SECTION 4
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 dictate 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.

4.1.1.1 Geologic Inputs

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, nearly all 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.

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 2003, the number of wells has increased along with the growing population in the Boerne vicinity. For most of these wells, subsurface data is 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 July 2003, 31 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 is 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.

4.1.1.2 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.

4.1.1.3 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 and CS-16-LGR (formerly CS-16). From these tests, ranges of aquifer yield, 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 all wells located on-post. Additionally, select wells are gauged for water levels on a weekly basis. 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.

4.1.1.4 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, 31 new monitoring wells within the Middle Trinity aquifer have been installed on-post. Through June 2003, a total of 40 off-post locations, both public and private, have also been sampled for VOC contamination.

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 this 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.

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.

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.

Through August 2003, 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 4.7 shows the exposed surface of the UGR Limestone. 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 mappable 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.

4.2.1.1 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 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.

4.2.1.2 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.

4.2.1.3 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 solutioned 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.

4.2.1.4 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.

4.2.1.5 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 all but 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 August 2003, 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.

4.2.2.1 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.

4.2.2.2 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.

4.2.2.3 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.

4.2.2.4 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.

4.2.2.5 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.

4.2.2.6 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.

4.2.3.1 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.

4.2.3.2 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.

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.

4.2.4.1 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.

4.2.4.2 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 sluff 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 fabric selective features are not present, 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) are currently being studied as part of a different project. 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 being performed under the TO58 delivery order is also investigating 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 just begun to monitor the LGR. In addition, CS-WB04 also monitors the entire thickness of the LGR, BS, and CC at an off-post location. 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 is 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 limited temporal 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 31 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 potential 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 is 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 is 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. Transducers have also been installed at wells CS-MW9-LGR, CS-MW9-BS, CS-MW9-CC, and CS-MW4-LGR. 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 33 wells between June 2001 and June 2003.

Table 4.2 Comparison of CS-16-LGR Weather Station Precipitation and Average Overall Groundwater Elevation Change[1]

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	1124.94	1101.85	1074.56	0.015	South-SW

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 June 2004 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 current monitoring network of 39 well locations 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**).

4.4.1.1 Upper Glen Rose

Through June 2003, very little data is 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 all poor producers, and were subsequently plugged and abandoned as specific site closures were granted by the TCEQ.

Currently, all 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 all 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.

4.4.1.2 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 seven monitoring events) were generated using Surfer™ v7.0, and are presented in Appendix A (Figures A-1, -4, -7, -10, -13, -16, and -19). 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. 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 June 2004, 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, until further control points are established, this mounding effect remains as one of the most notable features of the groundwater surface.

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.

4.4.1.3 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 (Figures A-2, -5, -8, -11, -14, -17, and -20)

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.

4.4.1.4 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 (Figures A-3, -6, -9, -12, -15, -18, and -21). 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 pumping test pilot study was undertaken at well CS-MW16-CC. At this location, CC groundwater is extracted at an average rate of 12 gpm and treated and released through a permitted outfall. Since March 2004, the affects of the pumping action have been evident on subsequent quarterly groundwater events (Figures A-15, -18, and -21). 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. Through nearly nine months of continual pumping, the change groundwater gradient within the CC is still evident. 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.

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) is 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.

4.4.2.1 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 all of 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. 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-1 has a range of only 167 ft. Both wells respond similarly to large rainfall events, in terms of their lag time, but their magnitude of response is somewhat different.

The response of the wells screened in the LGR Formation is similar for all wells, 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.

As an example, wells CS-MW3-LGR, CS-MW4-LGR, CS-MW5-LGR, and CS-MW9-LGR did not appear to respond to the July 2002 rainfall events until the end of August; however, the wells were not sampled until then, likely missing the peak in water level near the middle of July exhibited by CS-MW6-LGR, CS-MW8-LGR, CS-MW10-LGR, and CS-16-LGR. After extreme rainfall events in October of 1998, August 2001, November 2001, and July 2002, as well as a sustained period of more moderate wet weather in the fall of 2000, the peak water levels observed in most wells was around 1,160 ft mean sea level (MSL). This elevation may represent a significant level at which some spring discharge may occur locally.

