

THE CHEMICAL AND BIOLOGICAL GROUNDWATER QUALITY
OF THE EDWARDS AQUIFER IN THE SINK CREEK DRAINAGE
BASIN, HAYS COUNTY, TEXAS

A thesis submitted in partial fulfillment of
the requirements for the degree of
Master of Science

By

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ABSTRACT

A study of chemical and biological groundwater quality was conducted in an area of the Edwards Aquifer recharge zone, the Sink Creek Drainage in the Guadalupe River Basin. This study is based on evidence of bacterial contamination of groundwater found in the San Marcos area during a hydrogeological study of the spring and groundwater flow (Ogden, Quick, Rothermal and Lunsford, 1986). The study revealed high levels of fecal and total coliforms in several test wells following a large rainfall. To expand on these findings a study was developed in an effort to determine the possible sources and frequency of bacterial contamination of local water wells.

The study site was the Country Estates Subdivision west of San Marcos. The subdivision is located adjacent to Sink Creek and the Williamson-Freeman Flood/Control Recharge Structure. The flood control/recharge structure, built over Sink Creek, is located on the Freeman Ranch. The flood plain is used for grazing cattle. The fecal material from these cattle was thought to be the primary source for bacterial contamination of the wells in the area.

Twenty-two wells were sampled before, during and after rainfall events for a period of one year from July 1985 to June 1986. Samples collected for bacterial and chemical analysis were run using U.S. Environmental Protection Agency (1984) approved methods. Bacterial analysis for fecal and total coliforms was done using the membrane filter technique. These indicator organisms were used to detect the possible presence of pathogens in the water. Chemical analysis was done to find any patterns or changes in the water chemistry before, during and after rainfall events.

The largest rainfall occurred in late November 1985 (sample days 130 to 132) and May/June 1986 (sample days 316 to 335). Although rainfall did

occur in September and October 1985, these rainfalls were less important than the others because they followed a long period of drought. The two largest rainfalls corresponded to changes in both the concentration of chemical constituents and the levels of bacterial contamination. Decreases in chemical concentrations were found following the two largest rainfalls. This was due to the rapid recharge of surface runoff in the area of the contaminated wells. The chemical concentrations in surface water were lower and mixing with the groundwater caused a dilution effect within the groundwater. The uncontaminated wells showed no distinct changes following rainfall events.

Fecal and total coliforms showed similar peaks following the two major rainfall events in November 1985 and May/June 1986. Increases in the coliform levels corresponded to the decreased concentrations of the chemical constituents. The presence of coliforms during other periods of rainfall was evident, but not in the same order of magnitude. Rainfall which occurred over a longer period of time had less impact on water quality. Only heavy rainfall occurring over a short period of time caused counts greater than 200 colonies/100 ml in the test wells. To aid in determining possible sources of contamination, fecal coliform/fecal streptococcus (FC/FS) ratios were calculated for ten of the most heavily contaminated wells. The major source indicated by the FC/FS ratios was found to be non-human.

Bacteriological contamination occurred in 68.2% of the wells sampled with 40% of those wells having coliform counts > 200 colonies /100 ml. Contamination had a direct relation to the turbidity in wells following heavy rainfall.

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INTRODUCTION

The importance of groundwater quality is of growing concern in the United States. Forty-eight percent of the United States population relies on groundwater with 94% of that population living in rural areas. Texas ranks second among the five states with the largest daily consumption of groundwater (9.7 billion gallons per day). In Texas 58% of the 4.5 million people being served by public water supplies rely on groundwater. Another estimated two million people living in rural areas rely on groundwater for 100% of their water supply (Canter, Knox and Fairchild,1987; Patrick, Ford and Quarles,1987).

The Edwards aquifer is one the largest and most productive aquifers in the United States. The aquifer is located along the Balcones Escarpment in one of the largest contiguous karst regions in the United States (Fig. 1). As the principle source of water for the central Texas region this aquifer supplies water to large municipalities, irrigation systems, major springs and supports several rare and endangered species of wildlife found within the aquifer system and in the San Marcos River. The importance of the aquifer to this area of Texas is demonstrated by the Federal government having designated it as the first "sole source" aquifer in the United States (USEPA,1985; Rothermal,1984; Kastning,1984; Longley,1981).

The towns and cities located over the Edwards aquifer are growing. The aquifer supplies water to over a million area residents. Rapid increases in growth over the recharge zone creates the potential for adverse affects to the quality and quantity of groundwater in the Edwards aquifer. As individuals move into rural developments not serviced by municipal water supplies, homeowners are utilizing the aquifer by drilling private wells. An often incorrect assumption made by these homeowners is that the water they are pumping from the ground is pure and free from any kind of

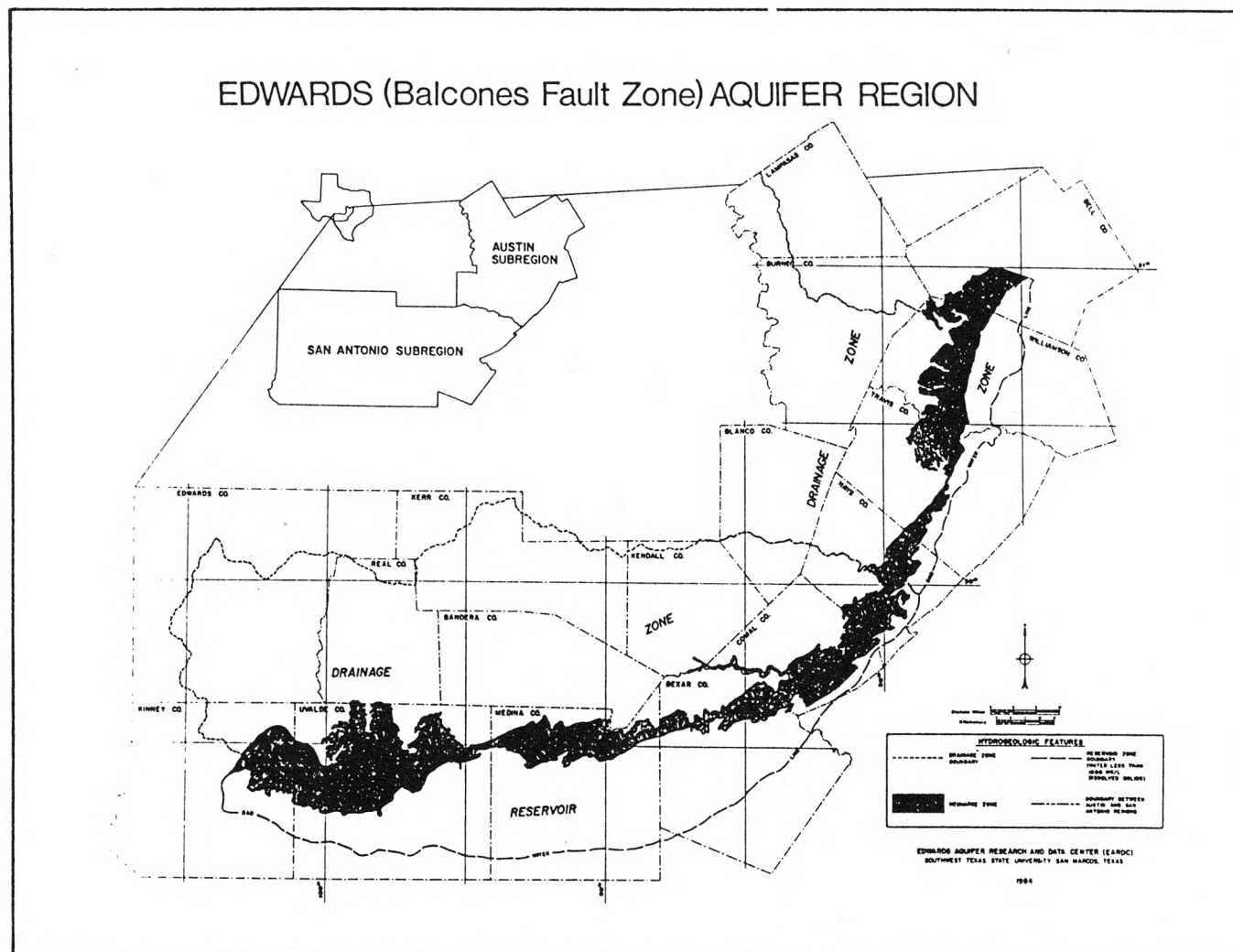


Fig. 1. The Edwards (Balcones Fault Zone) aquifer San Antonio and Austin Subregions.

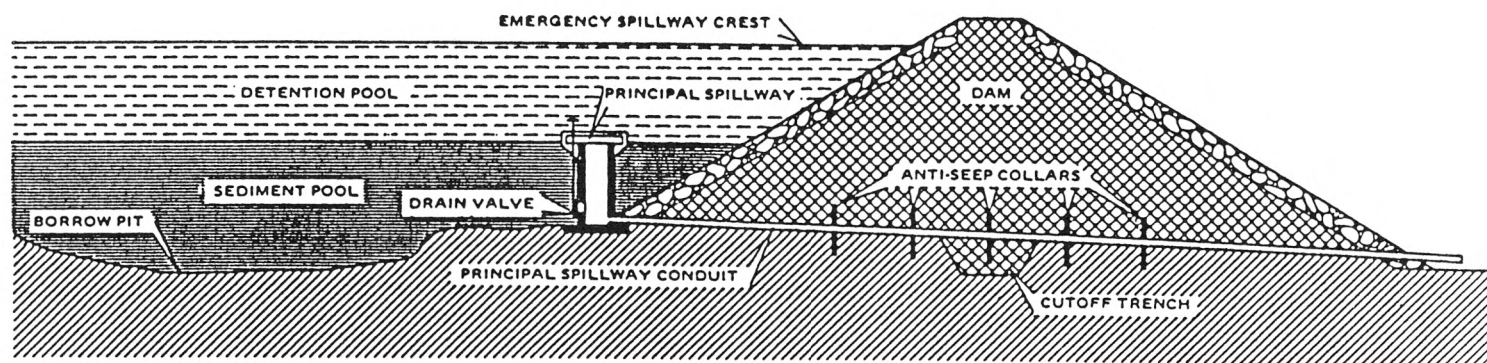
contamination. In the majority of the cases this assumption is at the moment true and contaminants are filtered out of the water after running through successive layers of soil. However due to faulting and the porous/cavernous nature of limestone karst, contaminants can often enter directly into sections of the aquifer. These characteristics make limestone aquifers among the easiest to contaminate, and if a well is located in one of these areas contamination is highly probable. With the increased use of groundwater, there is a growing concern for not only the quantity, but the quality of the water.

The Edwards aquifer region is divided into three areas, the drainage area, the recharge zone and reservoir (storage) zone (Fig. 1). Fractured and cavernous limestone allows for the movement and storage of large quantities of water within the aquifer. The study site was located within the recharge zone, an area where Edwards and Georgetown limestones are exposed at the surface.

In order to facilitate the recharge of storm runoff and prevent costly flood damage, earthen dams have been built over the recharge zone of the Edwards aquifer. Adjacent to the study site is the first of five dams to be built by the Soil Conservation Service for the Upper San Marcos Watershed Reclamation and Flood Control District (Fig. 2).

Although the dam may not be the direct cause of well contamination, it increases the probability of contaminants entering the aquifer, since more water is recharged. Soil was blasted and scrapped from the bedrock surface of the dam site. The dam slows the flow of runoff and the decreased layers of soil allow for faster recharge. If a large cave or fault is in the pool area of a reservoir water may enter directly into the area of a well without any cleansing effect of the soil. This particular flood control/recharge structure is located on a ranch; therefore, obvious sources of bacterial contamination are the cattle and wildlife.

Evidence of groundwater contamination by microbial organisms has been observed throughout the United States. Studies in South Carolina, Tennessee, Georgia and Colorado have revealed that coliforms were found



U. S. D. A., SOIL CONSERVATION SERVICE
USDA-SCS-FORT WORTH, TEX., 1974

Fig. 2. Cross section of a typical flood control/recharge structure.

in up to 85% of rural drinking water samples and fecal coliform organisms were found in 75% of the same samples (Miller,1985). The correlation between rainfall and bacterial contamination has also been seen during studies on groundwater quality (Gerba,1985).

Due to the economic importance of karst aquifers numerous hydrogeological and water quality studies on the Edwards aquifer in the Austin and San Antonio regions have been conducted by the U.S. Geological Survey and the Edwards Underground Water District (Ozuna, Nalley and Bowman,1987; Reeves and Ozuna,1985 & 1986; Slade, Dorsey and Stewart,1986; Reeves,1976 & 1978; Wells,1985). The study by Reeves (1976) directly addressed the correlation between rainfall and bacteriological contamination of groundwater.

The occurrence of coliforms in drinking water wells has been observed in the study area during hydrogeological and hydrochemical studies (Ogden, Quick, Rothermal and Lunsford,1986; Ogden, Spinelli and Horton,1985 & 1986; Rothermal, 1980; Quick,1985). The study revealed high levels of fecal coliform indicator organisms in test wells following heavy rainfall events. In June 1985 a heavy rainfall caused the San Marcos River to reach flood stage. At the same time levels of fecal coliform bacteria in test wells located in the Sink Creek Drainage Basin ranged from 0 to 1500 colonies/100 ml (Ogden, et. al,1986). To expand on these findings a study dealing with the chemical and biological groundwater quality in the Sink Creek Drainage was designed in an effort to determine the possible sources and frequency of bacterial contamination.

DESCRIPTION OF STUDY AREA

Location of Study Area

The study site was located within the recharge zone of the Edwards aquifer at Country Estates, a subdivision that lies 4.3 km (2.7 mi) west of San Marcos on Ranch Road 12 in Hays County Texas (Figs. 3 & 4). The sole source of water for homes in Country Estates are private wells. Drinking water wells in this and other areas around San Marcos have experienced bacteriological contamination and turbidity following rainfall events (Ogden, et. al,1986).

The Williamson-Freeman Dam is a flood control/recharge structure built on the Freeman Ranch, adjacent to the study site. The earthen dam was built to facilitate the recharge of storm runoff and prevent flood damage in the Upper San Marcos River Watershed (Fig. 2). This structure was built across Sink Creek, one of three major tributaries discharging into the upper San Marcos River (Longley,1975) (Fig. 5).

Location

The study area is located on the dissected margin of the Edwards Plateau in Hays County, Texas. This margin, the Balcones Escarpment, forms a topographic boundary between two major provinces of the Southwestern United States, the Edwards Plateau (the Texas Hill Country) section of the Great Plains Province and the West Gulf Coastal Plain (Fig. 6). The karst topography of the Edwards Plateau, lying to west of the escarpment, has an area of 82,900 km² (32,008 mi²) making it one of the

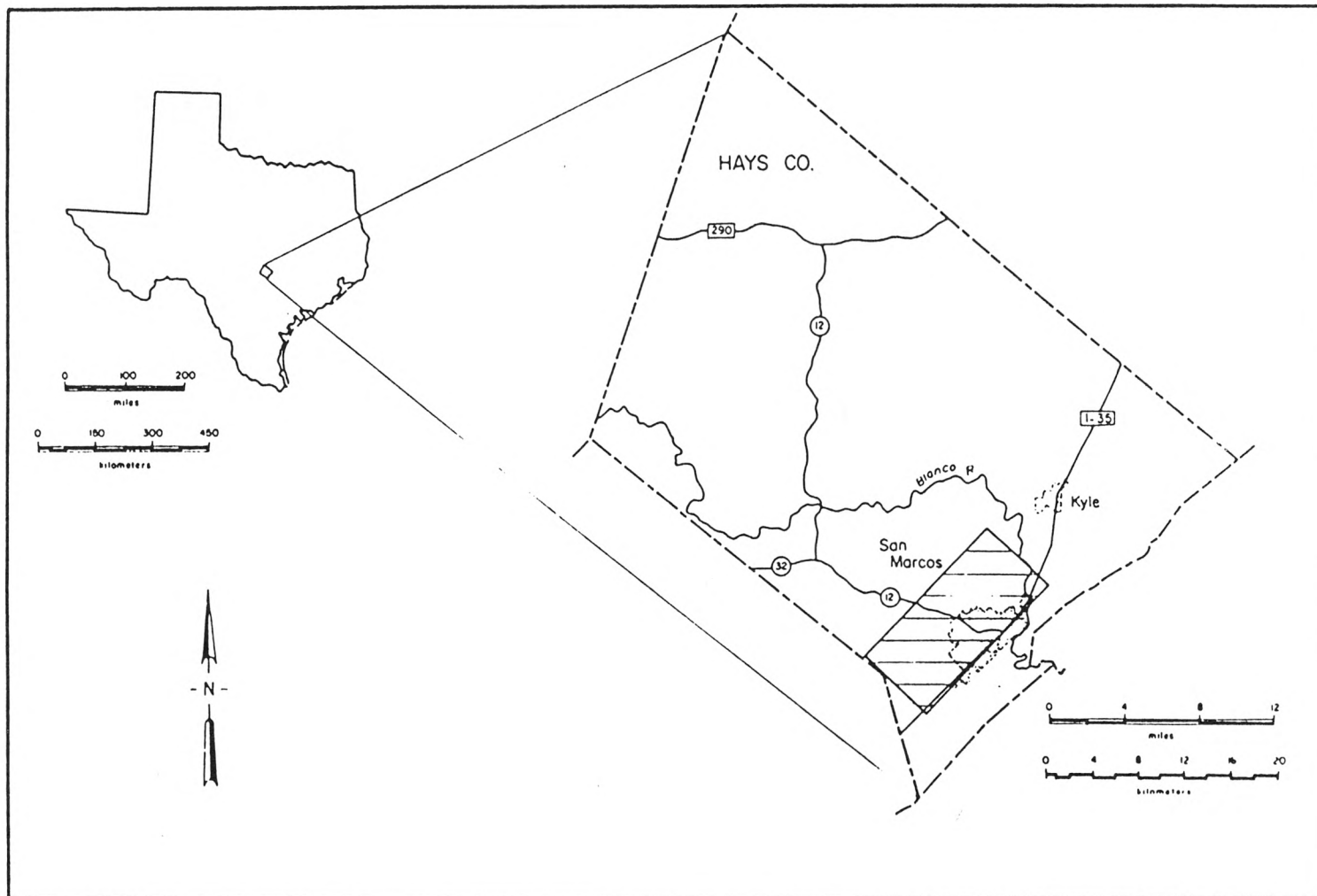


Fig. 3. Location of study area, Hays County, Texas.



