: A limestone description based upon the Dunham Mudstone Classification (1062). Wackestones are carbonate rocks which are matrix-supported; i.e., there are more than 10% grains, but the fine grain clay size matrix essentially surrounds the grains.

Water table: The boundary of the phreatic and vadose zones. A potentiometric surface but the term is used only in unconfined aquifers.

Sources

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