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 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 all 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. It is also possible that the water levels in the BS do not recede as rapidly as in the CC Limestone. Thus, the wells in both the BS and CC Formation can respond quickly and dramatically to intense rainfall after periods of drought, but after sustained wet weather the magnitude of the response is dampened.

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. The latter half of 2003 was quite dry, and the wells responded accordingly with depressed groundwater levels. The beginning of 2004 noted the start of an unusually wet year where nearly 28 inches of precipitation had fallen by the end of August 2004.

4.4.2.2 Seasonal Variations

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.

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 143 ft, and when the data set is weighted by well for the number of actual monitoring events, that average increases to nearly 195 ft. 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. 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 2003, the maximum recorded elevation was 1168.89 ft above mean sea level (MSL). 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.

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.

4.4.2.3 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 is 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 potential head (*e.g.,* elevation) will move towards a zone with a lower potential 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 potential 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 September 2003.

The graphics show that at an individual location, the potential head in the LGR well is typically greater than in the CC well. The graphics also suggest that the potential 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 not hydraulically unique 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. Figure 4.25 is a long-term hydrograph of transducer data collected from well cluster CS-MW9 in the North Pasture. 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.

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 2003 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 potential head of the LGR becomes less than the potential 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 potential 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.

Figures 4.26 and 4.27 present flow nets that depict the Middle Trinity aquifer in June 2003 after a recharge event. These diagrams illustrate that while most of the flow in the LGR and CC is horizontal, a strong downward gradient is present within the BS.

4.4.2.4 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.

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	CSWB-04
UGR(D) UGR(E)	UGR-01	UGR-01
LGR(A)	LGR-01	LGR-01
LGR(B)	LGR-02	LGR-02
	LGR-03	LGR-03
LGR(C)	LGR-04	LGR-04
	LGR-05	LGR-05
LGR(D)	LGR-06	LGR-06
	LGR-07	LGR-07
LGR(E)	LGR-08	LGR-08
	LGR-09	LGR-09
LGR(F)		LGR-10
		LGR-11
BS(A)		BS-01
BS(B)		BS-02
CC(A)		CC-01
		CC-02
CC(B)		CC-03

Figure 4.28 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 4.29). 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 scare and the potential 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 potential 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

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 4.30. 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, nearly all 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 potential head of lower zones (LGR-07, -08, -09, and CS-MW8-LGR) exceed the potential head of these upper zones. In Figure 4.29, 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 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 potential head of CS-MW8-LGR is typically greater than the potential head of CS-MW8-CC (Figure 4.29), 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 feet per second [ft/sec]) in all three formations (LGR, BS, and CC) to 5.03×10^{-5} ft/sec 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 3.47×10^{-8} ft/sec. Within this 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 5.4, 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.

4.5.2 Pumping Tests

Pumping tests were performed in July and August 2001 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, two 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 CS-16. Further information regarding the pumping tests may be found in **Volume 5: Groundwater, Groundwater Pumping Tests for CS-10 and CS-16**.

Table 4.5 Statistical Summary of Injection Packer Tests

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=0.00E+00)

Hydrologic Unit	Count (n)	(ft/sec)				Ratio of Normalized Average Permeability compared to BS (x)
		Min	Max	Median	Average	
LGR	19	0.00E+00	5.03E-05	1.00E-06	4.47E-06	7.5
BS	7	0.00E+00	3.47E-06	0.00E+00	5.98E-07	1.0
CC	12	0.00E+00	2.69E-05	1.68E-06	6.56E-06	11.0

Summary Statistics for Subset (n=27)
(not including tests where K=0.00E+00)