Fig. 4. Location of sampling sites in the Sink Creek drainage basin, Hays County, Texas (from U.S.G.S. San Marcos Quadrangle, scale 1:24,000, 1964).

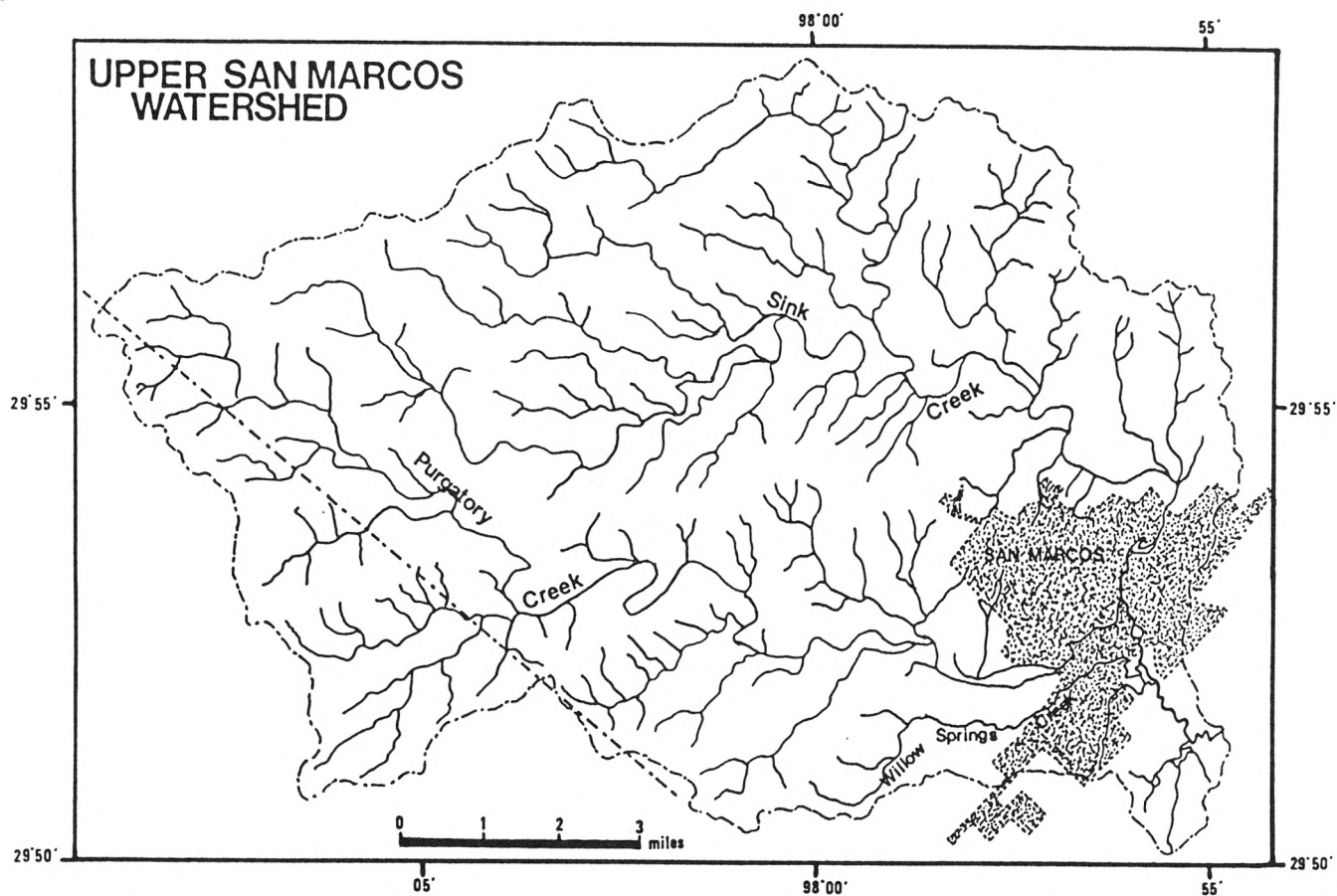


Fig. 5. Location of the study area, Sink Creek drainage, within the Upper San Marcos Watershed.

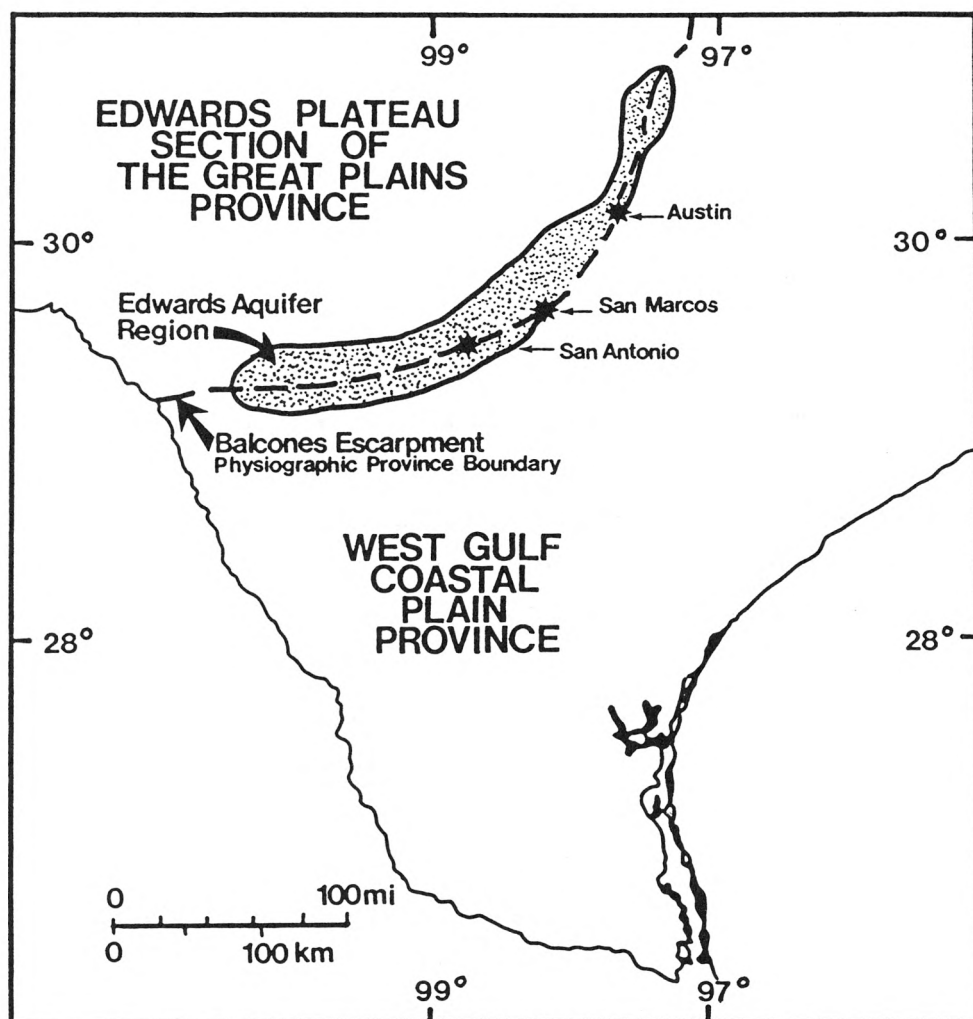


Fig. 6. Location of the Edwards aquifer (Balcones Fault Zone) region in relation to the physiographic divisions of south central Texas (adapted from Ogden, Quick, Rothermal and Lunsford, 1986).

largest contiguous karst regions in the United States (Ogden, et. al,1986; Kastning,1984). This area is characterized by limestone bedrock, thin soils, steep relief and typical karst features (caves and sinkholes). The characteristic Edwards limestone outcrop lying within the study area defines the recharge zone of the aquifer. The approximate elevation of this area ranges from 427 to 701 m (1,400 to 2,300 ft) (Maclay and Land, 1987). The Blackland Prairie of the Gulf Coastal Plain lies to the east and is characterized by clay substrate, thick soils and rolling hills (Quick,1985). The gentle slopes of the lowland Gulf Coastal Plains have an altitude which ranges from 183 to 274m (600 to 900 ft) (Maclay and Land,1987) (Fig. 7).

Climate

The San Marcos area is located within a temperate climate zone, dominated by semi-arid, subtropical conditions. This type of climate is characterized by long hot summers and short mild winters. There is a mean annual temperature is 19.9°C (67.8°F) and a mean annual precipitation of 83.3 cm (32.81 in) (DeCook,1960; Quick,1985). During the study period of July 1985 to June 1986 the mean minimum and maximum temperatures were 27.2°C (81.0°F) and 14.7°C (58.4°F) respectively (NOAA,1985-86). Rainfall measured at Country Estates totaled 103.4cm (40.7 in) during the study period (Table 1). The rainfall measured at the official San Marcos recording station during this period was 113.56cm (44.7 in) (NOAA,1985-86). The heaviest rainfalls occurred (at Country Estates) during the months of September, October, November, May and June (Table 1). There is no specific rainy season, but the heaviest rainfall occurs in the late spring (May and June) with slightly less in the summer and fall (September, October and November) and the least amount occurring in the winter months (DeCook,1960; Johnson,1931). The approximate annual evaporation potential of the San Marcos area is less than twice the annual precipitation, 161.97 cm (63.77 in) (DeCook,1960).

GENERALIZED PHYSICAL DIAGRAM SAN MARCOS, TEXAS AREA

2500 0 2500 5000 7500 10000 FEET

COMPILED BY A.D. HELLMAN FROM
USGS NORTH SAN MARCOS QUADRANGLE
1:24000 (1964). DIAGRAM SCALE
APPROX. 1:30000 (CENTER). VERTICAL
EXAGGERATION 8:1 (ON ORIGINAL) 1970

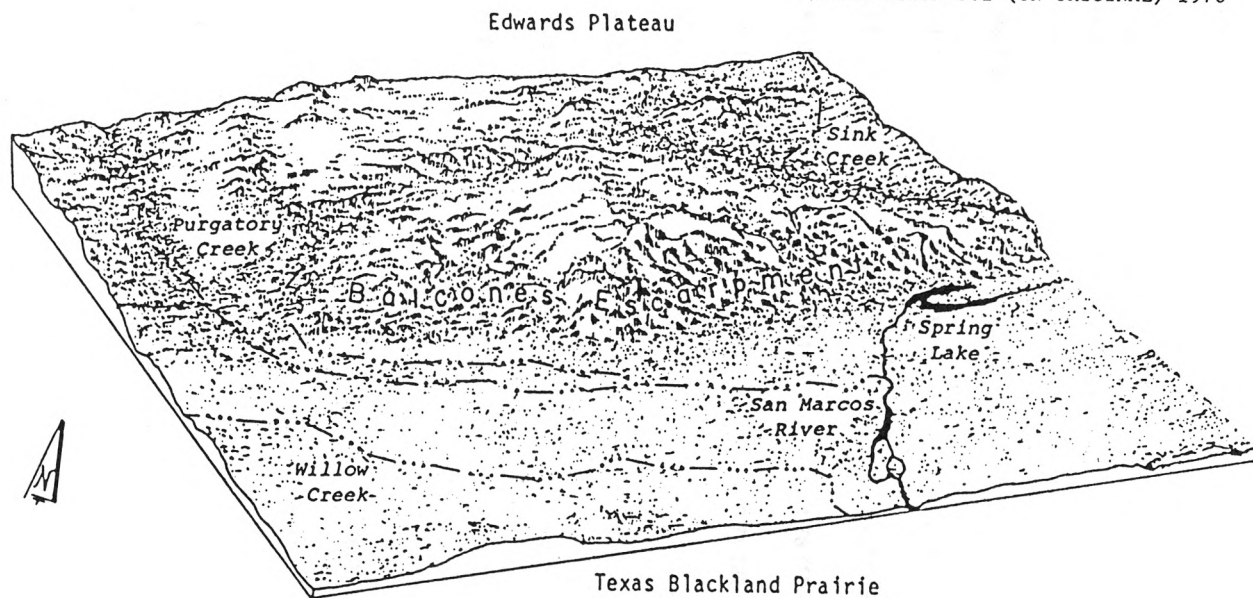


Fig. 7. Generalized physical diagram of San Marcos, Hays County, Texas.

Table 1. Ambient air temperature and rainfall (7/85-6/86).

MONTH	AMBIENT AIR TEMPERATURE *		RAINFALL †
	Maximum °F(°C)	Minimum °F(°C)	
July 1985	93.3(34.2)	72.6(22.5)	no record
August 1985	98.8(37.1)	73.6(23.1)	no record
September 1985	91.6(38.1)	68.6(33.1)	6.82(17.32)
October 1985	81.2(27.3)	62.8(17.1)	4.88 (12.40)
November 1985	73.5(23.0)	55.2(12.9)	8.71 (22.12)
December 1985	62.9(17.2)	37.9(13.3)	0.67 (1.70)
Janaury 1986	65.4(18.5)	40.5 (4.7)	1.15 (2.92)
February 1986	70.5(21.4)	44.1(6.7)	1.12(2.85)
March 1986	76.9(24.9)	47.1(8.4)	0.29(0.737)
April 1986	82.0(27.8)	61.2(16.2)	1.91(4.86)
May 1986	84.5(29.2)	64.8(18.2)	12.16(30.89)
June 1986	90.9(32.7)	72.1(22.3)	7.67(3.02)
Annual Mean:	81.0(27.2)	58.4(14.7)	Total: 40.72(103.43)

* temperature (NOAA, 1985-1986)

† rainfall recorded at study site

Soils

The topographic boundary formed by the Balcones Fault Zone (Escarpment) also forms a barrier between two distinctly different soil types. Differences in relief and bedrock material are the main reasons for the abrupt changes from east to west. The gentle slopes and soft unconsolidated bedrock (Upper Cretaceous clay-shale) are ideal conditions for the development of thick rich soils to the east. The rough topography and steep slopes of the west make the area resistant to soil development. The hard limestone bedrock (consolidated) resists erosion and soil erosion generally exceeds formation (Grimshaw,1976). Other factors influencing the soil development on the Edwards Plateau are climate, living organisms and time (U.S. Soil Conservation Service,1984). The high evaporation rate in the San Marcos area, in addition to the porous characteristics of the aquifer have influenced the development of thin soils. These soils are suitable for the growth of sparse vegetation consisting of cactus, mesquite, live oak and other drought tolerant vegetation (Quick,1985). Soil types in the study area are dominated by Comfort-Rock Outcrop Complex (CrD) and Rumble-Comfort association (RUD) (Fig. 8) (Table 2).

