# ENVIRONMENTAL IMPACT ASSESSMENT OF CITY PUBLIC SERVICE ELECTRICAL TRANSMISSION LINES PROPOSED FOR PLACEMENT IN THE SAN GERONIMO VALLEY, BEXAR AND MEDINA COUNTIES, TEXAS

**by**
**George Veni Ph.D.**

## Introduction

City Public Service (CPS), the electrical and natural gas utility service of the City of San Antonio, is proposing to install a 345-kilovolt electrical transmission line to provide increased, more accessible, and in case of system failures, more reliable electrical power to northwest Bexar County and northeastern Medina County. The line would connect CPS' Cagnon Substation, near the intersection of Loop 1604 and US Highway 90 in western Bexar County, to the Lower Colorado River Authority (LCRA) Transmission Services Corporation's Kendall Substation in southernmost Kendall County along Balcones Creek.

One of the initially considered routes by CPS for the transmission line was to follow mostly existing easements along a relatively straight north-south line between the stations. A second option CPS considered was to follow a route slightly to the west that would extend though portions of Government Canyon State Natural Area. The Bexar-Medina Landowners Association offered an option that mostly followed the easement east of Government Canyon State Natural and diverted to avoid and existing infrastructure. In January 2004, CPS determined that those options were not feasible, and focused their attention on potential routes west of Government Canyon State Natural Area in far western Bexar County and in eastern Medina County (Anderson, 2004a, 2004b). Some of those options include linking to an existing power station at Medina Lake and/or crossing through the San Geronimo Valley.

Douglas V. NcNeel, in coordination with other landowners in the San Geronimo Valley, contracted this study to assess the potential environmental impacts of the possible routes through the San Geronimo Valley. The major environmental concerns are the transmission line's effects on:

a) the San Antonio Segment of the Edwards (Balcones Fault Zone) Aquifer (hereafter called the "Edwards Aquifer"), the primary water supply for the region;
b) federally listed endangered species of birds and karst invertebrates;
c) and archeological sites.

This report focuses on water resources and endangered karst invertebrate species issues. Potential effects on endangered bird species and archeological sites are only superficially considered. The effects of possible land use changes in the San Geronimo Valley that might result from the placement of an electrical transmission line are examined, but evaluating the likelihood of such changes is beyond the scope of this study.

This report is organized into four parts. The first describes the geological, hydrological, and biological characteristics of the San Geronimo Valley and associated areas under consideration for the proposed transmission line. The second part compares the probable environmental impacts and considerations of selected segments of the proposed routes. The third part of this environmental impact assessment provides conclusions and recommendations. The bibliography and appendices comprise the final section. Appendix A is a glossary of geological, biological, and karst terms used in this report. Appendix B is a conversion index from the International System of Units to English units. Appendix C provides my biography per U.S. Fish and Wildlife Service (USFWS) guidelines for endangered species research.

The study area is evaluated per the methods proposed and described by Veni (1999, 2004) as the standards for karst environmental impact assessments. Analysis of all karst-related data used in this report is based on principles of karst hydrogeology and biology, such as in the texts and reports of Culver (1982), White (1988), Ford and Williams (1989), Elliott (1993, 1994, 2000), Klimchouk (2000), and Gunn (2004), with consideration of local factors as discussed by Veni (1994, 2002).

## Hydrogeological and Biological Description of the San Geronimo Valley Area

San Geronimo Creek is a tributary to the Medina River and joins the river 2 km southwest of the town of Rio Medina near the intersection of FM 1957 and FM 471. The creek extends 10 km to the north onto the southeastern portion of the Edwards Plateau Physiographic Province and continues north for another 20 km. For the purposes of this report, the San Geronimo Valley is considered the drainage basin of San Geronimo Creek upstream of the southern limits of the Edwards Plateau, which is marked by the San Geronimo Creek recharge dam.

The San Geronimo Valley is comprised of 142.6 $km^2$ of rolling to steep hills and gently sloping to nearly level valley floors. Its elevation ranges from 568 m above mean sea level at its north end to 322 m at its south end where San Geronimo Creek flows downstream of the recharge dam. Drainage west of the valley flows to the Medina River, to the east into Government Canyon, and north into Balcones Creek. The topography of the study area and surrounding terrain and its nomenclature as used in this report are established primarily on the Jack Mountain and San Geronimo 7.5' U.S. Geological Survey topographic quadrangles.

Hydrogeologic and ecological zones in the study area can be divided into three basic east-west bands. The northern band is the contributing zone of the Edwards Aquifer. The middle band is the aquifer's recharge zone. The southern band is off the Edwards Plateau and on the artesian zone of the aquifer. Detailed descriptions of the area's hydrogeology and ecology are provided below. These generalized bands are mentioned here to explain that at any given location in the San Geronimo Valley, the geology and ecology is similar to the east and west. They are also mentioned to explain the rationale in comparing potential transmission line routes through the study area later in this report.

### Lithology

The San Geronimo Valley is underlain by the Cretaceous Glen Rose Formation and the Edwards Limestone Group. Several maps show its geology. Arnow (1959) drafted the first geologic map of the Bexar County portion of the area, and Holt (1956, 1959) produced the first geology map for Medina County. Barnes (1983) updated these and others within a regional geologic map, which Collins (2000) remapped at a finer scale with a few differences.

The most detailed mapping of the area has been conducted by the U.S. Geological Survey. Stein and Ozuna (1995) and Small and Clark (2000) produced detailed maps of the Edwards Limestone outcrops in the Edwards Aquifer recharge zone in Bexar and Medina counties. Amy Clark (2003a) included a detailed map of the Edwards and Glen Rose outcrops in northern Bexar County based on a revision of the upper member of the Glen Rose by Allan Clark (2003).

The Glen Rose Formation is the uppermost formation of the Trinity Group. Only the upper member of the Glen Rose is exposed in the valley. The lower member of the Glen Rose averages about 100 m thick and is exposed near the study area north of Medina Lake. The 30-cm-thick "*Corbula* bed" marks the top of the lower Glen Rose. This traceable bed is easily distinguished throughout the outcrop area. Above the *Corbula* bed, the upper member of the Glen Rose at Camp Bullis is about 125-137 m thick, as determined from recent mapping by the U.S. Geological Survey (Allan Clark, 2003). It is characterized as a fossiliferous sequence of resistant limestones and dolomites alternating with less resistant beds of marl and clay to create a distinctive "stair-step" topography when eroded.

Until recently, hydrogeologic study of the Glen Rose Formation had been severely hampered by the coarse level of geologic mapping of the unit. Allan Clark's (2003) mapping of the upper member of the Glen Rose Formation divided it into five intervals. While many previous hydrologic studies have treated the upper Glen Rose as non-cavernous and effectively impermeable, this recent mapping defined and described the lithology of cavernous and groundwater-bearing zones.