Hydrologic Unit	Count (n)	(ft/sec)				Ratio of Normalized Average Permeability compared to BS (x)
		Min	Max	Median	Average	
LGR	13	3.47E-08	5.03E-05	1.79E-06	6.53E-06	4.7
BS	3	1.89E-07	3.47E-06	5.22E-07	1.40E-06	1.0
CC	11	8.45E-07	2.69E-05	6.42E-06	7.48E-06	5.4

Summary Statistics for Tests Performed within the Screened Interval

Hydrologic Unit	Count (n)	(ft/sec)				Ratio of Normalized Average Permeability compared to BS (x)
		Min	Max	Median	Average	
LGR	8	6.15E-07	1.01E-05	1.70E-06	2.73E-06	2.1
BS	3	0.00E+00	3.47E-06	5.22E-07	1.33E-06	1.0
CC	6	0.00E+00	2.69E-05	4.01E-06	8.02E-06	6.0

4.5.2.1 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. 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 5.7 x 10^{-4} cm/sec.

4.5.2.2 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. 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 4.2 x 10^{-4} cm/sec.

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)	
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)**
Specific Capacity *(gpm/ft)*	N/A	N/A	N/A	1.13	0.71
Transmissivity *(gpd/ft)*	1,700	5,740 to 16,110	240 to 3,220	2,400	1,600
Hydraulic Conductivity *(cm/sec)*	N/A	1.4 x 10^{-3} to 3.5 x 10^{-3}	3.4 x 10^{-5} to 1.0 x 10^{-3}	5.7 x 10^{-4}	4.2 x 10^{-4}
Storativity	N/A	N/A	0.00003	0.0005	0.00008

N/A – Not Available from Literature Review

4.5.3 Hydrophysical™ Logging

In July 2003, Hydrophysical Logging (HpL) was performed at four locations by COLOG of Golden, Colorado. The process is capable of measuring the intervals of groundwater inflow/outflow 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 all the 23 water-bearing zones identified in Table 4.7, the average hydraulic conductivity was 1.343 ft/day (1.55×10^{-5} ft/second). That average value is more than twice the average LGR hydraulic conductivity ((6.53×10^{-6} ft/second) 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.

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.

A comparison of hydraulic parameters derived from both pumping tests and the HpL testing have resulted in a wide range of hydraulic conductivities and transmissivities. The CS-10 and CS-16 pumping tests resulted with hydraulic conductivities between 4.2×10^{-4} to 5.7×10^{-4} cm/sec (Table 4.6). Whereas, the average hydraulic conductivity for the Middle Trinity aquifer intervals given in Table 4.8 is 1.311×10^{-3} cm/sec (3.71 ft/day), which is two to three times more permeable than the pumping test results. The variability could result from a combination of testing methodologies and inherent heterogeneities between the test locations.

The biggest difference between results are the transmissvity values, which ranged between 1,600-2,400 gpd/ft (Table 4.6) at the pumping test wells, and 713 gpd/ft (94.9 ft^2/day) in Table 4.8. Since transmissivity is a function of both hydraulic conductivity and saturated thickness, the calculation can be sensitive to underlying assumptions such as the thickness of the water bearing intervals. 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 transmissivities derived during the pumping tests may overestimate the true value by three-fold due to assumptions of the true aquifer thickness.

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 2002)
(CS-16 Weather Station)

Year	Annual Rainfall (inches)
1999	16.99
2000	32.51
2001	40.17
2002	51.87
4-YEAR AVERAGE	35.39

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.

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 4.31.

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 2002 (Tables 4.11 through 4.14). 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 4.15.

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 17,308 (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 57,744 acre-ft/yr (2002). The data show that the 4-year average (1999-2002) is 95 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 well to the long-term precipitation normal.