Comfort-Rock Outcrop (CrD)

The Comfort-Rock Outcrop Complex (CrD) is a combination of shallow stony clay type soils and rock outcrops on hilltops, ridgetops and steep slopes (Fig. 8) (Table 2). Comfort soils are found between bands of rock outcrop and make up between 45 and 95 % of the complex. The rock outcrops and areas of soil depth less than four inches make up 5 to 36 %. The surface soil, with a depth of approximately 15.2 cm (6 in), is dark brown and an extremely stony clay. Forty-five percent of the surface is covered by cobbles and stones. A dark reddish brown subsoil extends to a depth of 33.02cm (13 in) and is also an extremely stony clay (U.S. Soil Conservation Service,1984). The parent material is composed of hard fractured

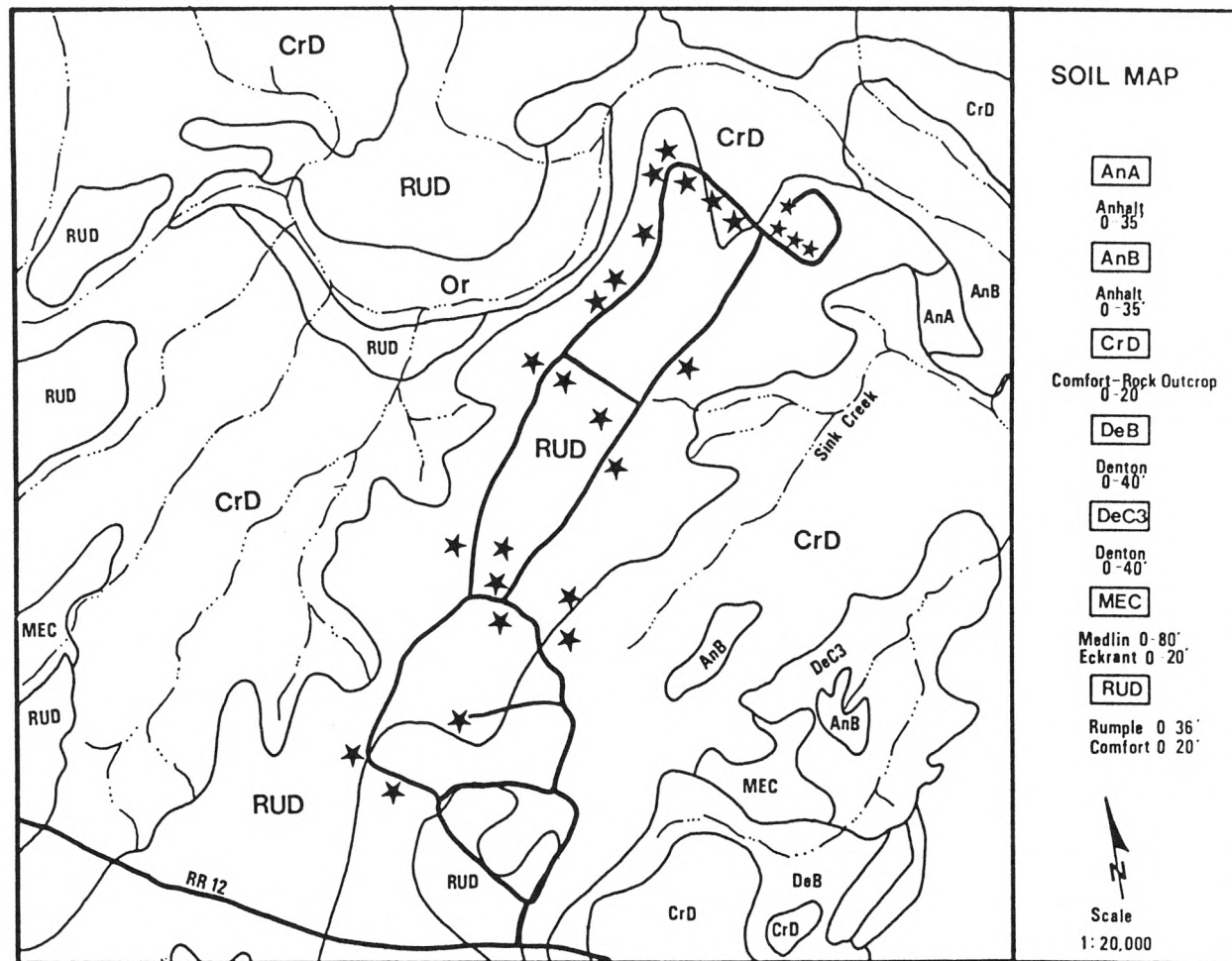


Fig. 8. Soil types in the study area, Sink Creek drainage, Hays County, Texas.

Table 2. Soil types of the study site, Sink Creek drainage basin, Hays County, Texas. *

	Soil Type	Permeability (In/hr)	Depth (ft)	pH	Septic Tank Absorption Fields
AnA	Anhalt clay	< 0.06	20 - 40	6.1 - 8.4	Severe ; depth to rock, infiltrates slowly
AnB	Anhalt clay	< 0.06	20 - 40	6.1 - 8.4	
CrD	Comfort-Rock outcrop complex, undulating	0.06 - 0.2	9 - 20	6.6 - 8.4	Severe : depth to rock, large stones
DeB	Denton silty clay	0.06 - 0.2	24 - 40	7.9 - 8.4	Severe : depth to rocks, infiltrates slowly
DeC3	Denton silty clay	0.06 - 0.2	24 - 40	7.9 - 8.4	
MEC	Medlin-Eckrant association undulating, composition variable				
	Eckrant	0.2 - 0.6	35 - 60	7.4 - 8.4	Severe : depth to rock, large stones
	Medlin	< 0.06	40 - 60	7.4 - 8.4	
Or	Orif soils, frequently flooded	6.0 - 20.0	> 60	7.9 - 8.4	Severe : flooding, poor filter
RUD	Rumple-Comfort association undulating variable composition	0.2 - 0.6	20 - 40	6.1 - 8.4	Severe : depth to rock, large stones, infiltrates slowly

*(adapted from U.S. Soil Conservation Service, 1986)

limestone. Comfort soils are well drained and carbonates are leached from them forming mild alkaline conditions and noncalcareous soils. The surface runoff is slow to medium and permeability slow.

The Rock-Outcrop is limestone/dolomitic limestone with soil absent from all but narrow fractures in the rock. Cobbles and stones are found on the surface and in the soil of the outcrops (U.S. Soil Conservation Service, 1984).

Rumple-Comfort Association (RUD)

The Rumple-Comfort association (RUD) soils are shallow to moderate in depth (Fig. 8) (Table 2). Rumple soils are found on ridgetops and gentle slopes. The first 25.4 cm (10 in) of surface soil is a dark brown cherty loam. Limestone/chert cobbles and gravel cover approximately 20 % of the surface. The next 35.56 cm (14 in) of subsoil is composed of a dark reddish brown cherty clay and to a depth of 71.12 cm (28 in) the soil is also a dark reddish brown containing of 75 % (by volume) of limestone fragments. The soil is also mildly alkaline and noncalcareous (U.S. Soil Conservation Service, 1984).

Comfort soils are found mainly in sloping areas near rock outcrops and drainage ways. The surface soil, approximately 17.78 cm (7 in) thick, is a dark brown extremely stony clay. The next 30.5 cm (12 in) of subsoil is a dark reddish brown, extremely stony clay that is mildly alkaline (U.S. Soil Conservation Service, 1984).

Rumple-Comfort association soils are well drained. Runoff from large areas of this soil type, as in the study area, is slowed down due to water entering caves, sink, fractures and stream beds (Fig. 8). The underlying bedrock material in the Comfort-Rock Outcrop association is hard fractured limestone (U.S. Soil Conservation Service, 1984).

Drainage

The study area is in the Upper San Marcos Watershed of the Guadalupe River basin (Fig. 5). The direction of drainage off the Balcones Escarpment is to the east and southeast (Quick, 1985). The Upper San Marcos Watershed covers an area of 244.5 km² (94.42 mi²) in both Hays and Comal counties, Texas. The watershed consists of Sink, Purgatory, and Willow Springs creeks (tributaries of the San Marcos River) (Longley, 1975). Ninety percent of the watershed is located over the Edwards aquifer (Soil Conservation Service, 1978). Sink, Purgatory and Willow Springs creeks are intermittent streams flowing in an easterly direction before joining the San Marcos River within the San Marcos city limits. Sink creek has a drainage area of approximately 124.8 km² (48.17 mi²) (Longley, 1975). Following rainfall events Sink and Purgatory creeks are responsible for significant amounts of local recharge into the Edwards aquifer (Quick, 1985).

Geology

The geology of the Edwards aquifer underlying the San Marcos area is composed of three stratigraphic units with a total depth of approximately 145 m (475 ft), (Grimshaw and Woodruff, 1986). The oldest unit at the bottom is the Kainer member with a thickness of approximately 76 m (250 ft). The second unit, at a depth of 55 m (180 ft), is the Person member (Maclay and Small, 1984). Both the Kainer and Person formations make up the Edwards Limestone formation. The third unit lying on top of the Edwards limestone is the Georgetown Limestone formation (Ogden, et. al, 1986). These three formations are further subdivided into eight subgroups according to physical characteristics and water transmitting capabilities. The Edwards aquifer is a heterogeneous system where recharge and water flow occur in some units more than others. The impermeable lower layer of the aquifer is formed by Walnut Clay and upper Glen Rose formations. The overlying impermeable Del Rio Clay is present in artesian conditions (Figs. 9 & 10) (Ogden, et. al, 1986). A limestone exposure 7.6 km (4.7 mi) northwest of San Marcos and 1.9 km (1.2 mi) north of Ranch Road 12, adjacent to the study area is

SYSTEM	SERIES	GROUP	FORMATION	THICKNESS (FEET)	GENERAL LITHOLOGY		
Quaternary	Recent		Alluvium and Colluvium	0 - 30 ±			
	Pliocene		Leona Formation and Onion Creek Marl	0 - 50 ±			
				Uvalde Gravel		0 - 20 ±	
Upper Cretaceous	Gulf	Navarro		300 ±			
			Taylor Marl	300 ±			
			unconformity				
			Austin Chalk	160 - 200 ±			
Lower Cretaceous	Comanche	Washita		unconformity			
				Eagle Ford Shale		15 - 30 ±	
				unconformity			
				Buda Limestone		2 - 70 ±	
		Fredericksburg		Del Rio Clay		20 - 60 ±	
				Georgetown Limestone		5 - 50	
			Edwards Group			unconformity	
						Person Formation	350 - 500 ±
				Kainer Formation			
				Comanche Peak Limestone		20 - 55	
			Walnut Clay	1 - 15 ±			
		Trinity	Glen Rose Limestone			Upper Member	500
						Lower Member	1150 ±
			Travis Peak Formation (Pearsall in subsurface)		Hensell Member	85 ±	
					Cow Creek Limestone Member	60 - 70	
					Sycamore Sand Member	50	
Cochille of Mexico		Silgo Formation	0 - 200 ±				
		Hosston Formation	0 - 500 ±				
Ellenburger		Ouachita Trend	?				

Fig. 9. Generalized stratigraphic section for Hays and Comal Counties, Texas (Ogden, et. al, 1986).

Current Edwards Subdivisions (Rose,1972)		USGS Aquifer Subdivisions (MacLay & Small, 1976)	Thickness (Feet)	General Lithologic Descriptions and Hydrologic Characteristics (Guyton and Assoc ,1979)
Del Rio Formation		Del Rio Formation		Blue-gray to tan gypsiferous, ferruginous marly shale. Yields no water. Principle confining bed above Edwards.
Georgetown Formation		Georgetown Formation	29	Dense, shaly limestone; mudstone and wackestone; isolated fossil molds; few closed fractures; very low matrix permeability.
Edwards Group	Person Formation	Marine and Cyclic Member	73	Hard, dense, recrystallized limestone; mudstone; rudistid biomicrite; some moldic porosity; many, open fractures; low matrix permeability.
		Leached and Collapsed Member	61	Recrystallized, leached limestone; burrowed mudstone and wackestone, highly leached in places; solution breccias, vuggy, honeycombed; many, open fractures; low to high matrix permeability.
		Regional Dense Member	23	Limestone, shaly to wispy, dense; mudstone; no open fractures; very low matrix permeability.
	Kainer Formation	Grainstone Member	56	Limestone; chalky to hard cemented miliolid grainstone, with associated beds of mudstones and wackestones; locally honeycombed in burrowed beds; few, open fractures; low to moderate matrix permeability.
		Kirschberg Member	60	Limestone and leached evaporitic rocks with boxwork porosity; most porous subdivision; low to very high matrix permeability.
		Dolomitic Member	164	Limestone, recrystallized from dolomite, honeycombed in a few burrowed beds; more cavernous in upper part; many, open fractures; low to high matrix permeability.
Walnut Formation		Basal Nodular Member	45	Limestone, hard, dense; clayey mudstone to wackestone, nodular, wispy, stylolitic, mottled; isolated molds; few, open fractures; low matrix permeability.

Fig. 10. Generalized subdivisions of the Edwards limestone group northeast of San Antonio (Ogden, et. al, 1986).

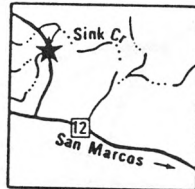
shown to be Edwards formation limestone with dolomitic and dolomitized limestone (Fig. 11) (Rodda, et. al,1966). This outcropping of Edwards limestone and the geology underlying the study site are known to be primarily the Person formation with small patches of Georgetown (Kgt), Buda (Kbu), and Del Rio Clay (Kdr) formations (Fig. 12) (Ogden,1985). The characteristics of the Edwards limestone formation make it one of the most permeable and productive aquifers in Texas (Maclay and Small,1984).

Karst Topography

Karst, a complex geological feature is associated with terrains having specific hydrological characteristics. The formation of karst topography is related to specific rock types, limestones, dolomites, gypsum, halite and other soluble rocks. The solubility of these rocks along with faulting, fracturing and the solution of the bed rock create the unique characteristics associated with karst topography. Caves, sink holes, springs, dry river valleys, denuded rocky hills and various other features are characteristic of karst terrain (Milanovic',1981). These features are evident in the study area where caves and sink holes are common (Fig. 13). Cavern development is most pronounced along the Balcones Escarpment. Of the over 2000 documented caves existing on the Edwards Plateau the majority are clustered along the Escarpment (Kastning,1984). Sink holes are formed by the continued solution of caves and the subsequent collapse of the cave ceilings. Sinkholes in Hays County range in size from a few hundred square feet to several acres (DeCook,1960). In addition to sinkhole collapse aquifer recharge is considered a significant karst process in the limestone aquifer (Grimshaw,1976).

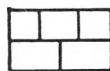
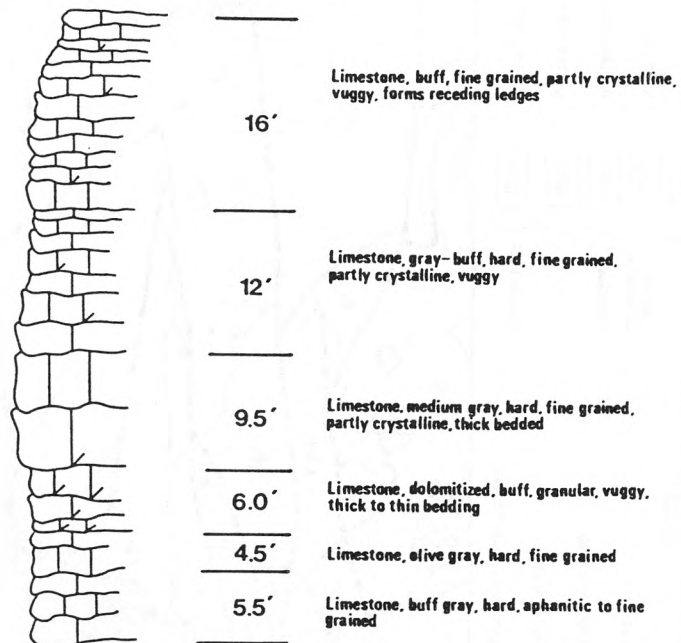
Edwards Aquifer Formation

The geologic formations in the area of the Edwards aquifer northeast of San Antonio consist of Cretaceous limestones (Comanche Peak, Edwards

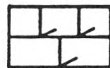


★ Limestone exposure: 1.2 m north of RR 12 and 4.7 m northwest of San Marcos

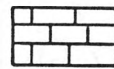
EDWARDS FORMATION



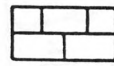
Limestone



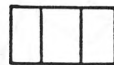
Dolomitic & Dolomitized Limestone



Thin: <3"



Medium: 3-5"



Thick: >8" *

* individual bed thickness

Fig. 11. Edwards limestone outcrop adjacent to the study area (adapted from Rodda, Fisher, Payne and Schofield, 1966).

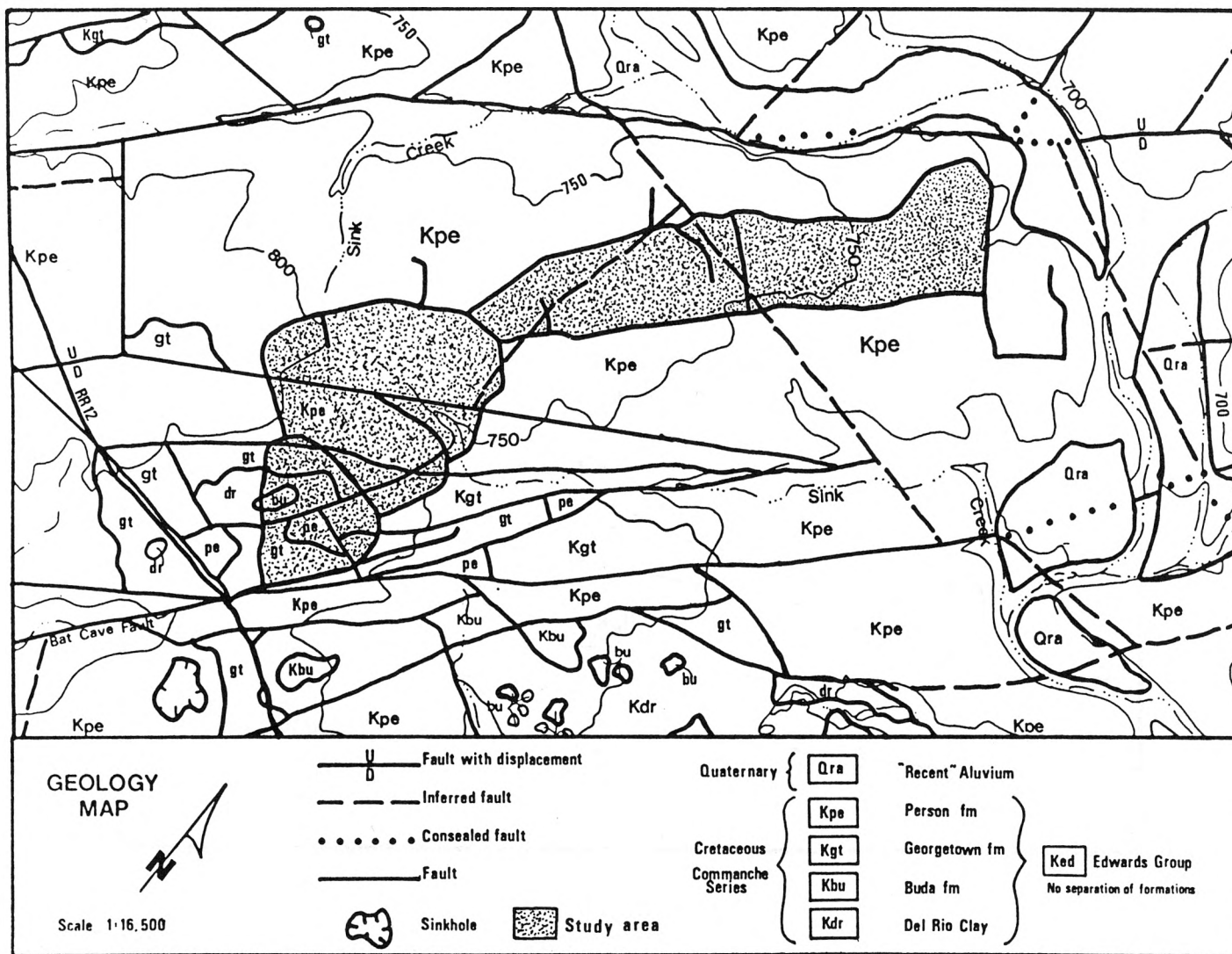


Fig. 12. Geological formations in the study area, Sink Creek drainage, Hays County, Texas.