The Edwards Limestone Group was subdivided by Rose (1972) into the Kainer Formation at the base, with ascending Basal Nodular, Dolomitic, Kirschberg, and Grainstone members, and the Person Formation at the top, with ascending Regional Dense, Collapsed, Leached, Marine, and Cyclic members. Maclay and Small (1984) included the Basal Nodular Member as the base of the Kainer, equivalent to the Walnut Formation described by Collins (2000) and other geologists. The Edwards is a hard, crystalline, fossiliferous, and cavernous rock that is locally about 137 m thick.

Within the southern portion of the study area, the Kainer Formation is the primary unit exposed. The Person Formation is present on a few hilltops in the San Geronimo Valley and most extensively to the west along uplands adjacent to Diversion Lake of the Medina River. Northward, the Kainer is less exposed, limited to hilltops, and the upper Glen Rose dominates. All but the lower 4 km of San Geronimo Creek are on the upper Glen Rose in the San Geronimo Valley.

**Structure**

The dominant structural feature of the region is the Balcones Fault Zone, formed along the homoclinal hinge between the relatively flat-lying strata of the Edwards Plateau to the northwest and the more steeply dipping strata in the Gulf of Mexico Basin to the southeast. The fault zone is characterized by a series of en echelon normal faults, mostly downthrown toward the Gulf. Faulting decreases in intensity from south to north across the region. Individual fault displacements in the study area are as much as 180 m at the Haby Crossing Fault, but most major fault displacements are only about 10-15 m. Many faults with less than 3 m of throw do not appear on geologic maps due to difficulty in mapping them. Joints are by far the most abundant structures in the study area and are generally formed by stresses associated with faulting.

In the San Geronimo area, Wermund, Cepeda, and Luttrell (1978) found that the occurrence of short fractures (joints and faults <4.5 km in length) averaged about 400 per 7.5' topographic quadrangle, as visible in aerial photographs, and were predominantly oriented at 50-70º. This trend is parallel to Balcones faulting and consistent with the faults identified by geologic mapping. Wermund, Cepeda, and Luttrell (1978) also found that fracturing was not related to lithology, because it extended through underlying formations, indicating ongoing fracture propagation. However, Veni et al. (1998) found that dipping joints occur more frequently in the upper Glen Rose, whereas in the Edwards, dipping fractures usually prove to be faults.

**Hydrogeology**

Groundwater in the study area occurs in the Upper Trinity and Edwards aquifers, with water in the Upper Trinity flowing downgradient into the Edwards. Until the past decade, most studies recognized little or no hydrologic connection between the units, and some did not recognize that both are karst aquifers. Consequently, the following few paragraphs provide, with examples, a conceptual explanation of groundwater movement in the area.

The terms "regional" and "local" groundwater have been used to described flow components within karst aquifers of the region (e.g. Hammond, 1984; Everett, 1990; Waterreus, 1992). In the regional system, groundwater movement occurs through voids of primary porosity and permeability which have undergone little solutional enlargement; flow is laminar and slow, often measured in units of meters per year. In contrast, the local groundwater system is characterized by groundwater movement through voids of secondary porosity and permeability, following the solutional enlargement of bedding planes and fractures; flow is turbulent and rapid, often measured in units of tens of meters per day or greater.

The terms regional and local groundwater systems imply certain areal extents and flow characteristics which may not be valid, especially in karst aquifers. The terms "diffuse" and "conduit," first proposed by White (1969), better describe actual flow conditions in karst and are more commonly used in the hydrogeologic and karst literature. In addition to the qualities also ascribed to the respective regional and local flow systems, White (1969) described the diffuse flow system as having slow and subdued hydrographic and geochemical responses to recharge, and the conduit flow system as having rapid responses.

To further define the characteristics of karst aquifers, Atkinson (1985) proposed the term "fissure flow" (more commonly called "fracture flow") to be used in conjunction with White's (1969) model and thus segregate groundwater movement along fractures from the intergranular flow of the diffuse system. In fact, groundwater movement in karst does not occur in just three modes, but varies across a continuum of permeabilities, from microscopic intergranular movement to turbulent stream flows in conduits larger than 100 m in diameter. Conduits within the upper Glen Rose and the Edwards achieve diameters greater than 10 m. The trimodal terminology system of conduit, diffuse and fracture flow is merely a convenient means of discussing the major flow regimes in karst and will be used in this investigation as general descriptions of groundwater flow properties of the study area.

The trimodal permeability of karst aquifers usually produces a wide range of values of their hydrologic properties. For example, pump tests are usually of value in describing conditions in the immediate area of the wells and in the general diffuse flow portions of karst aquifers which are the most extensive; however, they seldom accurately represent the full range of permeabilities within karst aquifers, including those of conduits. Permeabilities within karst range over several orders of magnitude, from scales of meters per year to nearly 10 km/day in some parts of the Edwards Aquifer (Barton Springs/Edwards Aquifer Conservation District, 2003).

Most hydrogeologic studies to date have focused on the diffuse and fracture flow components of the karst aquifers in the study area, due to the ease of access from drilled wells. However, Worthington et al. (2000) demonstrated that while only 0.05 to 2.8% of groundwater in karst aquifers is stored within conduits, 94 to 99.7% of the water that moves through karst aquifers over time moves through conduits. This finding is critically important to groundwater supply and contaminant investigations, since it identifies conduits as the segments of karst aquifers to receive and transmit the largest volumes of water and pollutants.

The upper member of the Glen Rose Formation is the sole unit of the Upper Trinity Aquifer. This aquifer is unconfined and locally recharged. Although the upper Glen Rose contains enough clay and marl beds to make it the lower aquiclude for much of the Edwards Aquifer, its outcrop exposes enough limestone and dolomite beds to absorb some recharge. Regionally, there is little use or demand for the aquifer's groundwater because of its typically low yield and its occasional contact with gypsiferous zones that results in high sulfate concentrations. Yet in the north Bexar County and northeast Medina County areas, many privately owned wells tap upper Glen Rose water, especially since those areas have cavernous porosity that store and yield larger volumes of water. In addition to wells, the Upper Trinity also discharges through seeps and minor springs (Reeves, 1967; Ashworth, 1983).