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 4.16). 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 4.15 Synopsis of Local Precipitation with Respect to the Conceptual Site Model Area (13,359 Acres)

Measurement Period		1971-2000	1999	2000	2001	2002	1999-2002 Average
Precipitation (inches per year)		**37.36**	**16.99**	**32.51**	**40.17**	**51.87**	**35.39**
Model Area Unit	**Acreage**	**Volume of Precipitation *(Acre-ft)***					
CSSA	4,004	12,467	5,669	10,848	12,778	17,308	11,651
HCSM Area							
Salado Creek	6,964	21,681	9,860	18,866	23,311	30,101	20,540
Leon Creek	1,754	5,460	2,483	4,751	5,871	7,580	5,172
Cibolo Creek	4,641	14,451	6,572	12,575	15,538	20,063	13,687
HCSM Area Total	13,359	41,592	18,915	36,192	44,720	57,744	39,399

Table 4.16 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 4.32, 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 4.14, presented previously in Section 4.6.1, and summarized in Table 4.17. 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 311.6 and 822.7 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 short-term data collected at weather station results in recharge estimates that range between 45 and 139 percent of 30-year period of record. As with the precipitation, the 4-year average (1999-2002) is nearly 95 percent of the 30-year average.

4.6.3 Groundwater Discharge

CSSA has kept accurate records for all pumping activities since 1980, with exception of 1981. Table 4.18 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 1987 and 1988, and consumption has been reduced by nearly sixty percent since the late 1990’s. Over the past 22 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 60.4 acre-ft. Current groundwater extraction volume is approximately 33 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 household connection used approximately 700 gallons per day. Significantly less data is 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

Table 4.17 Estimates of Groundwater Recharge with Respect to the Conceptual Site Model Area (13,359 Acres)

Measurement Period			1971-2000	1999	2000	2001	2002	1999-2000 Average
Precipitation (inches per year)			37.36	16.99	32.51	40.17	51.87	35.39
Model Area Unit	Acreage	Recharge Coefficient (%)	Volume of Recharge *(Acre-ft)*					
CSSA	4,004	2.5	311.6	141.7	271.2	319.4	432.7	291.3
		4	498.6	226.8	433.9	511.1	692.3	466.0
		6.6	822.7	374.2	715.9	843.3	1,142.3	768.9
HCSM Area								
Salado Creek	6,964	2.5	542.0	246.5	471.6	582.8	752.5	513.4
		4	867.2	394.4	754.6	932.4	1,204.0	821.4
		6.6	1,430.9	650.7	1,245.1	1,538.5	1,986.6	1,355.3
Leon Creek	1,754	2.5	136.5	62.1	118.8	146.8	189.5	129.3
		4	218.4	99.3	190.0	234.8	303.2	206.8
		6.6	360.3	163.9	313.6	387.4	500.3	341.3
Cibolo Creek	4,641	2.5	361.3	164.3	314.4	388.4	501.6	342.2
		4	578.0	262.9	503.0	621.5	802.5	547.5
		6.6	953.7	433.7	829.9	1,025.5	1,324.1	903.3
HCSM Area Total	13,359	2.5	1,039.8	472.8	904.8	1,118.0	1,443.6	984.8
		4	1,663.6	756.6	1,447.6	1,788.7	2,309.7	1,575.7
		6.6	2,745.0	1,248.3	2,388.6	2,951.4	3,811.1	2,599.8

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 up to 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 717 acre-ft/yr.

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).

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 Qd 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 4.19, Table 4.20, and Figure 4.33 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 4.19 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 all 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 4.19 and 4.20, and diagrammed in Figure 4.33.

Table 4.19 and Figure 4.33 show that under normal climatic conditions assuming the 20-year average of pumping at CSSA (60.4 acre-ft), only 12 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 87.7 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 nearly 27 percent of its recharge, or 9 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 4000-acre facility.

The more regional scale represented by the HCSM area indicates that over 43 percent (40 percent residential and 3 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 4.20 and Figure 4.33 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.