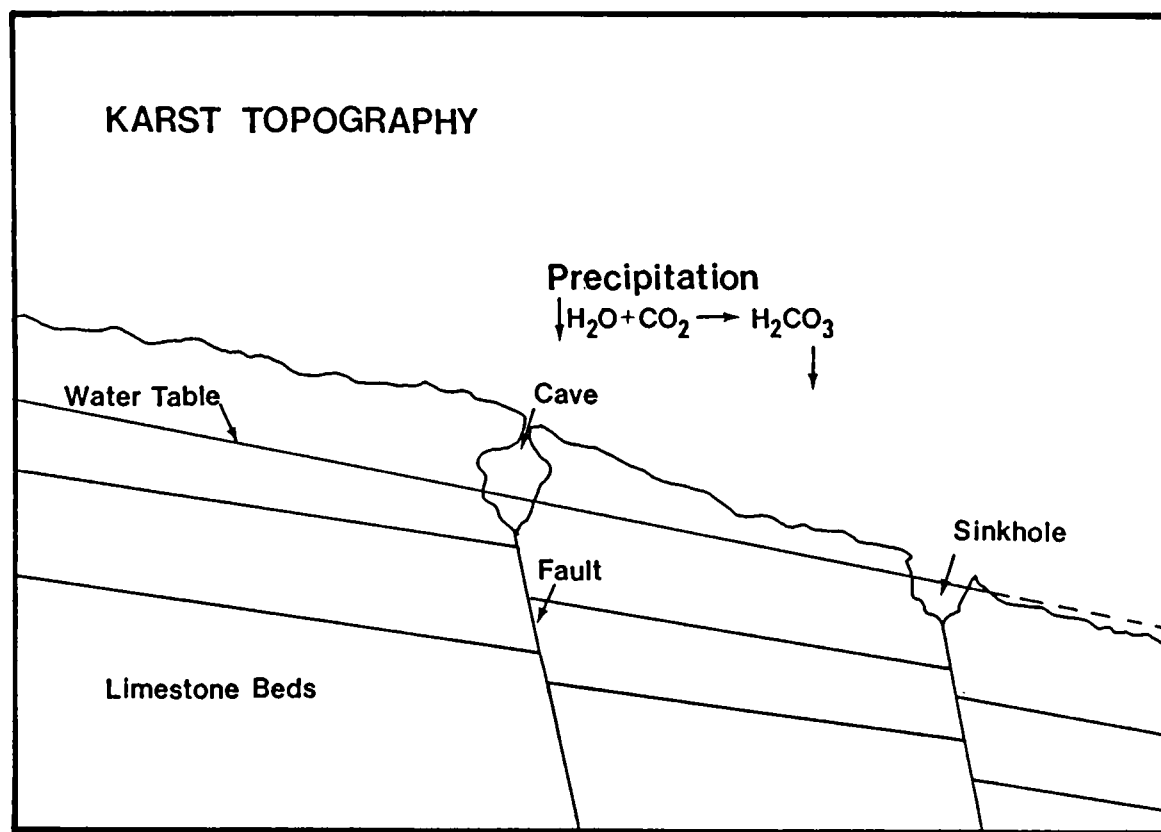


Fig. 13. Typical features of karst topography.

and Georgetown limestones), dolomites, shales and clays (Fig. 10 & 11). These rocks are heavily fractured and have been displaced by faulting in the Balcones Fault Zone (Guyton & Assoc., 1979). The limestones of Cretaceous age are the most important water-bearing strata. The shale and clay layers are less permeable than the limestones and act as aquitards or confining layers which inhibit the movement of groundwater flow (Quick, 1985). The Cretaceous age carbonates of the Edwards Plateau and the Balcones Fault Zone cover an area of 58,000 km² (22,394 mi²) (Milanovic, 1981).

The development of sedimentary rocks in the Edwards aquifer began in the Cretaceous period. The depositional phase occurred in the early Cretaceous with the accumulation of carbonate sediments in shallow marine environments. These sediments were later consolidated into Edwards limestone. Also occurring late in the early Cretaceous was an erosional phase. This was marked by the recession of the sea and the uplift of the Edwards Plateau. Uplift to elevations above sea level increased the weathering of existing deposits, removing more than 30.5 m (100 ft). The area experienced deep burial during the middle to late Cretaceous period by the inland movement of continental seas. At this time saline water was trapped within the deeply buried deposits. For a second time the seas receded and the Edwards Plateau experienced uplift. This second period of uplift created the Balcones Escarpment and fault zone. Deep caverns formed as the result of the weathering, solution and faulting of limestone, creating the Edwards aquifer as it is known today. The Edwards aquifer, in both the water table and artesian portions, exists within the narrow Balcones Fault Zone (Maclay and Small, 1984; Burchett, et. al, 1986).

Today the San Antonio region of the Edwards aquifer and the adjacent drainage zone covers an area of approximately 20,720 km² (8,000 mi²) (Fig. 1). The recharge and artesian zones cover approximately 9,324 km² (3,600 mi²) (Burchett, et. al, 1986). The drainage basins of streams recharging the aquifer cover 16,835 km² (6,500 mi²) (Maclay and Land, 1987). The aquifer is approximately 290 km (180 mi) long from east to west and the width varies from 8 to 64 km (5 to 40 mi) along its length

(Maclay and Small,1984). The aquifer is bordered on the southeast by the "bad-water line". This line marks the boundary between freshwater with less than 1000 mg/L of total dissolved solids (TDS) and water with concentrations greater than 1000 mg/L. The area where the TDS concentrations exceed 1000 mg/L generally coincides with an area of low transmissivity and is therefore hydrologically distinct. Water from the Edwards aquifer with TDS concentrations of < 1,000 mg/L can be found in an area covering 318 km² (825 mi²). Total dissolved solid concentrations of 1,000 to 3,000 mg/L are found within a 125 km² (325 mi²) area. Small openings in the limestone and poor connection inhibits the free circulation of water downdip from the line of quality transition (Ogden, et. al,1986; Baker, Slade, Dorsey and Ruiz,1986) (Fig. 1).

Recharge Zone

The recharge zone of the Edwards aquifer is considered to be the area where Georgetown and Edwards limestones are exposed at the surface in the Balcones Fault Zone. Recharge of the aquifer occurs by infiltration of surface waters from streams draining the Edwards Plateau. The majority of storm runoff enters the aquifer through porous fractured limestone within stream channels (Maclay and Smith,1984; Rothermal,1980). Runoff can also enter through fractures and sinkholes (Grimshaw,1976). Part of the Sink Creek drainage basin is located within the study area. Local storm runoff enters Sink Creek, an intermittent stream channel, where recharge is aided by a flood control/recharge structure adjacent to the study site. The porous nature of the limestone and the presence of caves and fractures allow the direct entry of storm runoff into areas of drinking water wells with little or no prior filtration. The Edwards aquifer, a limestone karst aquifer, is considered a sole-source aquifer in this area. Increasing urban development introduces the possibility of substantial amounts of local surface runoff containing pollutants, thus degrading the water quality with little potential for recovery. The average pumping rate is approaching the

yearly recharge rate of 74,564 m³ (604,500 acre-feet) which increases the chance for groundwater contamination (Ozuna, Nalley and Bowman,1987) (Table 3).

Hydrogeology

The hydrogeology of limestone aquifers is not as well defined as other non-carbonate type aquifers. The characteristics of conduit flow and diffuse circulation are common to karst terrains and are absent in most other non-karst terrains (DeCook,1960). The aquifer is a heterogeneous unit made up of hard, porous and fossiliferous limestones and dolomites of the Lower Cretaceous age. These limestones and dolomites are broken by faults and fractures (Maclay and Land,1987). Much of the porosity in carbonate systems is secondary being formed by the process of dissolution. Rain water moves through the soil picking up carbon dioxide and forming a weak carbonic acid. This slightly acidic water causes the dissolution of limestone along joints, fractures and bedding planes. Over time the solutioning of limestone forms large subsurface conduits and large cavern spaces formations typical of karst terrain (Bögli,1980). The water in the aquifer moves along a hydraulic gradient approximately parallel to the bedding planes. Flow may also be horizontal through transverse joints or fractures changing from vertical to lateral flow when impervious beds are encountered. A large part of the water in the aquifer moves through small interconnected openings formed by the solutioning of shrimp burrows (DeCook,1960).

The solutional porosity of the aquifer increases the probability of groundwater degradation with little potential for renovation from the recharge of polluted surface runoff (Grimshaw,1976).

Table 3. Annual recharge and discharge to the Edwards aquifer, 1934-85.*

Discharge/Recharge	1934-85 *	1985*	Hays County 1934-85	Hays County 1985
	acre-ft (ha-m)	acre-ft (ha-m)	acre-ft (ha-m)	acre-ft (ha-m)
Annual Spring Discharge	353,930.. (43,657)	334,000.. (41,198)	-	117,800.. (14,530)
Annual Well Discharge	263,800.. (32,539)	522,500.. (64,450)	-	-
Total Discharge	617,730.. (76,196)	856,000.. (105,648)	110,500.. (13,630)	144,900.. (17,873)
Annual Recharge	604,500.. (74,564)	1,003,300.. (123,755)	36,700 † (4,527)	50,700 † (6,254)

*(adapted from Ozuna,Nalley and Bowman,1987)

**Kinney-Uvalde, Medina, Bexar, Comal and Hays Counties

† Blanco River basin

ZONES OF CAVERN DEVELOPMENT IN THE EDWARDS AQUIFER

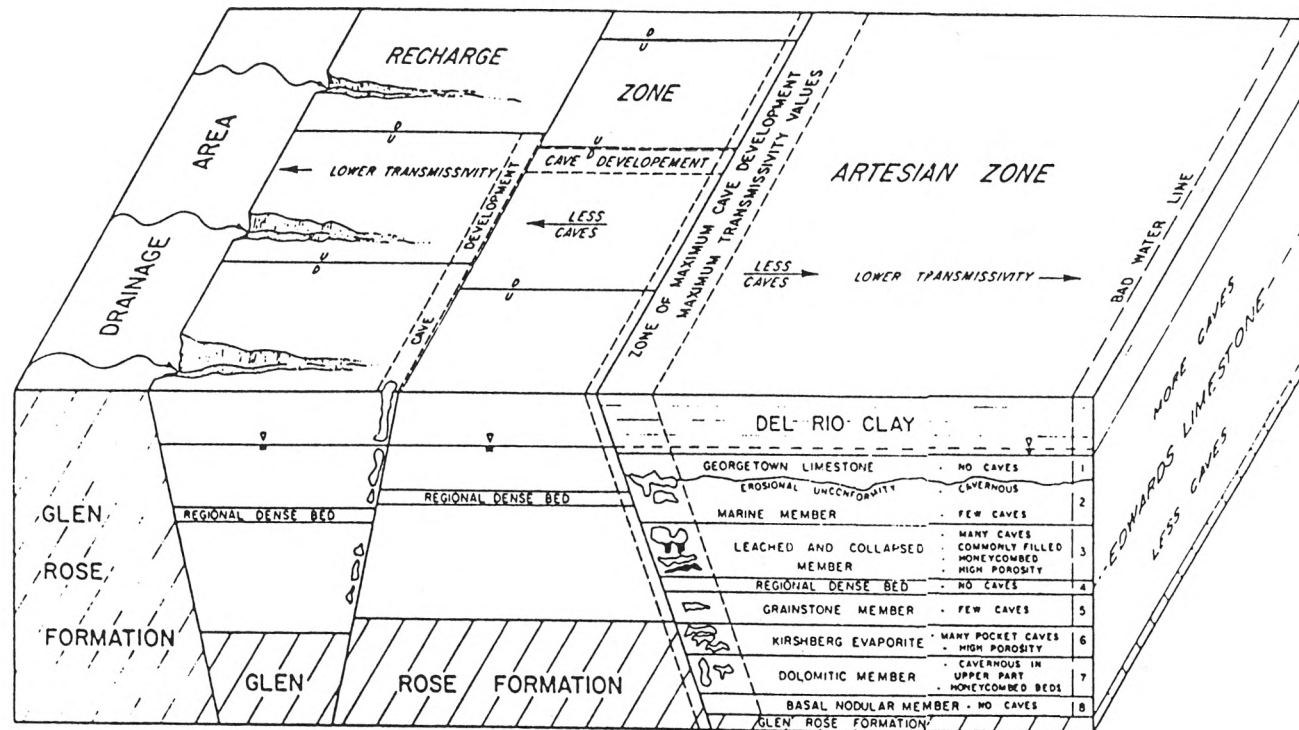


Fig. 14. Zones of cavern development and transmissivity in a cross-section of the Balcones Fault Zone (Ogden, et. al, 1986).

Faults

The Balcones Fault Zone consists of a belt of normal faults and joints that strike N 35°E to N 45°E. The faults have a net displacement downward to the east and southeast. These faults can act as a barrier to ground water or as a zone of high transmissivity and cavern development (Fig. 14). Springs, Kyle, Comal Springs, Bat Cave and Baptist Academy Faults are the major faults in the study area (Fig. 15). In general the faults of Hays County strike N45°E with the individual faults striking between N35°E and N50°E. The San Marcos Springs Fault forms the boundary at the southeastern end of the Edwards limestone outcrop with a fault strike of N40°E. The Kyle Fault, striking N30°E, is formed by a northern extension of the San Marcos Springs Fault (DeCook,1960; Ogden, et. al,1986) (Fig. 15).

The Comal Springs Fault runs along the southeastern boundary of the Edwards limestone outcrop. It also marks the boundary between the fresh and bad water zones (> 1000 ppm TDS). The fault strike in Hays County is N40°E (DeCook,1960) (Fig.15).

The two major faults in the study area are the Bat Cave Fault and the Baptist Academy Fault striking approximately N35°E (Fig.15). Although exact vertical displacement of the faults is unknown, the potentiometric map indicates significant displacement. This displacement impedes groundwater flow (Quick,1985). These major faults and approximately 70 minor faults act as conduits and barriers to groundwater flow (DeCook,1960).

Potentiometric Surface

The water table in the study area is very complex due to the heterogeneous nature and structural complexity of the Edwards aquifer. The flow of ground water can be enhanced or impeded depending on the position of the numerous faults, cross faults and joints that dissect the San Marcos area. In the study area the ground water occurs in water-table conditions. Water in the recharge zone is unconfined and will not rise above the level at which it is found. Potentiometric maps were developed in order to determine flow patterns of water in the Edwards aquifer. The most recent

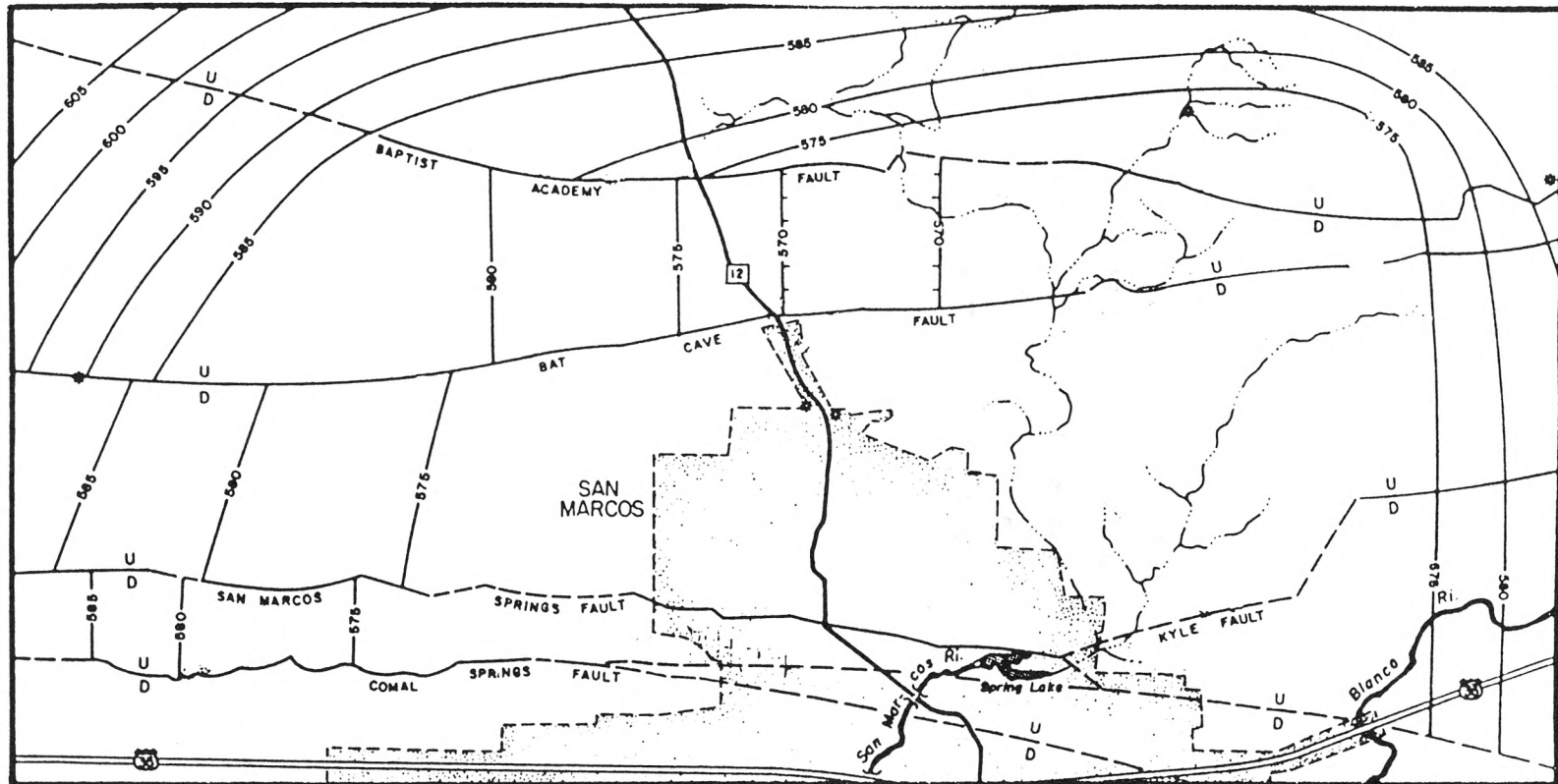


Fig. 15. Major faults underlying the San Marcos Area, Hays County, Texas (Ogden, et. al, 1986).

of these maps found very complex flow patterns in the San Marcos area (Ogden, et. al,1986). By using the potentiometric surface map the depth to the top of the water table in the recharge zone can be determined. The water table in the study is relatively flat (Figs. 15 & 16). The potentiometric map revealed a slight ground water depression occurring in the study area. Two hypothesis were formulated, (1) ground water mining in an area of restricted flow due to numerous faults and low potential recharge and (2) an isolated potentiometric surface was formed by a small structural graben occurring within a larger graben (a depression in the earth's surface between two parallel faults). The lines of equal water table elevation show that ground water flow occurs within an isolated block from the west-southwest (Edwards Plateau/San Antonio) and from the north-northwest (Blanco River) to the study area (Country Estates subdivision) (Quick,1985).