Veni et al. (2002) conducted a detailed evaluation of permeability within the Upper Trinity Aquifer based on draft stratigraphic intervals, later published by Allan Clark (2003). The upper 12 m of Interval D was demonstrated as a highly permeability unit. A thin, 3-m-thick, but possibly important water-bearing section was identified in Interval B. Interval A, the uppermost 39 m of the upper Glen Rose, was found quite cavernous and permeable. This is highly significant since it varies the most from descriptions of the Glen Rose Formation in other areas. Throughout most of the Edwards Plateau and Balcones Fault Zone area, the upper member of the Glen Rose Formation is poorly karsted and considered to form the regional impermeable base of the Edwards Aquifer because sufficient interbedded clay and marl prevent significant groundwater recharge, movement, and storage. Nonetheless, a cavernous limestone interval occurs in the uppermost section of the upper Glen Rose in Bexar and parts of Comal and Medina counties and contains many of the largest caves in the region (e.g. Natural Bridge Caverns) and in the San Geronimo Valley (e.g. Goat Cave). Despite this occurrence of significant caves, cave entrances and karst features do not develop as readily where the cavernous unit is exposed in the outcrop. Clays and silts within the unit readily erode in the outcrop and settle into incipient karst features, reducing their permeability and their potential to develop into caves.

The Edwards Aquifer is a complex hydrologic system within the Edwards Limestone in the Balcones Fault Zone. It is divided into four segments: San Antonio, Barton Springs, Northern Balcones, and Washita Prairie (Yelderman, 1987). A drainage divide, an incised valley, and a gap of Edwards Limestone outcrop within the fault zone respectively separate the segments. The San Antonio Segment of the Edwards is divided into four zones: drainage or contributing zone, recharge zone, artesian or confined zone, and saline zone. The San Geronimo Valley is located in the contributing and recharge zones. The contributing zone is the upgradient Glen Rose area from which streams flow onto or cross the recharge zone, which is the exposure of Edwards Limestone within the fault zone where water enters the aquifer. The artesian zone is that area where the Edwards Limestone is down-faulted into the subsurface, and its groundwater is confined between upper and lower less permeable formations. The lowermost 10 km of San Geronimo Creek flow over the artesian zone. The aquifer's largest springs occur where artesian groundwater rises up fractures to discharge in stream valleys that intersect the potentiometric surface. The "bad water line" is the downgradient boundary of the artesian zone with the saline zone, where total dissolved solids in the groundwater exceed 1,000 mg/l. Groundwater flow in the aquifer is complicated but generally down-dip southward, then east or northeastward along strike. Studies of the aquifer are too many to mention in this report. For a detailed listing of Edwards Aquifer investigations, see the bibliography by Esquilin (1999).

The precise route of groundwater recharged in the San Geronimo Valley is not known. Tracer testing is the most effective means of delineating flow paths in karst, and while successful tracer studies have been performed in other areas of the Upper Trinity Aquifer and Edward Aquifer, none have been conducted in western Bexar County or anywhere in Medina County. Groundwater modeling studies by Maclay and Land (1988) and Kuniansky and Holligan (1994) suggest that groundwater flows predominantly south through the recharge zone in the study area until it reaches the Haby Crossing Fault. This fault juxtaposes the permeable rocks of the Glen Rose and Edwards formations against impermeable to poorly permeable rocks, creating a southward barrier to most groundwater flow. The models disagree at this point. Maclay and Land (1988) show some groundwater in the San Geronimo Valley moving northeast and around the fault in the Helotes area, but most flows southwest into the artesian zone, until it can flow south and east around the barrier, then northeast to discharge from the Comal Springs in New Braunfels. Kuniansky and Holligan's (1994) model suggests all San Geronimo flow moves northeast, while southwestward flow in the aquifer begins near the Medina River. But their model is based on fewer data for that area and may be less accurate in that locale. Both models agree with the geologic mapping and hydrologic data examined to date, but at their scale and without further research, conclusions about the directions and volumes of groundwater movement around the Haby Crossing Fault cannot be drawn.

**Water quantity and cross formational flow**

For many years, the water recharged into the lower member of the Glen Rose in the Cibolo Creek watershed has been believed to migrate into the Edwards Aquifer. George (1947) first proposed this groundwater link due to the lack of spring discharge from the Cibolo watershed and the extensive faulting that increased the probability of cross-formational flow. Tritium isotope studies later indicated that Cibolo recharge was a tributary to the Edwards Aquifer (Pearson, Rettman and Wyerman, 1975), and the bed and floodplain of Cibolo Creek were added to the state's regulatory maps that officially define the Edwards recharge zone. Waterreus's (1992) hydrogeologic thesis research of Camp Bullis further supported a connection to the Edwards, which was demonstrated by Veni (1995, 1997) and found to include all of the lower Glen Rose outcrop in the Cibolo basin. Groundwater modeling by Kuniansky and Holligan's (1994) and Mace et al. (2000) supported that conclusion. Despite these and other findings, the State-designated Edwards Aquifer recharge zone boundaries have not yet been revised in that area.

The cross-formational flow from the lower Glen Rose into the Edwards Aquifer is relevant to the San Geronimo Valley where similar observations have been made, demonstrating that significant volumes of water discharge from the cavernous zone of the upper Glen Rose into the Edwards Aquifer. This hydrologic connection was demonstrated in northern Bexar County by a continuous water table flowing downgradient from the upper Glen Rose into the Edwards, the absence of a lithologic barrier to impede flow, the presence of several recharge caves that cross from one unit into the other, supportive modeling by Kuniansky and Holligan's (1994) and Mace et al. (2000), and the lack of an outlet for the considerable recharge entering the upper Glen Rose (Veni, 1995). This last point is evident especially following storm events when relatively few streams on the upper Glen Rose discharge water onto the State-designated portion of the Edwards Aquifer recharge zone. Most streamflows, including those in San Geronimo Creek, are lost down fractures and sinkholes before reaching the recharge zone.

The volume of water recharging the Edwards Aquifer via the upper Glen Rose of the Upper Trinity Aquifer in the San Geronimo Valley has not been quantified, but an approximation can be made. From 1979 through 2002, the period of record for the San Geronimo Creek recharge dam (Hamilton et al., 2003), mean annual rainfall for the San Antonio area was 83.4 cm (National Weather Service website, http://www.srh.noaa.gov/ewx/html/cli/sat/satmonpcpn.htm). Veni (2001) examined evapotranspiration (ET) rates throughout Texas, including the San Antonio area, by use of historic potential evapotranspiration (PET) rates from the Texas Evapotranspiration Network website at Texas A&M University (http://texaset.tamu.edu/pet.php). The annual historic PET for San Antonio is 159.5 cm. This number exceeds mean annual rainfall and must be adjusted since most ET occurs during storms and not continuously as provided by the PET figures. Based on Veni's (2001) testing and findings, actual ET is possibly about 25% of PET, or 39.9 cm/year. The difference between mean annual rainfall and ET is 43.5 cm/year of precipitation that can runoff into

San Geronimo Creek or recharge the aquifer. Multiplying that precipitation value by the 142.6-$km^2$ area of the San Geronimo Valley's drainage basin yields a mean annual volume of 62,000,000 $m^3$. Hamilton et al. (2003) reported an average 1,000,000 $m^3$ of recharge at the San Geronimo Creek recharge dam. Since most recharge events do not overflow the dam to exit the recharge zone, it is safe to conclude that the majority of the remaining mean 61,000,000 $m^3$/year (49,400 acre-feet/year) sink underground as aquifer recharge. During baseflow and following small storm events, all of the water in San Geronimo Creek sinks into the upper Glen Rose well upstream of the recharge dam, further demonstrating that unit's capacity as an aquifer. As indicated in the previous paragraph, that recharge is transmitted into the Edwards Aquifer. While these values should not be considered anything more than rough estimates, even with a broad margin for error, they strongly support the field observations that substantial recharge occurs within the San Geronimo Valley.