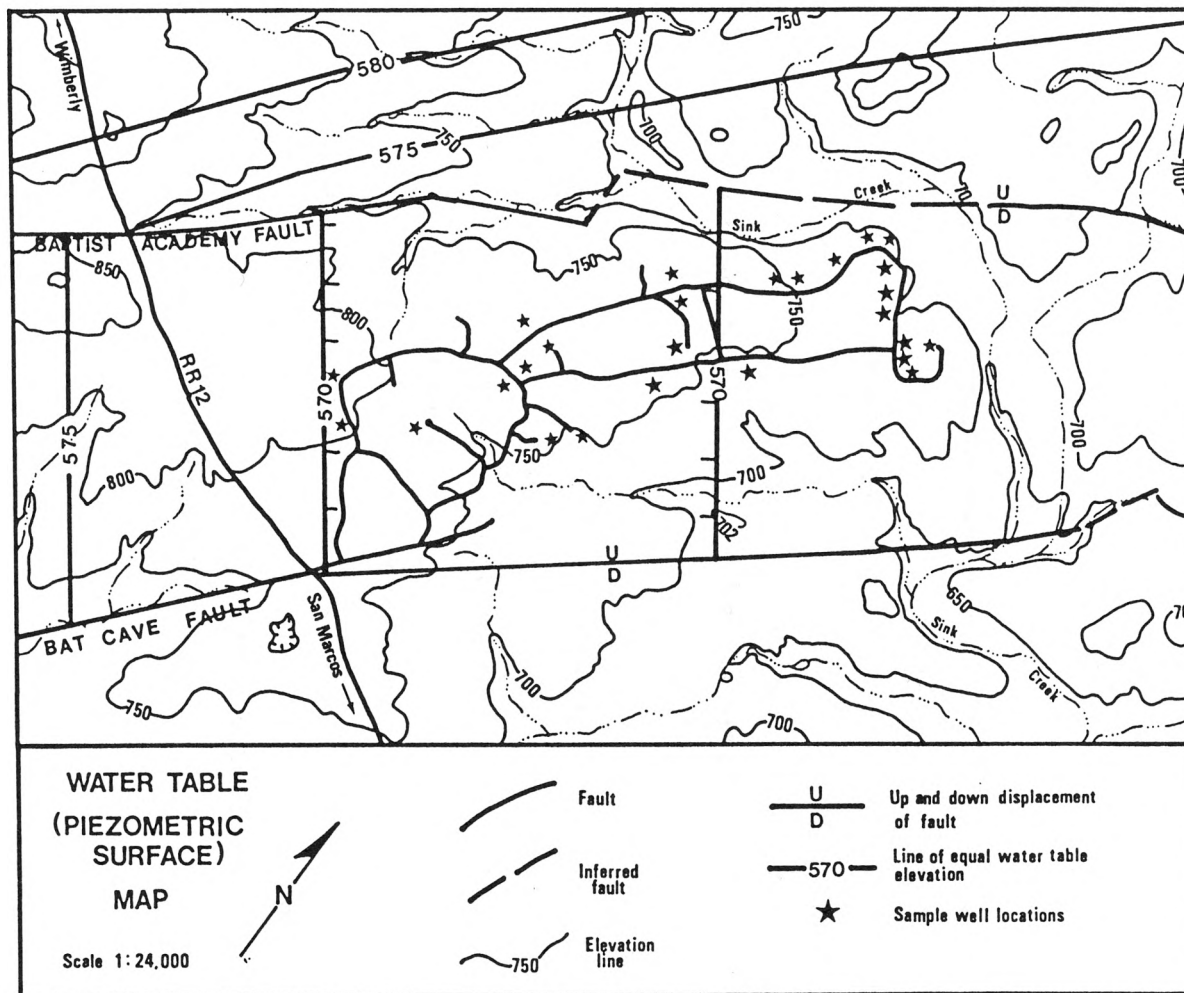


Fig. 16. Piezometric surface (water table) map of the study area (adapted from Ogden, et. al, 1986).

METHODS AND MATERIALS

Sampling Methods

The sampling of 26 groundwater wells began at the Country Estates Subdivision July 18, 1985 (sample day 1) and continued until June 23, 1986 (sample day 341). Samples were taken before, during and after rainfall events. During dry periods wells were sampled once a week for both bacteriological and chemical parameters. Wells were sampled during and after rainfall events and those which exhibited bacteriological contamination were sampled more frequently until coliform levels decreased to pre-rainfall conditions.

The water from each well was run for a minimum of 10 min before sample collection from the faucet at or closest to the well. Chemical samples were refrigerated from the time of collection until analysis in an effort to prevent changes in the ionic concentration.

Bacteriological samples were taken using sterile techniques. Prior to sample collection bottles were washed, wrapped in brown paper and autoclaved at 120°C for 30 min. The faucet was flamed with an alcohol lamp to destroy any existing contaminants. The sample was collected, rewrapped and put on ice until returned to the laboratory.

Analytical Methods

Samples for the analysis of chemical parameters were also taken to determine the effects, if any, rainfall had on the water chemistry of the well water. All sampling was conducted according to Standard Methods

(APHA,1985) and the U.S. Environmental Protection Agency (1984). The samples were analyzed for the following parameters:

- A. Temperature (°C)
- B. pH (Units)
- C. Conductivity (µmhos/cm)
- D. Chloride (mg/L)
- E. Sulfate (mg/L)
- F. Nitrate Nitrogen (N-NO₃) (mg/L)
- G. Orthophosphate (mg/L)
- H. Total Alkalinity (mg/L and CaCO₃)
- I. Total Hardness (mg/L as CaCO₃)
- J. Calcium Hardness (mg/L)
- K. Magnesium Hardness (mg/L)
- L. Bacteria: Total Coliform (colonies/100 ml)
 - Fecal Coliform (colonies/100 ml)
 - Fecal Streptococcus (colonies/100 ml)

The following is a summary of the methods used to analyze the chemical and biological parameters of this study (Table 4). All analyses were run using U.S. Environmental Protection Agency approved methods. Analysis was run within established holding times. Those which had holding times of seven days or greater were analyzed within 72 to 96 hrs of collection (USEPA, 1984).

Methods for Chemical Analysis

Temperature

The temperature of each sample was taken in the field at the time of collection with a Fisher hand held Celcius (°C) thermometer.

Table 4. Methods for biological and chemical analysis.

PARAMETER	METHODS
Temperature (°C)	Mercury Thermometer
pH (Units)	Orion Research Model 221 Digital pH/ Temperature Meter
Conductivity (µmhos/cm)	Std. Methods* 205:YSI Conductivity Bridge Model 31
Chloride (mg/L)	Std. Methods* 407B-Mercuric Nitrate
Sulfate (mg/L)	HACH** Turbidimetric Method/Std. Methods* 426C-Barium Sulfate Turbidimetric Method
Nitrate-Nitrogen (mg/L)	HACH** Cadmium Reduction Method
Orthophosphate (mg/L)	Std. Methods* 424-Ascorbic Acid Method; Perkin Elmer 35 Spectrophotometer
Total Alkalinity (mg/L)	Std. Methods* 403: Orion Research 901 Microprocessor Ionalyzer/901
Total Hardness (mg/L)	Std. Methods* 314B-EDTA Titrimetric Method
Calcium Hardness (mg/L)	Std. Methods* 314B-EDTA Titrimetric Method
Magnesium Hardness (mg/L)	Std. Methods* 314B
Total Coliform (colonies/100 ml)	Std. Methods* 909A-Membrane Filter
Fecal Coliform (colonies/100 ml)	Std. Methods* 909C-Membrane Filter
Fecal Strep (colonies/100 ml)	Std. Methods* 909B-Membrane Filter

*(APHA, 1985) (USEPA approved, 1984)

** (Hach, 1984)

pH

The pH of each sample was measured in the field with a portable Orion Research Model 221 Digital pH/Temperature Meter.

Conductivity

Conductivity was measured within 24 hrs of sample collection on a YSI Model 31 Conductivity Bridge in $\mu\text{mhos/cm}$ (APHA,1985). The value was multiplied by the cell constant of 2.1195 and the temperature conversion factor (22°C -1.043; 23°C -1.043; 24°C -1.024; 25°C -1.000).

Chloride

The chloride concentration (mg/L) was measured using the Mercuric Nitrate Method (APHA,1985). Diphenylcarbazone acidifier indicator reagent (1 ml) was added to 100 ml of sample and titrated with 0.0140 N mercuric nitrate. The mercuric nitrate (HgNO_3) reacts with all the chloride (as Cl^- ions) and form mercuric chloride and free nitrate ions. When all the existing chloride had complexed excess mercury ions (Hg^+) combines with the diphenylcarbazone indicator causing the purple endpoint. The same procedure was run on a distilled water blank. The volume (ml) of mercuric nitrate used was entered in the following equation to obtain mg/L of chloride:

$$(\text{ml HgNO}_3 (\text{sample}) - \text{ml HgNO}_3 (\text{blank})) (0.0141\text{N}) (35450) / 100 \text{ ml of sample}$$

Sulfate

From July 17, 1985 to January 15, 1986 sulfate analysis was done by the Hach Turbidimetric Method (Hach,1984). Turbidity was formed by the addition of SulfaVer® 4 Sulfate Reagent Powder Pillows to 25 ml of sample and allowed to stand for a maximum of 10 mins. Absorbances were read at 450 nm on the Perkin Elmer Model 35 Spectrophotometer. During the

second half of the sampling period (September 27 to June 23, 1986) analysis was done according to the Barium Sulfate Turbidimetric Method (APHA,1985). Exactly 5 ml of conditioning reagent and 0.2 gm of barium chloride were added to each sample and allowed to mix for 1 min. The solution was poured into an absorption cell (1/2 inch) and absorbances were read at 420 nm. The barium chloride combines with sulfate to form a turbid solution. The amount of turbidity was related to the sulfate concentration. A standard curve was produced using various concentrations (ranging from 0-40 mg/L) of 1000 mg/L sodium sulfate standard and plotting absorbance versus concentration. Samples falling outside this range were diluted accordingly. Unknown sample concentrations were derived from the standard curve. This method increased the accuracy of the results. The holding time for sulfate was seven days (USEPA,1984).

Nitrate

Nitrate concentrations (mg/L) were measured using the Cadmium Reduction Method (Hach,1984). NitraVer®6 Nitrate Reagent Powder Pillows were used to generate color. The reagent was added to 25 ml of sample in an absorbance cell (1/2 inch) and mixed for one min. After a period of 5 mins, but no longer than 15 the sample absorbances were read at 500 nm on the Perkin-Elmer 35 Spectrophotometer. Nitrate samples were analyzed within 24 hrs of collection (USEPA,1984).

Orthophosphate

Orthophosphate (mg/L) concentrations were measured using the Ascorbic Acid Method (APHA,1985). Exactly 8 ml of conditioning reagent containing 50 ml 5N sulfuric acid, 5 ml potassium antimonyl tartrate solution, 15 ml ammonium molybdate solution and 30 ml ascorbic acid solution was added to 50 ml of sample. If orthophosphate was present a blue color developed. Solution was added to an absorption cell (1/2 inch) and

absorbances were read at 700 nm. Unknown sample concentrations were determined from a standard curve. In order to produce the standard curve standards ranging from 0 to 0.2 mg /L were made from a 1000 mg/L potassium nitrate solution and absorbance values were plotted against concentration. The determination of orthophosphate was completed within 24 hrs of sample collection (USEPA,1984).

Total Hardness

Total Hardness concentrations, expressed as CaCO_3 , were measured using the EDTA (ethylenediaminetetraacetic acid) Titrimetric Method (APHA, 1985). Added to each sample in this sequence were 1 ml of Hach Hardness 1 Buffer Solution (ph 10.1 ± 0.1 at 20°C), 0.5 g potassium cyanide (KCN) and a Hach ManVer®2 Reagent Powder Pillow as an indicator. The samples were buffered to a pH of 10.1 where the efficiency of the test is greater. Each 50 ml sample was titrated with Hach 0.20 N TitraVer® (EDTA) Standard Solution from pink to the blue end point. The milliliters of EDTA used were multiplied by 20 to obtain mg/L of total hardness. Total hardness has a holding time of six months (USEPA,1984).

Calcium Hardness

Calcium hardness (mg/L as CaCO_3) concentrations were also analyzed using the EDTA Titrimetric Method, with two distinct changes (APHA,1985). Potassium cyanide was again added to remove end point interference metals such as copper, iron, aluminum, cobalt, and nickel. One milliliter of 8 N potassium hydroxide (KOH) and a Hach CalVer®2 Reagent Powder Pillow Indicator were added to 25 ml of sample/25 ml of distilled water and titrated with Hach 0.20 N TitraVer® EDTA Standard Solution from pink to a blue end point. As the EDTA was added to a sample it first combines with calcium. In order to use the EDTA method for the direct detection of calcium the pH had to be increased. At an elevated pH the magnesium precipitates

out as hydroxide (8 N KOH) and the indicator Cal Ver®2 combines with calcium. The number of milliliters of EDTA used were multiplied by 40 to get mg/L. Calcium hardness also has a holding time of six months (USEPA,1984).

Magnesium Hardness

Magnesium hardness (mg/L) was obtained by subtracting the calcium hardness concentration value from the total hardness (APHA,1985; USEPA, 1984).

Total Alkalinity

Total alkalinity, measured as mg/L CaCO_3 was determined by titration of a 100 ml sample against Hach 0.20 N Sulfuric Acid Standard Solution (APHA, 1985). The end point of 4.5 was detected by a pH probe on the Orion Research Microprocessor Ionalyzer/90. Milliliters of 0.20 N sulfuric acid were multiplied by 20 to get mg/L. Alkalinity was determined within 24 hrs of collection (USEPA,1984).

Bacteria

The membrane filter technique was used in determining the level of contamination by coliform organisms (APHA,1985). Samples were collected in sterilized 175 ml glass milk bottles, re-wrapped in brown paper to prevent contamination and stored on ice. Samples were analyzed within six hrs of collection. All materials used in the analysis were sterilized and sterile technique was strictly observed. Total coliform, fecal coliform and fecal streptococcus were determined using the same basic technique with variations in broth types, incubation time and water bath temperature. An absorbent pad was placed into each petri dish (50x9 mm) with 2 ml of the appropriate nutrient broth. A sample volume of 100 ml was filtered through

a white-grid marked membrane filter with a pore size of 0.45 μm and 47 mm in diameter (Millipore,1973). An equal volume of phosphate buffer dilution water was used to rinse the filter funnel between each sample. When turbidity was present smaller volumes were filtered so the colonies were not obscured by turbidity and high colony counts. The membrane filter was placed into the petri dish on top of the nutrient rich pad, sealed in plastic bags and submersed in a water bath at the appropriate temperature and for the proper incubation time. After incubation the colonies were counted and reported in colonies/100 ml (USEPA,1984; APHA,1985).

Total Coliform

Total coliform organisms were grown on M-Endo broth and incubated at 35 ± 0.2 °C for 24 ± 2 hrs. The colonies were identified by the characteristic metallic green sheen using a florescent light and dissecting microscope (USEPA,1984; APHA,1985).

Fecal Coliform

Fecal coliform organisms were grown on M-FC broth at 45 ± 0.2 °C for 24 ± 2 hrs. The colonies were identified by the presence of a blue color using a florescent light and dissecting microscope (USEPA,1984; APHA,1985).