In 1989, the Trinity Aquifer area in Bexar, Medina, and adjacent northern counties was listed as a critical water supply area by the state of Texas (Groundwater Protection Unit, 1989). Burgeoning growth in the region is putting considerable stress on the aquifer's water resources. Mace et al.'s (2000) groundwater modeling study of the Trinity Aquifer does not show the impact of increased pumping on the Upper Trinity Aquifer. However, it does project that the Middle Trinity Aquifer in much of northern Bexar County will likely have its groundwater depleted by the year 2020 due to increased demand and if the drought of record is repeated, and probably by 2050 by increased demand alone. Since the Upper Trinity Aquifer has much less storage than the Middle Trinity, it will probably be even more rapidly affected by increased pumping.

**Water quality**

Another water management concern for the San Geronimo Valley involves groundwater contamination which occurs easily in karst aquifers. The Ground Water Protection Unit (1989) of the Texas Water Commission listed the karst aquifers of Texas as generally having the greatest pollution potential of all the state's aquifers. The Trinity Aquifer group was listed as having the sixth highest pollution potential of the ten major Texas aquifers; it is likely that the Upper Trinity in the San Antonio area would have received a higher rank if it had been considered separate from the non-karst segments of the Trinity group. Karst aquifers are widely recognized as the type of aquifer most vulnerable to contamination. For detailed reviews of environmental problems that can afflict karst areas, see White (1988), Ford and Williams (1989), Drew and Hötzl. (1999), Veni and DuChene (2001), and Gunn (2004).

The Edwards Aquifer is the primary water supply for the City of San Antonio and approximately 1.5 million people. The aquifer has been the subject of intense political and public debates on the management of its water quantity and quality. The growing population and demand for aquifer water in the region has led to efforts to increase the volume of recharge entering the aquifer, such as the construction of recharge enhancement structures (e.g. Hamilton et al, 2003). However, some of this growth and its urban development have been on the recharge zone where water enters the aquifer. This has prompted concern about potential groundwater contamination and recharge reduction. Kipp, Farrington, and Albach (1993) concluded that under existing management conditions, contamination of the Edwards Aquifer was "imminent," and since their study, reports of contamination of aquifer wells have increased.

On 6 May 2000, the citizens of San Antonio voted to approve the ballot item listed as "Proposition 3," a 1/8 cent sales tax to raise $65 million over four years for the purchase of environmentally sensitive lands within the city's limits and extraterritorial jurisdiction within Bexar

County. Of that total, $45 million were allocated for the purchase and management of land over the Edwards Aquifer recharge and contributing zones. The purpose of the land purchases is to reduce adverse impacts on surface and groundwater quality by preserving critical, undeveloped lands to maintain natural, uncontaminated flows into the aquifer and creeks. The City organized a Scientific Evaluation Team to provide scientifically based information to identify properties for possible acquisition (Veni et al., 2001). Some of the larger, sensitive tracts identified were within the San Geronimo Valley. Allan Clark (2000) also identified areas of relatively higher vulnerability to groundwater contamination in the valley within Bexar County's portion of the Edwards Aquifer recharge zone. Amy Clark (2003b) had similar findings for the area to the north on the aquifer's contributing zone.

**Caves and karst features**

The San Geronimo Valley is a karst area underlain by karst aquifers. Caves and karst features are primary sources of hydrogeologic data in such areas and give significant insights into the structure and function of the aquifers. They also provide underground habitat that can be occupied by rare and federally listed endangered species.

Few caves are recorded in the files of the Texas Speleological Survey (TSS) within the San Geronimo Valley. Reddell (1967) published a TSS report on the caves of Medina County and listed only Goat Cave. Veni (1988) provided a review of 208 caves in Bexar County, but none from the San Geronimo Valley. This seeming lack of caves is only an explorational bias. The area has not been generally searched for caves and/or few results of searches have been reported. Within Goat Cave in the San Geronimo Valley are some of the largest passages and rooms known in Medina County. In the adjacent and geologically identical Government Canyon State Natural Area, Miller (2004) reported 38 caves and 258 karst features known to date. Neal Hernandez (personal communication, 2004) reported 12 caves and one karst feature in just a 1.8-$km^2$ area of the valley's western margin. Doubtless many caves and karst features occur in the San Geronimo Valley and remain to be found. Detailed hydrogeological studies of caves in the general Bexar County area were conducted by Veni (1987, 1994, 1996, 2002).

**Soils and epikarst**

This report focuses on the karst features, hydrogeology, and karst ecosystems of the San Geronimo Valley, for which it is important to understand the epikarst. Many caves in the area have small entrances that capture little surface water. Much of their water, nutrient, and potential contaminant input is derived through epikarstic features and related shallow vadose flowpaths.

Most published data relating to epikarst in the study area are soil studies. The soil survey of Bexar County (Taylor, Hailey, and Richmond, 1966) and Medina County (Dittmar, Deike, and Richmond, 1977) shows primarily Tarrant and Brackett series soils. These soils are dark brown to black, poorly permeable, stony, usually <1 m deep, and often absent. They frequently lack sufficient thickness and lateral extent to retard groundwater recharge. Where they are relatively thick, the soils crack deeply during dry conditions and allow rapid recharge when rain falls. Consequently, the soils, while described as poorly permeable, do not significantly mitigate for contaminants on the surface. They allow substantial surface water to readily enter the limestone formations to recharge their local aquifers, even supporting perennial springflows in very steep and less permeable sections of the upper Glen Rose.

The extent of the epikarst and interstitial zone of upper Glen Rose caves varies far more than Kainer Formation caves. Interbedded clays are easily eroded in the upper Glen Rose and deposited in small fractures and conduits where they reduce permeability. This occurs both within caves and within karst features exposed on the surface. The upper Glen Rose has better interstitial development where clay and marl interbeds are fewer and thinner.