Fecal Streptococcus

Fecal streptococcus organisms were grown on fecal strep broth at 35 ± 0.2 °C for 48 ± 2 hrs. The colonies were identified by the small size and red color using a florescent light and dissecting microscope (USEPA, 1984; APHA, 1985).

RESULTS AND DISCUSSION

Water Chemistry

Twenty-six drinking water wells in the Sink Creek drainage area were sampled from July 17, 1985 to June 23, 1986 (Fig. 4). Four of the 26 wells were eliminated from the study, three due to inaccessibility and one had a filter attached to the well throughout the study invalidating the results. The significance of the chemical and biological characteristics in relation to the quality of groundwater were determined by water quality standards set by the U.S. Environmental Protection Agency (USEPA, 1976) (Table 5). The data was represented in two ways, (1) daily values were plotted on graphs in order to show day to day trends and (2) monthly averages were represented in tables to make the data more presentable and to show monthly trends. Sampling for chemical analysis was not always done on the same day (for all wells) as the bacteriological sampling and monthly averages show the same trends in a more organized fashion.

Rainfall

A relationship between rainfall and bacteriological contamination in drinking water wells has been shown in several studies and is a key factor in the analysis of well water quality. Increased levels of bacterial contamination in drinking water wells were found following rainfall events (Gerba, 1985; Ogden, et. al, 1986; Reeves, 1976; Slade, 1986). During this study the two largest rainfalls occurred in late November 1985 and May/June 1986 (Fig. 17) (Table 1). These rainfalls caused distinct changes in both the chemical concentrations and the levels of bacterial

Table 5. Inorganic substances dissolved in groundwater commonly affecting water quality (USEPA, 1976 & 1985).

SUBSTANCE	SOURCES	SIGNIFICANCE	CONC. AFFECTING WATER QUALITY (mg/L)
Nitrate	Decaying organic matter, sewage, fertilizers and water treatment	May cause methemoglobinemia (blue babies) and may produce undesirable taste in water due to increased algal growth	10
Orthophosphate	Decaying organic matter, sewage, fertilizers and water treatment	Causes increased growth of aquatic plants which lower oxygen levels in water	none listed
Sulfate	Industrial waste or dissolved from rock and soil containing sulfur	Gives water a bitter taste and can have a laxative effect	300-400 (taste) 600-1,000 (laxative)
Chloride	Oil field and industrial brines or dissolved from rocks and soil, seawater trapped in sediments	Combined with sodium it gives a salty taste to water and may increase corrosiveness of water	250
Alkalinity (Bicarbonate and Carbonate)	Products of the dissolution of carbonate rocks, primarily limestone and dolomite	Alkalinity to neutralize strong acids. Bicarbonates of calcium and magnesium form scale in water heaters and release corrosive carbon dioxide gas	150-200
Total Hardness	Calcium and magnesium in water or dissolved from rocks and soil (carbonate rocks)	Creates scale in pipes	0-60: Soft 61-120: Mod. hard 121-180: Hard > 180: Very hard

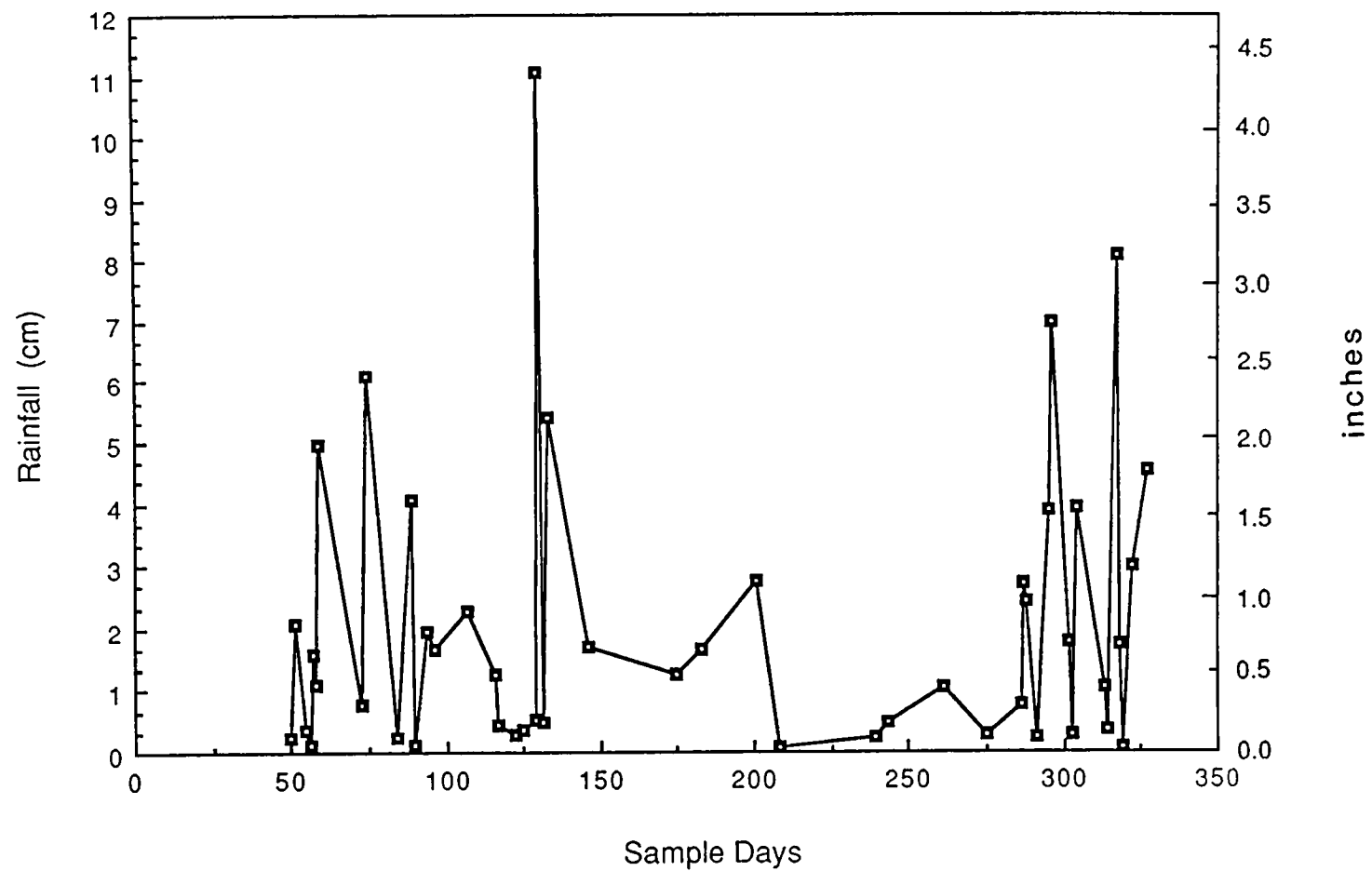


Fig. 17. Rainfall during study period - July 17, 1985 (day 1) to June 23, 1986 (day 341).

contamination. Although rainfall did occur during other sample months, these rainfalls had less effect than the other two. Rainfall in September and October followed a long drought period. The majority of the surface runoff was absorbed into the soil and surrounding vegetation. There were periods of rainfall which lasted for several days with an accumulation of two or more inches (Fig. 17). Although these rainfall events caused moderate contamination they did not cause the changes in chemical concentrations as did the two larger rainfalls. These findings are no less significant as far as bacterial contamination is concerned, but they provided no concrete information as to the source of the contamination or changes in the chemical concentrations (Table 5 & 6).

Conductivity

Conductivity is a measurement of the electrical current carrying capacity, in μmhos , of 1 cm^3 of water at 25°C (Table 5). Dissolved substances in water dissociate into ions with the ability to conduct electrical current. The normal range of conductivity for drinking water in the United States is 50 to 1500 $\mu\text{mhos/cm}$ with preferred values of less than 500 mg/L for domestic use. Conductivity is an important water quality indicator of dissolved solids in water (APHA, 1985; USEPA, 1985). Past studies have shown conductivity values in the Sink Creek drainage area ranging from 360 to 560 $\mu\text{mhos/cm}$ (Ogden, et. al, 1986). During the study, conductivity values ranged from 218 to 731 $\mu\text{mhos/cm}$ (Table 7). Wells exhibiting no bacterial contamination showed no definite pattern following rainfall (Figs. 18). The greatest decreases in conductivity were found in association with the two largest rainfalls (11/85 and 5/86) in wells which exhibited bacterial contamination (Fig. 19). Fluctuations in the conductivity values were also seen with other minor rainfall events. The conductivity of a bicarbonate type system reflects changes in the concentration of major ions. By plotting total dissolved solids, total hardness and alkalinity concentrations against conductivity this relationship can be seen (Figs. 20 & 21). Conductivity also reflected

Table 6. Physical and biological characteristics affecting water quality (USEPA, 1976 & 1985).

CHARACTERISTIC	SOURCES	SIGNIFICANCE	LEVELS AFFECTING WATER QUALITY
Conductivity (μ mhos/cm)	Dissolved minerals in water that form ions	Dissolved substances in water form ions that conduct electrical current is measured by conductivity	Conductivity is a measure of the mineral content of water
pH (hydrogen-ion activity)	Dissolved acids and bases in water and the dissociation of water molecules	The pH is a measure of waters reactive characteristics. Low pH values indicate corrosive (acidic) conditions and high values indicate depositional (alkaline) conditions	pH values: < 7.0 acidic 7.0 neutral > 7.0 alkaline
Total Dissolved Solids (TDS) (mg/L)	Dissolved minerals in water	TDS is a measure of the total dissolved mineral concentration in water. Water with concentrations < 500 mg/L is preferred for drinking water	$< 1,000$: Fresh $1,000-3,000$: Slightly saline $3,000-10,000$: Mod. saline $10,000-35,000$: Very saline
Fecal Coliform and Total Coliform (colonies/100 ML)	Feces of warm blooded mammals and birds, broken sewer lines and septic systems	Coliform bacteria are indicators of the possible presence of waterborne diseases such as typhoid, hepatitis, dysentary, eye, nose and throat infections	Drinking water - 0 * Swimming water - 200 *

* (Texas Department of Health, 1985)

Table 7. Monthly values for conductivity and total dissolved solids for the Sink Creek drainage basin, Hays County, Texas (7/85-6/86).

Conductivity ($\mu\text{mhos/cm}$)	1	2	3	4	5	6	7	8	9	10	11	12	13
Sample Months	Sample Well Number												
July 85	490	-	-	-	-	480	490	-	-	540	-	-	-
August 85	370	400	375	355	350	350	370	463	410	390	500	460	410
September 85	532	560	-	-	-	-	532	535	500	597	613	556	532
October 85	645	552	549.3	577	594	500	584	559	490	651	589	567	541
November 85	696	509	582	582	532	520	516	544	379	523	587	560	430
December 85	520	520	520	542	520	498	524	552	532	551	567	532	525
January 86	549	617	570.6	573	582	523	557	603	495	596	607	583	559
February 86	520	571	570.8	632	573	530	566	613	474	602	603	561	545
March 86	525	541	551.2	603	541	509	569	587	546	642	611	587	552
April 86	520	509	535.1	604	544	504	580	590	506	604	599	554	523
May 86	-	-	544	-	511	499	483	439	381	517	548	478	365
June 86	512	520	551.2	350	488	474	395	501	517	524	536	525	507
TDS													
(Cond. x .65)													
July 85	318	-	-	-	-	312	318	-	-	351	-	-	-
August 85	240	260	244	231	227	227	240	301	301	253	325	299	266
September 85	346	364	-	-	-	-	346	348	325	388	398	361	346
October 85	419	359	357	375	386	325	250	363	318	423	383	368	351
November 85	452	331	378	378	346	338	335	354	246	340	381	364	279
December 85	338	338	338	352	338	324	341	359	346	358	368	346	341
January 86	357	401	371	372	379	340	362	392	322	387	395	379	363
February 86	338	371	271	411	374	345	368	399	308	391	392	365	355
March 86	341	352	358	392	352	331	370	381	355	418	397	381	359
April 86	338	331	348	392	353	327	377	383	329	392	389	360	340
May 86	-	-	354	-	332	324	314	285	247	336	356	311	237
June 86	333	338	358	227	317	308	257	325	336	341	348	341	530

Table 7 .Monthly values for conductivity and total dissolved solids for the Sink Creek drainage basin, Hays County, Texas (7/85-6/86).

Conductivity (µmhos/cm)	14	15	16	17	18	19	20	21	22
<u>Sample Months</u>									
July 85	-	-	580	400	-	-	500	460	-
August 85	500	435	520	590	432	410	530	520	425
September 85	674	620	638	-	524	530	489	562	528
October 85	628	637	617	615	565	566	615	451	544
November 85	611	598	619	-	464	415	-	551	466
December 85	634	622	609	585	509	514	542	520	526
January 86	624	624	649	631	555	542	596	591	555
February 86	645	628	645	658	572	564	630	594	570
March 86	637	650	630	599	573	576	601	578	573
April 86	635	625	639	589	546	587	614	565	580
May 86	650	571	581	580	382	379	-	600	397
June 86	582	588	592	514	506	497	572	524	472
<u>TDS</u> (Cond.X.65)									
July 85	-	-	377	260	-	-	325	299	-
August 85	325	283	338	383	281	266	344	338	276
September 85	438	403	415	-	340	344	318	365	343
October 85	408	414	401	400	367	368	400	293	354
November 85	397	389	403	-	301	270	-	358	303
December 85	412	404	396	380	331	334	352	338	342
January 86	406	406	422	410	361	352	387	384	361
February 86	419	408	419	427	372	367	410	386	370
March 86	414	422	409	389	372	375	391	376	373
April 86	413	406	415	383	355	381	399	367	377
May 86	422	371	378	377	248	246	-	390	258
June 86	378	382	385	334	329	323	371	341	307

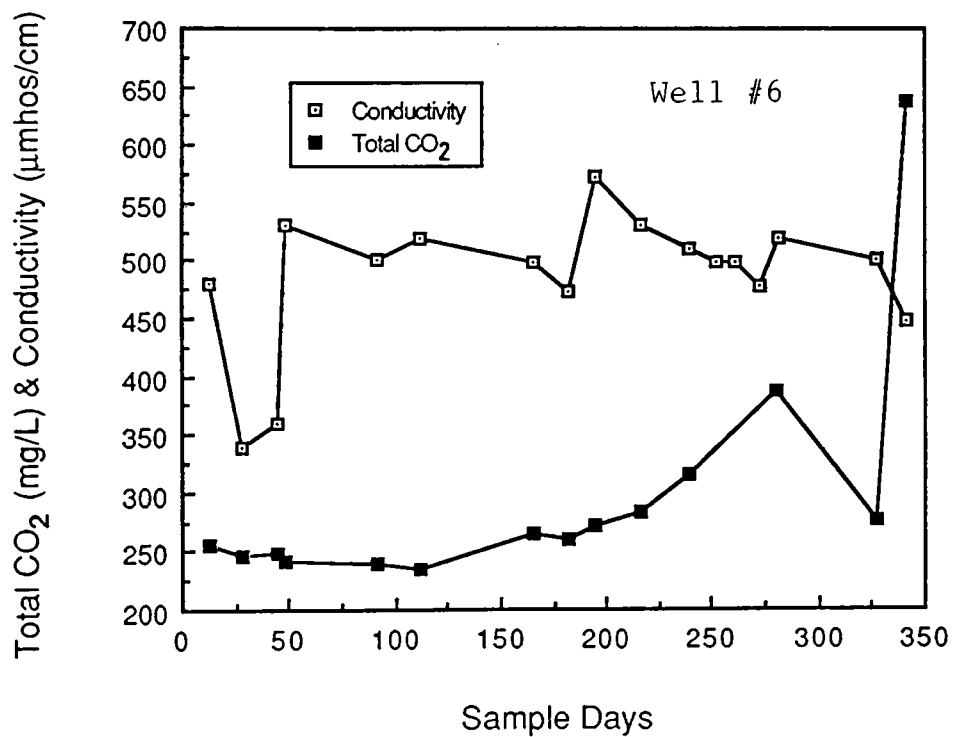
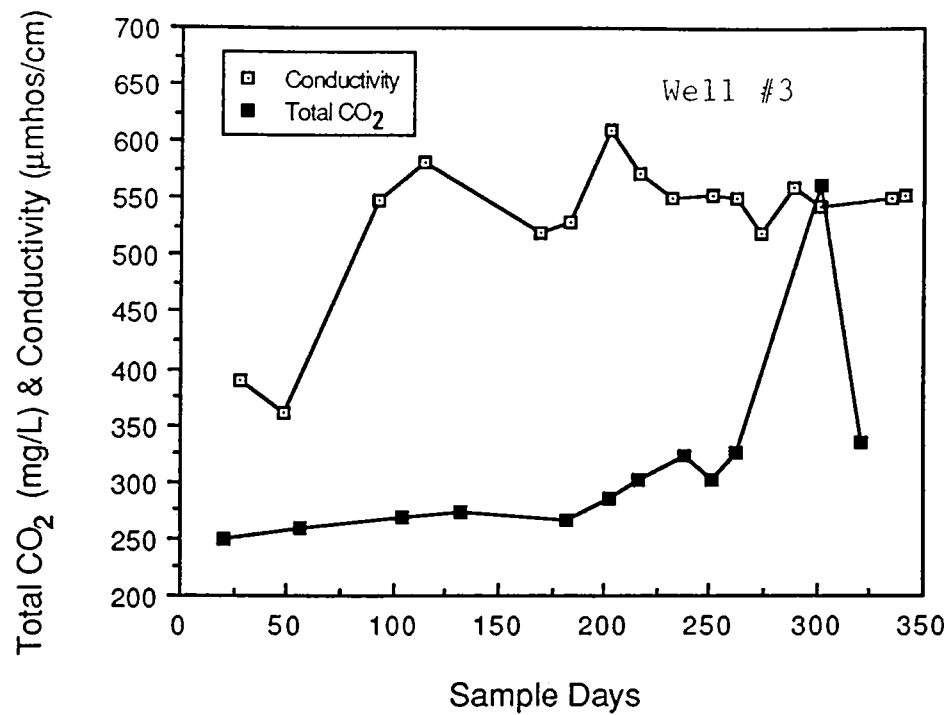