Excavation of karst features in the upper Glen Rose and Kainer Formation provides insights into the local epikarst. The presence of brown or reddish-brown soil of the B and C soil horizon indicates a karst feature will probably not open to a cave. Cavities at the land surface within marly beds, especially in the upper Glen Rose or the Kainer's Basal Nodular Member, have a high probability of being animal burrows or stump holes. Open fractures that parallel the contours of a hillside have a high probability of being stress-release slumpage features. The epikarst surface on the upper Glen Rose and Kainer is relatively smooth, and gently rises and falls toward valleys, sinkholes, and some cave entrances. Solutionally enlarged fractures are common but are narrow, highly localized, and do not significantly disrupt the mean epikarst topography.

Veni (1997) found that the epikarst and noncavernous portions of the vadose zone in the lower member of the Glen Rose Formation, which is not present in the study area, are hydrologically and chemically indistinguishable in areas with little or no soil cover. Much of the water storage and carbon dioxide production usually thought to occur in the epikarst was found within the vadose zone. The same conditions probably occur in the upper Glen Rose and Kainer where there is little soil cover.

**Endangered Karst Ecosystems**

The Bexar County, Texas region is hydrogeologically and biologically complex. Species living in its caves have become physically isolated from each other through time, resulting in genetic isolation that has produced new species known to occur only within small geographic areas. The northward expansion of San Antonio onto the karst where these species occur poses a threat to their survival due to the destruction of caves, sealing of caves, changes in nutrient and moisture input into caves, contaminants introduced into caves, and competition with and predation by non-native species introduced by urbanization (Elliott, 1993 and 2000).

To insure their survival, nine species of karst invertebrates were federally listed as endangered by the USFWS in December 2000 (USFWS, 2000):

*Batrisodes (Excavodes) venyivi*
*Cicurina (Cicurella) baronia*
*Cicurina (Cicurella) madla*
*Cicurina (Cicurella) venii*
*Cicurina (Cicurella) vespera*
*Neoleptoneta microps*
*Rhadine exilis*
*Rhadine infernalis*
*Texella cokendolpheri*

Veni (1994) examined the effects of the geology of the Bexar County area on the distribution of the species, which were petitioned for listing at the time, and that of other troglobite species identified by Reddell (1994a). That report included a series of 14 maps drawn on the U.S. Geological Survey (USGS) 7.5' topographic quadrangles for the area that delineated five zones that identified the probability of the presence of rare or endemic species. Those zones were updated and slightly redefined by Veni (2002) as:

**Zone 1.** Areas known to contain listed invertebrate karst species.

**Zone 2.** Areas having a high probability of containing suitable habitat for listed invertebrate karst species.

**Zone 3.** Areas that probably do not contain listed invertebrate karst species.

**Zone 4.** Areas which require further research but are generally equivalent to Zone 3, although they may include sections which could be classified as Zone 2 or Zone 5 as more information becomes available.

**Zone 5.** Areas which do not contain listed invertebrate karst species.

Veni (1994) divided the Bexar County karst for USFWS into six karst fauna regions. The Government Canyon Karst Fauna Region was defined as:

*Includes the outcrop of the Edwards Limestone and the immediate down-slope outcrop of the upper member of the Glen Rose Formation. Bounded to the north by a major fault, to the east by Los Reyes Creek, to the south by the Haby Crossing Fault, and to the west by San Geronimo Creek. Faulting is moderate.*

Veni (1994) noted this karst fauna region probably extended west from San Geronimo Creek and Bexar County to the Medina River in Medina County, but did not map karst zones for that area since no caves were known there. However, since the 1994 zone mapping, over 90 caves have been found in the Government Canyon Karst Fauna Region, whereas only one had been known. Most of the caves have not been biologically surveyed, but 15 are known to contain listed species, and three caves are reported to contain the species and await confirmation. These findings demonstrate the likelihood that several caves, some with listed species, will occur in the largely unexamined karst west of San Geronimo Creek. As a result, Veni (2002) extended the boundary of the Government Canyon Karst Region west to the Medina River.

Currently, Karst Zone 1 fills most of the Government Canyon Karst Fauna Region from its east end near Helotes to slightly west of the Government Canyon valley. Further west, the area, including the southern half of the San Geronimo Valley, was classified by Veni (2002) as Karst Zone 2. One finding of that study, in comparison to the original mapping by Veni (1994), was that in areas where adequate biological surveys for the species have been conducted in Karst Zone 2, listed species have been found to redesignate them as Karst Zone 1. This does not mean that listed species were found in every cave of a Karst Zone 2 area, since not every cave contains appropriate habitat for the species. But it does strongly suggest that listed species will be found in caves of the San Geronimo Valley. The listed species currently known in the Government Canyon Karst Fauna Region are the spiders *Cicurina vespera* and *Neoleptoneta microps*, the mold beetle *Batrisodes venyivi*, and the ground beetles *Rhadine exilis* and *Rhadine infernalis infernalis* (Veni, 2002).

Southeast of the San Geronimo Valley, federally listed endangered karst invertebrates are also known from the Culebra Anticline Karst Fauna Region, which Veni (1994) defined as:

*Includes the outcrops of the Austin Chalk and Pecan Gap Chalk along the Culebra Anticline, extending west from Culebra Creek to the end of the outcrops about 3 km into Medina County. Faulting is little to moderate.*

While small cave streams are known in this karst fauna region, the groundwater is not tapped for use, and so its hydrologic vulnerability relative to contaminating a drinking water supply is not considered in this report. Karst Zone 1 occurs as a large central area and a smaller area to the east along Loop 1604. The rest of the karst fauna region is defined as Karst Zone 2 and 3. Known listed species in the Culebra Anticline Karst Fauna Region are the spider *Cicurina venii* and the ground beetle *Rhadine infernalis* new subspecies (Veni, 2002).

For more information on geological and biological studies relating to area caves containing federally listed endangered species, see Reddell (1994a), USFWS (2000, 20001a, 2001b), and Veni (1994, 1996, 2002). O'Donnell, Elliott, and Stanford (1994) presented a recovery plan for related endangered karst invertebrates near Austin; Campbell (1995) and USFWS (2001c) discussed management of those species. Elliott (1993), Reddell (1994b), and Elliott (1994) provided overviews of issues and research on Texas cave fauna.

## Comparative Evaluation of Proposed Transmission Line Routes Through the San Geronimo Valley Area

CPS has not defined specific routes for the proposed transmission line. Instead, possible route segments have been defined which may be connected in such a way as to create the most favorable route. The following evaluation connects some segments into three possible routes for comparison: two northward routes across the recharge zone toward the LCRA Kendall Substation and one route northwest toward Medina Lake. For this report, only the routes over the Edwards Aquifer recharge zone and the area immediately to the north that also recharge the aquifer are considered. The area further north in the aquifer's contributing zone and the area south of the recharge zone are not addressed. As described earlier in this report, these three areas are for the most part hydrogeologically and biologically distinct and can be addressed individually. The transmission line segments discussed below are illustrated on the map attached at the end of this report, listed as "Map C, Proposed Alternative Routes as of January 29, 2004," prepared by PBS&J, Inc., for CPS.

**Edwards Aquifer Recharge Zone Routes**

Two primary routes extend northward across the Edwards Aquifer recharge zone and Karst Zone 2 in the Government Canyon Karst Fauna Region. Both routes begin at the north end of Segment T, extending north along Highway 211. The eastern recharge zone route continues along Highway 211, veering northeast to Segment W, Segment CC, and then Segment GG on the north side of the recharge zone. The central recharge zone route leaves Highway 211 and heads north along Segment V and then Segment X to exit the recharge zone. It continues north via Segment AA, then northeast into Bexar County along Segment FF. A third, western recharge zone route extends across the recharge zone and Karst Zone 2. It is defined by Segment ML1 which follows FM 1283 northwestward to tie into a proposed LCRA line running from the Medina Lake Substation.

Table 1 compares the positive and negative environmental attributes of the eastern, central, and western recharge zone routes and considers primarily water and endangered karst invertebrate issues. The western recharge zone route (Segment ML1) poses the fewest environmental impacts directly associated with the construction and maintenance of the transmission line due to the existing impacts of FM 1283, by far the shortest distance over the recharge zone and Karst Zone 2, and the likely presence of fewer of the listed species (allowing for easier mitigation if the species are found). The eastern recharge zone route is next in terms of minimizing potential impacts to endangered species and water quality impacts, although visual impacts would be highest along this route.

Indirect impacts from potential associated urbanization would be higher along the eastern recharge zone route due to the higher density of development it would probably support and the area's lesser capacity to dilute contaminants within a relatively short distance. However, placement of the line along the eastern or central recharge zone route will almost certainly not limit any subsequent urbanization to those locations and will extend over both areas. This renders any comparison of indirect impacts from possible urbanization along these routes as moot, since it is highly probably that both areas would be impacted regardless of which route was selected.

Since the western recharge zone route is not in the San Geronimo Valley, but along a road with suburban development associated with Medina Lake, it is not clear what indirect impacts would occur, if any, that could not be ascribed to Medina Lake area development. All three routes are essentially the same in their ability to easily and rapidly transmit contaminants to the Edwards Aquifer with little or no filtration.

**Table 1**
**Comparison of Edwards Aquifer Recharge Zone Routes**

| **Eastern Recharge Zone Route (State Highway 211)** | **Central Recharge Zone Route (San Geronimo Creek area)** | **Western Recharge Zone Route (FM 1283)** |
|---|---|---|
| Segments W and CC extend the greatest distance, about 8.4 km, over the Edwards Aquifer recharge zone and Karst Zone 2. | Segments V, X, and AA have a combined length of about 7.4 km with 3.7 km on the State-designated portion of the recharge zone. However, the entire length of these segments is within an area that without any doubt recharges the Edwards Aquifer, regardless of the state boundaries which need updating, and entirely within Karst Zone 2. | Segment ML1 has the shortest extent over the Edwards Aquifer recharge zone and Karst Zone 2 at a length of about 3.8 km. |
| Segments W and CC extend along Highway 211 where the probability of new water quality and endangered species impacts are decreased due to the pre-existing impacts of the highway. | Segments V, X, and AA extend through unimpacted and relatively unimpacted areas where the probability of new water quality and endangered species impacts is increased. | Segment ML1 extends along FM 1283 where the probability of new water quality and endangered species impacts are decreased due to the pre-existing impacts of the roadway |
| The probability of finding new endangered species localities is limited mostly to caves found while installing new transmission towers. | New endangered species localities might be found while installing new transmission towers, but will much more likely be found while clearing the easement for the towers and maintenance/construction roads. | If the transmission line is constructed in an area already impacted by the construction of FM 1283 and associated infrastructure, the probability of finding new endangered species localities is limited mostly to caves found while installing new transmission towers. If undisturbed land will need to be cleared, the chance of finding a cave with endangered species will increase significantly. |
| The endangered karst species mostly likely to occur along this route are *Cicurina vespera*, *Neoleptoneta microps*, *Rhadine exilis*, and *Rhadine infernalis infernalis*. *Batrisodes venyivi* is a less mobile species and may not range into this area. | The endangered karst species mostly likely to occur along this route are *Cicurina vespera*, *Neoleptoneta microps*, *Rhadine exilis*, and *Rhadine infernalis infernalis*. *Batrisodes venyivi* is a less mobile species and may not range into this area. | The endangered karst species mostly likely to occur along this route are *Rhadine exilis* and *Rhadine infernalis infernalis*. *Batrisodes venyivi*, *Cicurina vespera*, and *Neoleptoneta microps* are less mobile species and may not range into this area. |
| Access and maintenance to the transmission line, and emergency response in the event of a spill or contaminant release along the line, especially during periods of adverse weather, will be relatively easy due to access along Highway 211. | Access and maintenance to the transmission line, and emergency response in the event of a spill or contaminant release along the line, especially during periods of adverse weather, will be relatively difficult along the unpaved and gated roads to be built in the line's easement. | Access and maintenance to the transmission line, and emergency response in the event of a spill or contaminant release along the line, especially during periods of adverse weather, will be relatively easy due to access along FM 1283. |