Fig. 18. Non-contaminated wells - total carbon dioxide (mg/L) and conductivity (μmhos/cm) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

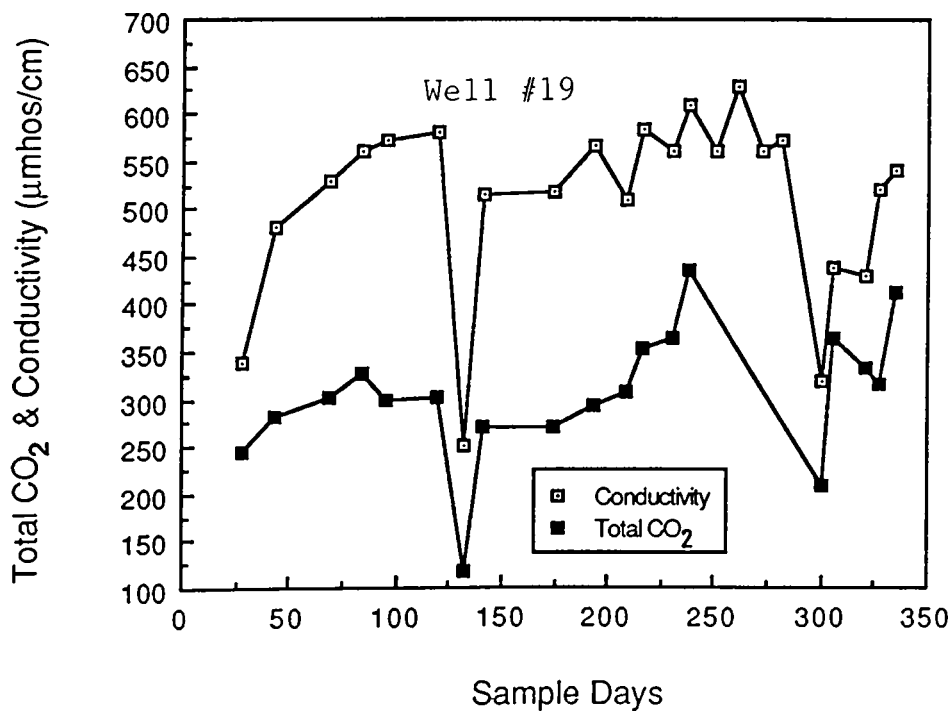
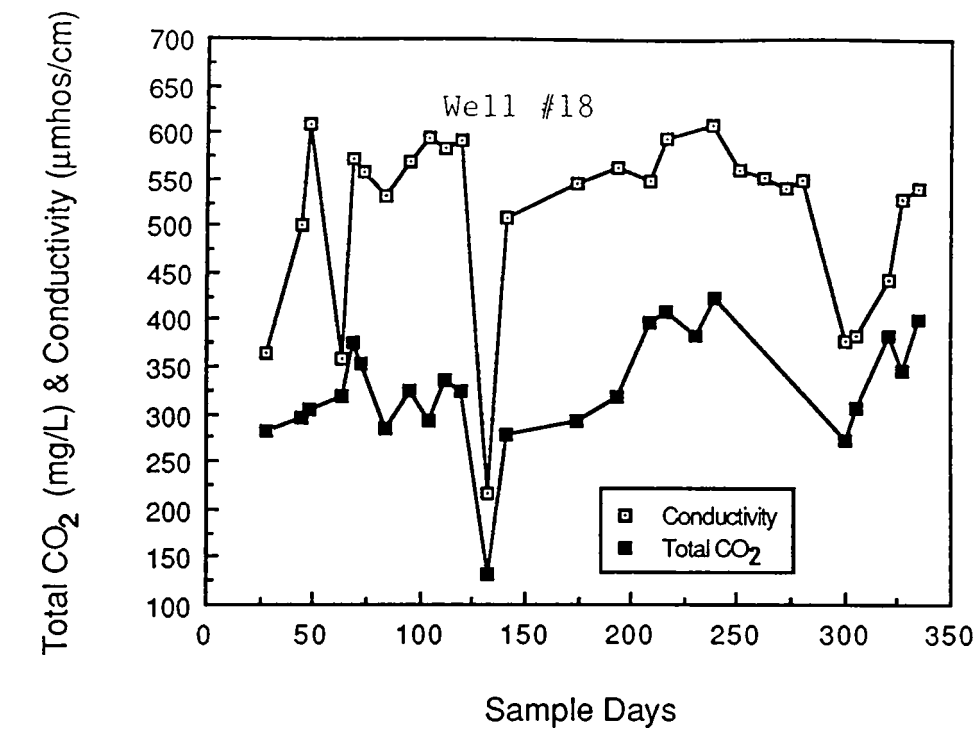


Fig. 19. Contaminated wells - total carbon dioxide (mg/L) and conductivity (μmhos/cm) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

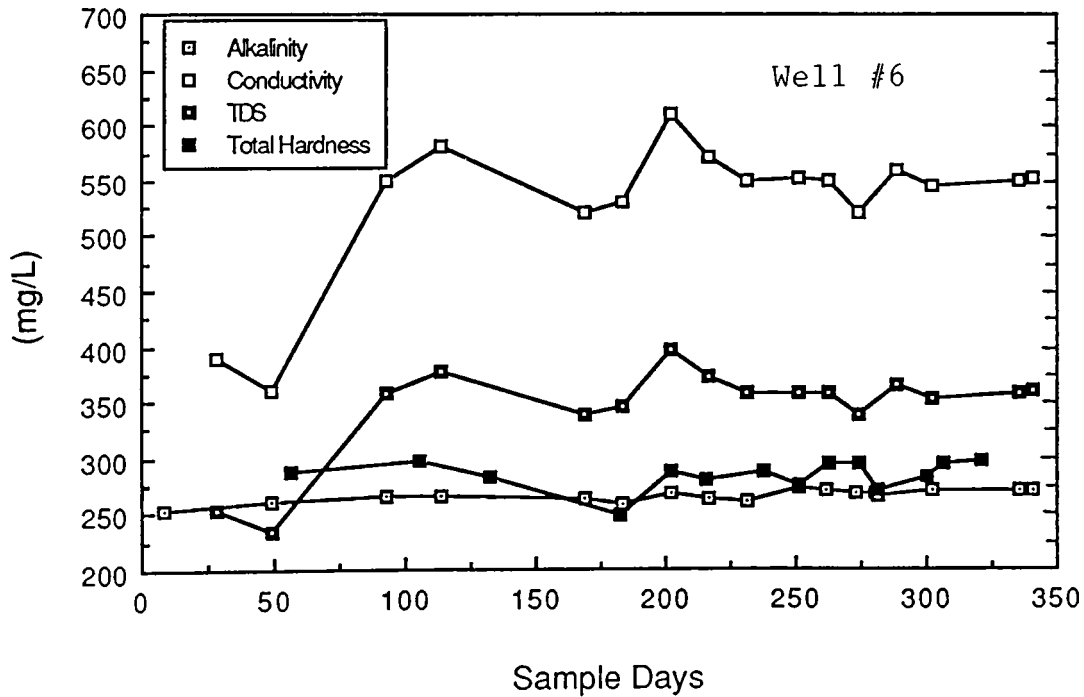
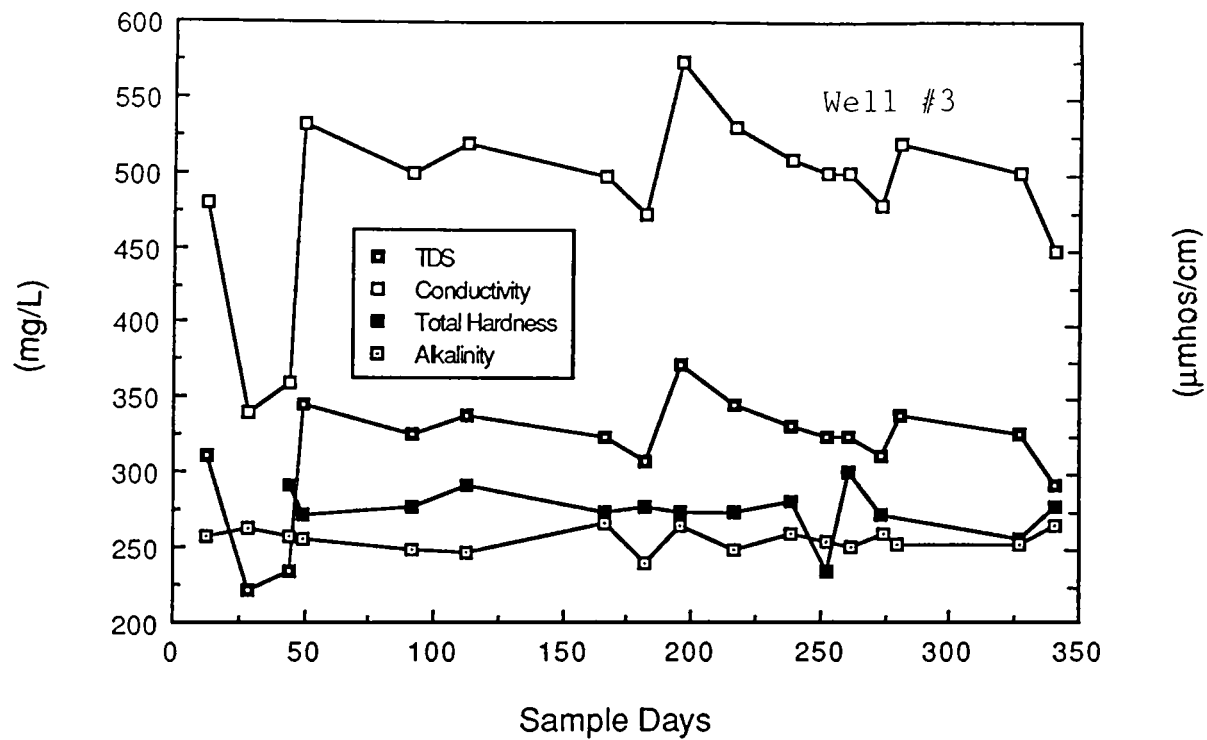


Fig. 20. Non-contaminated wells-dissolved solids (total dissolved solids, alkalinity, total hardness (mg/L) and conductivity ($\mu\text{mhos/cm}$) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

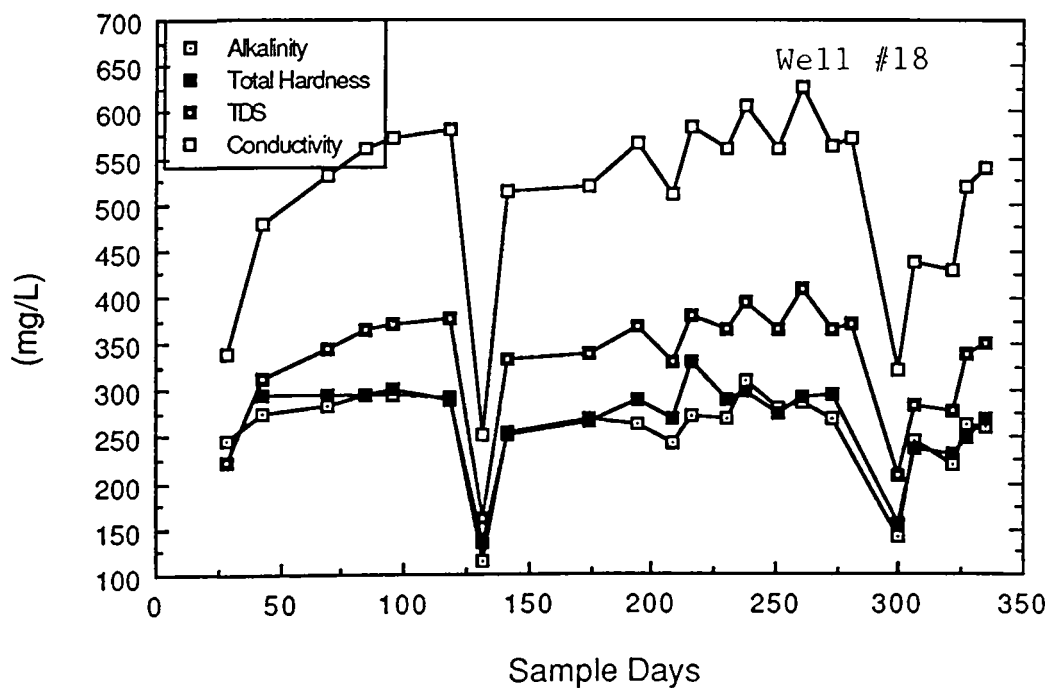
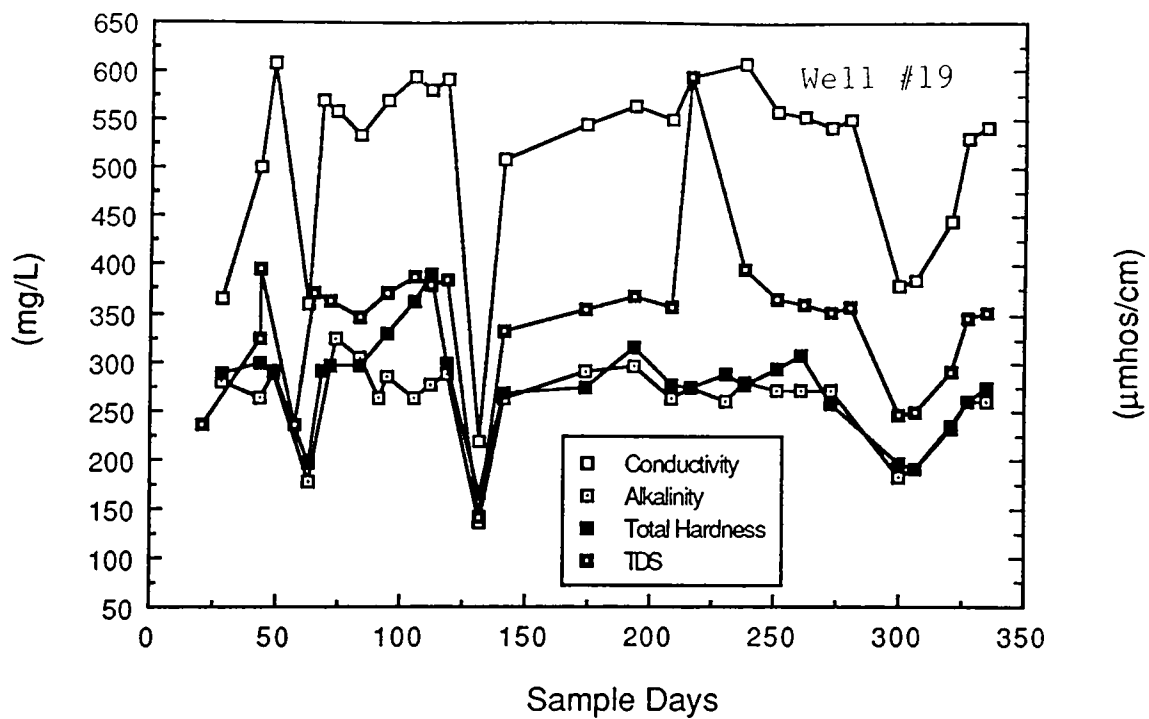


Fig. 21. Contaminated wells-dissolved solids (total dissolved solids, alkalinity, total hardness (mg/L) and conductivity (μmhos/cm) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

increased levels of carbon dioxide (CO₂), where calculated CO₂ values had curves similar to those of conductivity in wells with and without bacterial contamination (APHA,1985) (Figs. 18 & 19). Large decreases in these values were associated with the rapid infiltration of surface runoff in local faults, fractures, caves and sinkholes. The surface runoff contained lower ionic concentrations than that of the groundwater. This infiltration caused a mixing of large amounts of surface water with the ground waters causing a dilution effect. Higher values were associated with the non-contaminated wells and the normal dissolution process following rainfall (USEPA,1985).

Dissolved Solids in Groundwater

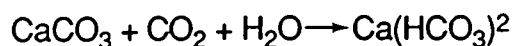
The majority of dissolved solids in groundwater are derived from substances released during the solutioning of the rocks in the aquifer. Minerals in the soil, in sediments within the aquifer and in the sediments found near the surface also contribute to the concentration of dissolved solids in groundwater. Recharge to the aquifer from precipitation contains trace amounts of various minerals. Rainwater with a natural pH of less than 7.0 percolates through the soil picking up additional organic acids increasing the corrosiveness. During recharge, water moves through the faults and fractures dissolving the limestone and releasing minerals in the process (Underground Resource Management,1980;Baker, et. al,1986). This process is evident in wells experiencing no bacterial contamination. Following rainfall events the chemical concentrations increased in these sample wells. The concentrations of dissolved solids in wells with bacterial contamination showed the same patterns as seen in conductivity values (Figs. 20 & 21). Dissolved solid concentrations in the recharge zone of the Edwards typically range from 200 to 400 mg/L and increase to 1,000 to 3,000 mg/L within varying distances of the "bad water" line to the east (Baker, et. al,1986).