**Table 1 (continued)**
**Comparison of Edwards Aquifer Recharge Zone Routes**

| Eastern Recharge Zone Route (State Highway 211) | Central Recharge Zone Route (San Geronimo Creek area) | Western Recharge Zone Route (FM 1283) |
|---|---|---|
| Without a deliberate or careful survey, 11 caves and two karst features are currently known within 150 m of Highway 211 over a distance of 3.5 km (USFWS [2001a] requires surveys for caves and karst features out to 150 m from an area of potential impact). None of the caves have been investigated for endangered species, which are likely present in several. If this distribution is representative of the minimum distribution of caves in that area, 32 caves within 150 m of Highway 211 are likely to be encountered. | No caves have been reported within 150 m of the central recharge zone route, but several are said to be in the area, which is consistent with the geology. This route is likely to contain a distribution of caves similar to the eastern recharge zone route, but proportionately fewer given this route's shorter length, and several are likely to contain endangered species. | No caves have been reported within 150 m of the western recharge zone route, but several are said to be in the area, which is consistent with the geology. This route is likely to contain a distribution of caves similar to the eastern recharge zone route, but proportionately far fewer given this route's much shorter length, and several are likely to contain endangered species. |
| The visual impact of the transmission line along the eastern recharge zone route would affect a high number of people because it follows a ridge between the San Geronimo and Government Canyon valleys and will be easily seen. Some of this impact would be ameliorated by the pre-existing visual impact of the highway, homes, and businesses in the area. The transmission line will impact some of the vistas of Government Canyon State Natural Area. | The visual impact of the transmission line along the central recharge zone route will affect the fewest people due to its less visible location in the San Geronimo Valley. However, due to the lack of pre-existing infrastructure in the valley, its visual impact will be proportionally greater when observed as compared to a line located in an already impacted area. | The visual impact of the transmission line along the western recharge zone route would affect a moderate number of people. It would be more easily seen where it would rise onto a narrow ridge between Lime Kiln Creek and Deep Creek, and be less visible within the creek valleys. Some of this impact would be ameliorated by the pre-existing visual impact of the roadway. |
| Potential habitat for endangered bird species occurs throughout the Highway 211 area but is already compromised by the highway and associated development. The addition of the transmission may have little or no additional impact and certainly much less adverse effect than in an area not already impacted. | Potential habitat for endangered bird species occurs throughout much of the central recharge zone route. This area is undeveloped, and the addition of the transmission line will almost certainly result in a much greater impact on the species than installation of the line along Highway 211 or FM 1283. | Potential habitat for endangered bird species occurs throughout the FM 1283 area but is already compromised by the roadway. The addition of the transmission may have little or no additional impact and certainly much less adverse effect than in an area not already impacted. |

**Table 1 (continued)**
**Comparison of Edwards Aquifer Recharge Zone Routes**

<table>
<tr><th>Eastern Recharge Zone Route<br>(State Highway 211)</th><th>Central Recharge Zone Route<br>(San Geronimo Creek area)</th><th>Western Recharge Zone Route<br>(FM 1283)</th></tr>
<tr><td>An environmental constraints map produced by PBS&J, Inc., for CPS shows several archeological sites at the south end of Segment V and Segment W, which are common to both the eastern and central recharge zone routes. The map shows four other sites along Highway 211, but these have likely been mitigated for during construction of the highway. The addition of the transmission line will likely have little or no additional impact.</td><td>An environmental constraints map produced by PBS&J, Inc., for CPS shows several archeological sites at the south end of Segment V and Segment W, which are common to both the eastern and central recharge zone routes. The map shows no other sites near the central route, but this area has not been archeologically surveyed. Given that many and often more significant archeological sites occur near streams, the placement of the central recharge zone route near San Geronimo Creek will likely result in the discovery of several new and potentially important archeological sites.</td><td>An environmental constraints map produced by PBS&J, Inc., for CPS shows no archeological sites associated with this route. The presence of FM 1283 suggests that either archeological surveys were conducted during its construction and/or any existing sites were impacted at that time, possibly reducing the need for mitigation from the construction of the transmission line.</td></tr>
<tr><td colspan="3">There is general concern that the construction of the transmission through the San Geronimo Valley will result in landowners selling their properties for urban development, which in turn, will increase the potential for contamination of the Edwards Aquifer. It is beyond the scope of this report to determine the likelihood of such actions, but below is a comparison of potential impacts should widespread development occur.</td></tr>
<tr><td>The area along Highway 211 is more prone to higher density development due to the presence of roughly level upland areas outside of floodplains and closer proximity to San Antonio. Higher density development equates to higher impervious cover with higher levels of water quality and general environmental impacts (Schuler, 1984).</td><td>The central recharge zone route through the San Geronimo Valley is a hillier terrain which would force a lower density of development, along with the presence of floodplains in lowlands and less accessibility from San Antonio. Lower density development equates to lower impervious cover with lower levels of water quality and general environmental impacts (Schuler, 1984).</td><td>The western recharge zone route is outside of the San Geronimo Valley and the least likely to encourage development in that area. It is similar to the central recharge zone route with a hillier terrain that would force a lower density of development. Lower density development equates to lower impervious cover with lower levels of water quality and general environmental impacts (Schuler, 1984).</td></tr>
<tr><td>In the event of a contaminant release, such as a fuel spill from a vehicle, the contaminants would likely travel relatively longer distances and impact more wells before being diluted due to the lesser volume of recharge that occurs in the upland areas than near creeks.</td><td>In the event of a contaminant release, such as a fuel spill from a vehicle, the contaminants would likely travel relatively shorter distances and impact fewer wells before being diluted due to the greater volume of recharge that occurs in creek areas than in the uplands.</td><td>In the event of a contaminant release, such as a fuel spill from a vehicle, the contaminants would likely travel relatively longer distances and impact more wells before being diluted due to the lesser volume of recharge that occurs in the upland areas than near creeks.</td></tr>
</table>

## Conclusions

The following conclusions are based on the data available for this report. They consider only potential environmental impacts and not costs, although, in general costs will likely be higher for a transmission route that is longer and/or extends through areas where more or greater environmental impacts may occur and require study and mitigation.

1) Environmental impacts from the proposed transmission line can be divided into three areas containing similar environmental issues: the Edwards Aquifer recharge zone and areas to the north and south. Only the Edwards Aquifer recharge zone and associated recharge areas to the north are considered in this report.

2) In the Edwards Aquifer recharge zone, all three routes examined in this report occur over areas that can readily transmit contaminants with little or no filtration to the Edwards Aquifer. They also all occur in Karst Zone 2, where there is a high probability that endangered karst species occur.

3) The western recharge zone route toward Medina Lake offers the lowest potential for environmental impacts of the three Edwards Aquifer recharge zone routes. By far, it covers the shortest distance over the recharge zone and Karst Zone 2. It follows the existing road FM 1283 where pre-existing impacts occur, so additional impacts from the transmission line would probably be few and minor. This route is also the least likely to encourage urban development within the San Geronimo Valley

4) The eastern recharge zone route has the longest extent over the recharge zone and Karst Zone 2 and is near several known caves. But because it follows Highway 211, it would almost certainly result in significantly fewer environmental impacts than the central recharge zone route through the middle of the San Geronimo Valley.

5) Indirect impacts associated with urbanization potentially prompted by the transmission line cannot be clearly evaluated between the eastern and central recharge zone route. Given their close proximity, urbanization would likely extend to both areas regardless of which route was selected.

## Recommendations

Karst areas are well known to have complex groundwater flow paths which are very sensitive to contamination and can impact human groundwater supplies and endangered karst species habitat. The following recommendations are based on this premise and the data of this study.

1) The north-south routes through the Edwards Aquifer recharge zone along Highway 211 and the middle of San Geronimo Valley should be avoided. They pose the highest risk of environmental impact to both the region's primary water supply and endangered species. The western route along FM1283, via Segment ML1, is by far the most favorable route because it poses the lowest risk of environmental impact. Additionally, its much shorter length over environmentally sensitive areas should make it cost-competitive, if not cheaper, than the other routes.

) It is beyond the scope of this report to evaluate the likelihood that urban development of the San Geronimo Valley would result from the construction of a transmission line in that location. However, it is important to note that the City of San Antonio and the State of Texas have invested millions of dollars in purchasing Government Canyon State Natural Area and several surrounding properties to help buffer the Edwards Aquifer from the increasing levels of urban development in the area which threaten the aquifer's quality and quantity. The San Geronimo Valley is adjacent to Government Canyon and currently, in its mostly undeveloped state, is equally important to protecting the water quality of the region. CPS and other agencies, the City of San Antonio, Bexar and Medina counties, and the property owners of the San Geronimo Valley should conduct and support actions that maintain the valley in its natural state for their benefit and that of the region.

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# APPENDIX A

## Glossary of Geological, Karst, and Biological Terminology

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

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

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

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

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

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

***Attitude:*** The position of a bed of rock with respect to the horizontal plane; typically measured as strike and dip.

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

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

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

***Beds:*** See strata.

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

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

***Chert:*** A microcrystalline silica rock, often found as nodules or small lens in limestone and dolomite; it is essentially the same as "flint."

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

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

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

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

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

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

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

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

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

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

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

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

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

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

***Endogean:*** Pertaining to species living beneath the surface of the earth, although not necessarily in a cave.

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

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

***Facies:*** The characteristic appearance or aspect of a rock unit; often subclassified or described based on stratigraphy, fossils, mineralogy, lithology, and other similar factors.

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

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

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

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

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

***Hillside slump:*** A non-tectonically formed slumping or downward movement of bedrock that has broken away from intact bedrock. It may initially originate as a stress release fracture but once detached the rock moves downslope by gravity; see *stress release fracture* for non-displaced and non-tectonically formed fractures.

***Holocene:*** An epoch of the Quaternary Period of the geologic time scale that began about 10,000 years ago and continues to the present.

***Homoclinal hinge:*** The axis of a single, uniform bend in strata.

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

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

***Hydraulic gradient:*** The continuous descending profile of a stream or an aquifer's water table or potentiometric surface from areas of water input to areas of discharge.

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

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

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

***Impermeable:*** Does not allow the significant transmission of fluids.

***Interstitial zone:*** Conduits of an aquifer and/or cave that are too small for human access; can be located both above and below the water table. Generally used to describe a type of habitat for cavernicole fauna. May include inferred conduits of probable humanly passable dimensions, but which are inaccessible for study.

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

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

***Karst fauna region:*** Regions defined by the U.S. Fish and Wildlife Service, based on hydrogeological barriers and/or restrictions to the migration of troglobites over evolutionary time, that result in speciation between regions and the creation of similar groups of troglobites within the caves of a particular region.

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

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

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

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

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

***Lithology:*** The description or physical characteristics of a rock.

***Loam:*** A rich, permeable soil with generally equal parts of sand, silt, and clay.
***Marl:*** Rock composed of a predominant mixture of clay and limestone.

***Miocene:*** An epoch of the Tertiary Period of the geologic time scale that occurred between 5 and 23 million years ago.

***Nodular:*** Composed of nodules (rounded mineral aggregates).

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

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

***Permeable:*** Allows the significant transmission of fluids.

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

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

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

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

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

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

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

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

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

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

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

***Soil horizons:*** Layers of soil, each of certain characteristics. The A and B horizons are nearest the surface, have the greatest amount of plant activity, are composed of decomposed organic material and inorganic sediment, and correlate to the cutaneous zone; the C horizon is the deepest, has minimal plant activity, is composed predominantly of weathered bedrock, and correlates to the subcutaneous zone.

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

***Stress release fracture:*** A non-tectonically formed fracture formed by the release of pressure that once confined the rock. Most commonly associated with fractures parallel to valleys where the released stress is perpendicular to the topographic contours. Rock on fracture side where stress was released has little or no notable displacement from the intact bedrock; see *hillside slump* for displaced rock.

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

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

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

***Stress-release:*** Generally refers to fractures which form as rocks expand following the loss of overlying or lateral pressure; commonly seen along hillsides and cliffs as fractures that run parallel to the topographic contours.

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

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

***Stump hole:*** A depression that resembles a sinkhole, but is formed by tree growth and is present after the tree has rotted away; often maintains a sinkhole-like appearance by burrowing mammals.

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

***Troglobite:*** A species of animal that is restricted to the subterranean environment and which typically exhibits morphological adaptations to that environment, such as elongated appendages and loss or reduction of eyes and pigment.

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

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

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

***upper Glen Rose:*** Pertaining to the upper member of the Glen Rose Formation.

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

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

# APPENDIX B

## Conversions:
## International System of Units to English Units

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

# APPENDIX C

## Biography of Research Personnel

The appendix provides brief biographical information on the personnel who conducted the fieldwork for this investigation or wrote or conducted key research for the report. This appendix also meets the U.S. Fish and Wildlife Service guidelines for biographical data on personnel associated with the collection, study, and related research on the endangered karst invertebrates that occur in the study area (USFWS, 2000, 2001a, 2001b). In meeting with those guidelines, the author of this report certifies direct responsibility for this report, that it is true, complete, and accurate, to the best of his knowledge, that the personnel involved were capable of performing their assigned tasks and did so as best as reasonably possible, and that non-supervisory personnel were supervised when needed.

**Dr. George Veni** is an internationally recognized hydrogeologist specializing in caves and karst terrains (Texas registered professional geologist license no. 682). He received his Master's degree from Western Kentucky University in 1985 and his Ph.D. from the Pennsylvania State University in 1994. Since 1987 he has owned and served as principal investigator of George Veni and Associates. Much of his work has been in central Texas, but he has also conducted extensive karst research throughout the United States and in several other countries. Among his organizational activities, he is currently President of the Texas Speleological Survey, Executive Secretary of the National Speleological Society's Section of Cave Geology and Geography, and is a member of the governing board of the International Union of Speleology. He serves as a doctoral committee advisor for geological and biological dissertations at The University of Texas and teaches karst geoscience courses as an adjunct professor for Western Kentucky University. He has taken college level biology courses, including Karst Ecology at Western Kentucky University, and has been collecting cave species and assisting in the study of cave ecosystems since 1976. Three cave-dwelling species have been named in his honor. He has published and presented over 100 papers, including four books, on hydrogeology, biology, and environmental management in karst terrains. He holds U.S. Fish and Wildlife Service Permit TE026436-0 (expires 31 August 2005) to collect and study federally listed endangered Texas karst invertebrate species.