Total Dissolved Solids

Total dissolved solids (TDS) in general consist of bicarbonate carbonate calcium, chloride, magnesium, potassium, sodium, sulfate and trace amounts of other organic and inorganic compounds (Table 5). The maximum preferred level for drinking water is 500 mg/L (APHA,1985; USEPA,1985). Waters with high TDS are generally undesirable for drinking and have adverse physiological effects on infrequent users (APHA,1985). TDS values for this study were estimated using the equation $TDS = 0.65 \times \text{conductivity}$ (Brown, Skougstad and Fishman,1974). Average monthly values for TDS ranged from 227 mg/l to 452 mg/L (Table 7). The lower values are associated with the two largest rainfalls and the dilution by surface runoff. The higher values were associated with non-contaminated wells and the dissolution of the limestone following the heavy rainfalls (Figs. 22 & 23).

Hardness

Total hardness is the sum of the calcium and magnesium concentrations, expressed as calcium carbonate in mg/L. Hardness values greater than 180 mg/L are classified as very hard by the USEPA (1985) (Table 6). Limestone is the principal source for hardness in the natural environment. In fresh water hardness is broken into carbonate and noncarbonate fractions. Carbonate hardness is equal to the bicarbonates present. The ionic concentration was $Ca > Mg > Na > K$ (Wetzel,1983; USEPA,1976). The calcium and magnesium components are very common in the earth's crust, but are relatively insoluble in water. The presence of carbon dioxide and acidic components cause the dissolution of carbonate minerals. In association with carbon dioxide, carbonates are converted to the more soluble bicarbonate (Brown, et. al,1974):



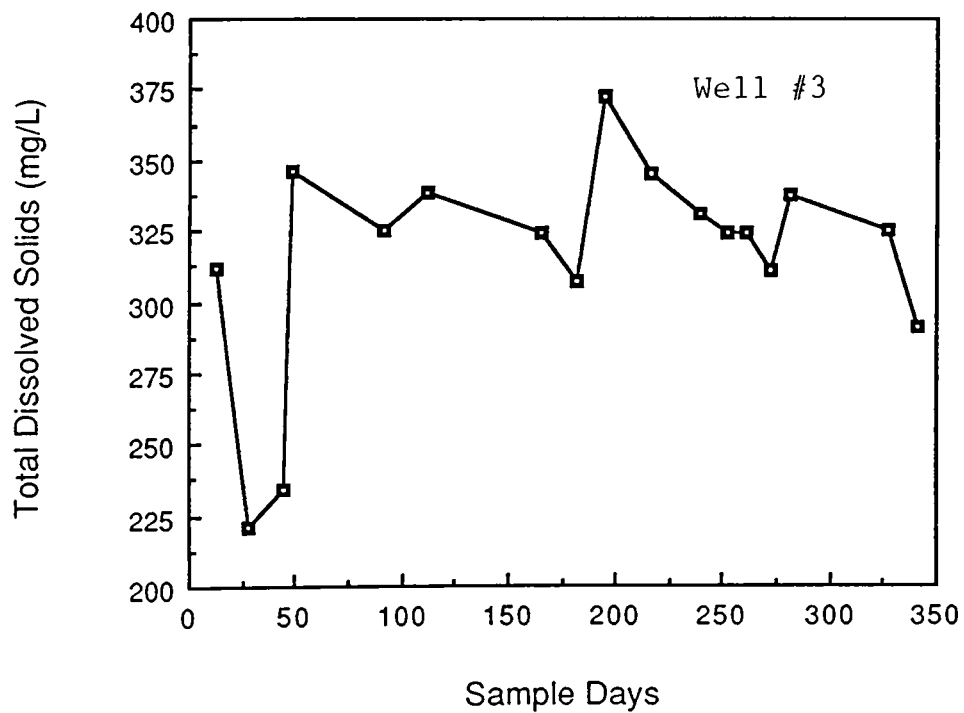
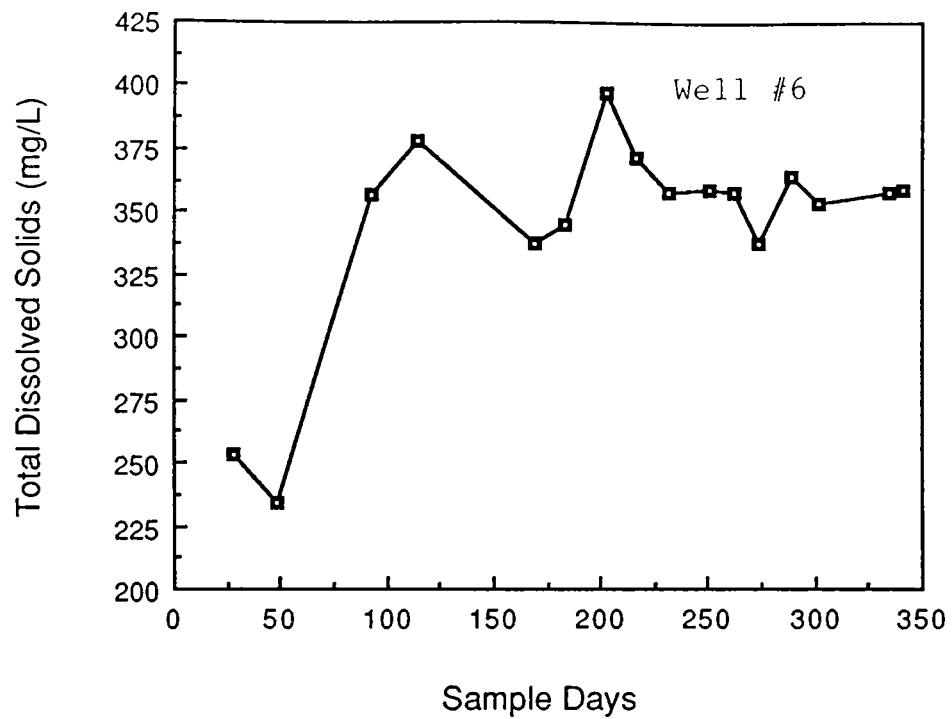


Fig. 22. Non-contaminated wells- total dissolved solids (mg/L) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

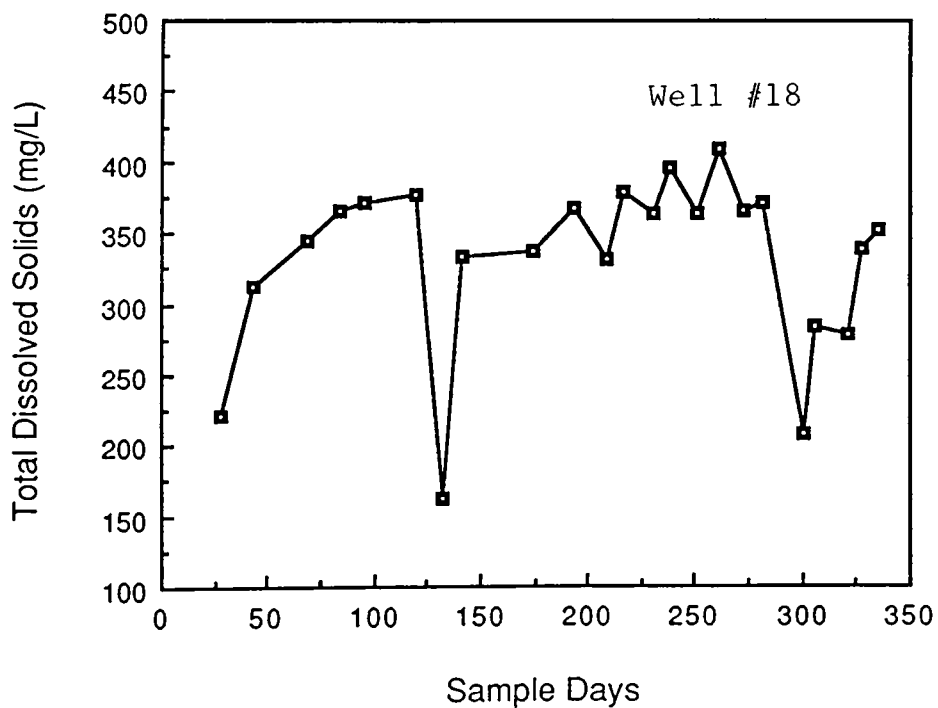
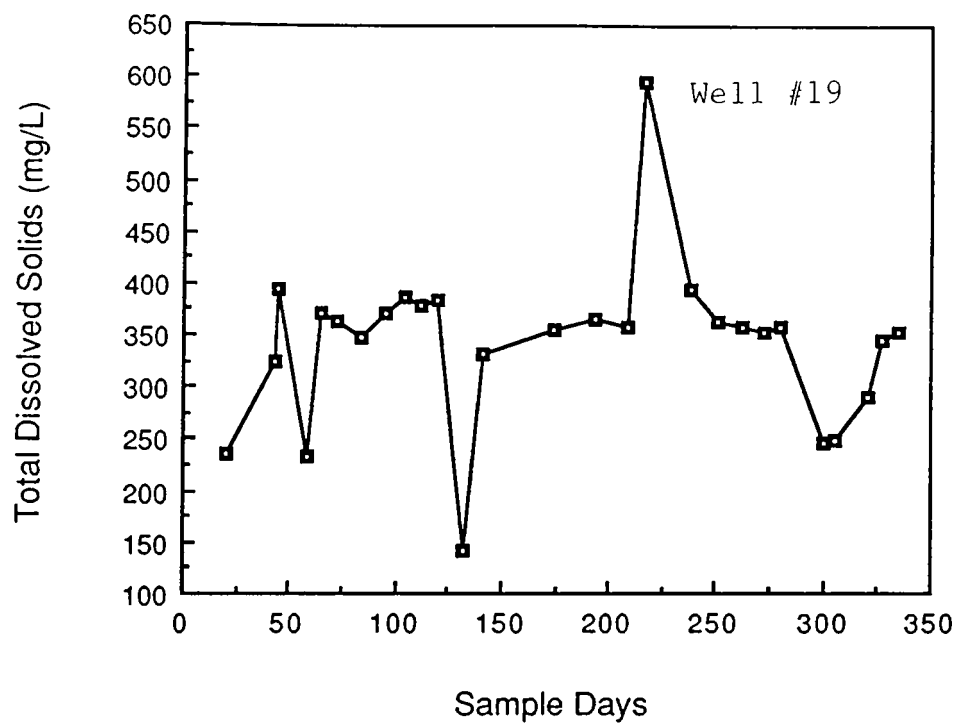


Fig. 23. Contaminated wells- total dissolved solids (mg/L) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

Hardness values ranged from 136 to 442 mg/L (Table 8). Values fluctuated throughout the sample period, but the largest decrease follows the two major rainfall events (11/85 and 5/86) (Figs. 24 & 25). The major component of hardness in the study area was calcium (110 to 340 mg/L) with smaller amounts of magnesium (0 to 158 mg/L) (Table 9) (Figs. 24 & 25).

Carbonates

The abundance of carbonate minerals and carbon dioxide in the environment are largely responsible for the common occurrence of carbonates and bicarbonates in water (Brown, et. al,1974).

In fresh water the concentration of the total inorganic carbon is dependent on the pH, which in turn is determined largely by the buffering capacity of the carbonic acid and bicarbonate/carbonates derived from the weathered rocks. The most important carbonate existing in an aquatic system is calcium carbonate occurring in natural waters primarily as calcite. The majority of carbon occurring in freshwater exists as equilibrium products of carbonic acid (H_2CO_3). Some of the free CO_2 in water, due to its high solubility, hydrates to form carbonic acid (Wetzel,1983; Bögli,1980):



The carbonic acid formed is weak and quickly breaks down to bicarbonate and carbonate:



An equilibrium is established as the bicarbonate and carbonate ions dissociate:

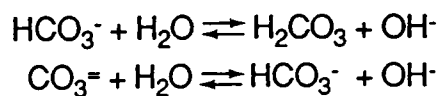


Table 8. Monthly alkalinity and total hardness values for the Sink Creek drainage basin, Hays County, Texas (7/85-6/86).

Alkalinity (mg/L)	1	2	3	4	5	Sample 6	Well 7	Number 8	9	10	11	12	13
<u>Sample Months</u>													
July 85	253	-	253	-	-	257	260	-	-	253	-	-	-
August 85	257	282.5	261	267	273	260	272	278	243	257	278	277	278
September 85	257	280	-	-	-	253	287	244	237	257	293	294	264
October 85	250	256	266	254	270	249	271	277	226	250	292	291	249
November 85	274	254	266	276	255	246	268	273	196	274	301	274	206
December 85	234	274	262	244	254	266	238	276	248	234	248	250	251
January 86	260	276	263	271	268	252	263	278	218	260	272	258	245
February 86	264	274	262	272	266	248	272	282	247	264	286	294	255
March 86	263.5	254.5	267	277	268	257	273	269	238	263.5	299	283	263
April 86	258	264	267	275	269	254	275	279	237.5	258	290	282	247
May 86	-	-	270	-	275	-	243	272	180	260	274.2	254	177
June 86	263	266	270	269	269	261	253	256	254	255	257	261	255
<u>Total Hardness (mg/L)</u>													
July 85	270	-	-	-	-	-	274	-	-	216	-	-	-
August 85	276	284	288	308	243	292	285	306	239	308	281	237	267
September 85	274	292	-	-	-	272	303	291	259	275	280	289	278
October 85	276	298	298	302	280	278	321	320	268	442	316	367	278
November 85	285	278	282	270	287	292	292	307	223	319	308	314	223
December 85	268	280	248	250	294	274	239	294	256	258	294	246	253
January 86	272	292	284	296	292	276	285	311	257	302	290	295	275
February 86	276	301	288	304	286	274	296	298	253	300	312	282	288
March 86	276	295	288	311	258	257	293	305	259	298	318	292	271
April 86	281	289	282	306	294	286	306	298	253	302	317	258	262
May 86	-	-	296	-	270	-	256	268	190	250	308	248	190
June 86	269	276	276	264	280	267	260	265	252	272	285	265	264

Table 8. Monthly alkalinity and total hardness values for the Sink Creek drainage basin, Hays County, Texas (7/85-6/86).

Alkalinity (mg/L)	14	15	Sample 16	Well 17	Number 18	19	20	21	22
<u>Sample Months</u>									
July 85	-	-	340	-	-	-	284	270	268
August 85	293	321	327	314	272	261	308	272	295
September 85	310	324	338	-	274	283	292	270	294
October 85	290	294	302	346	270	296	296	274	278
November 85	306	255	308	-	234	204	-	284	276
December 85	312	294	281	299	262	254	272	275	254
January 86	294	307	315	302	293	267	280	273	304
February 86	298	316	316	294	269	258	286	278	290
March 86	308	326	329	304	270	286	312	284	290
April 86	304	294	319	309	271	278	301	288	298
May 86	297	294	304	284	186	194	-	296	276
June 86	313	307	309	303	250	247	299	286	257
<u>Total Hardness</u>									
(mg/L)									
July 85	-	-	338	-	-	-	304	269	-
August 85	279	342	350	315	294	294	322	290	286
September 85	332	328	336	-	268	296	306	297	290
October 85	358	422	324	328	329	299	408	314	285
November 85	338	318	376	-	286	213	-	303	231
December 85	300	300	246	302	268	250	282	274	256
January 86	329	315	325	320	295	277	292	288	295
February 86	274	300	324	308	276	298	292	308	282
March 86	335	317	335	312	285	287	310	307	288
April 86	321	321	314	305	281	294	316	301	296
May 86	319	296	304	300	195	196	-	299	219
June 86	312	306	321	304	256	249	326	301	259

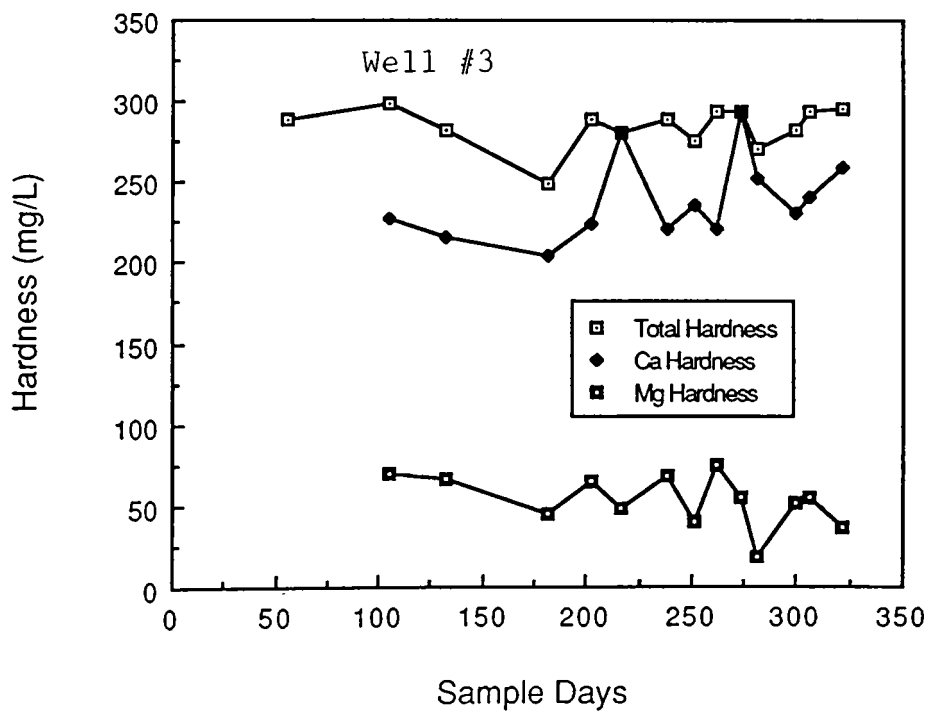
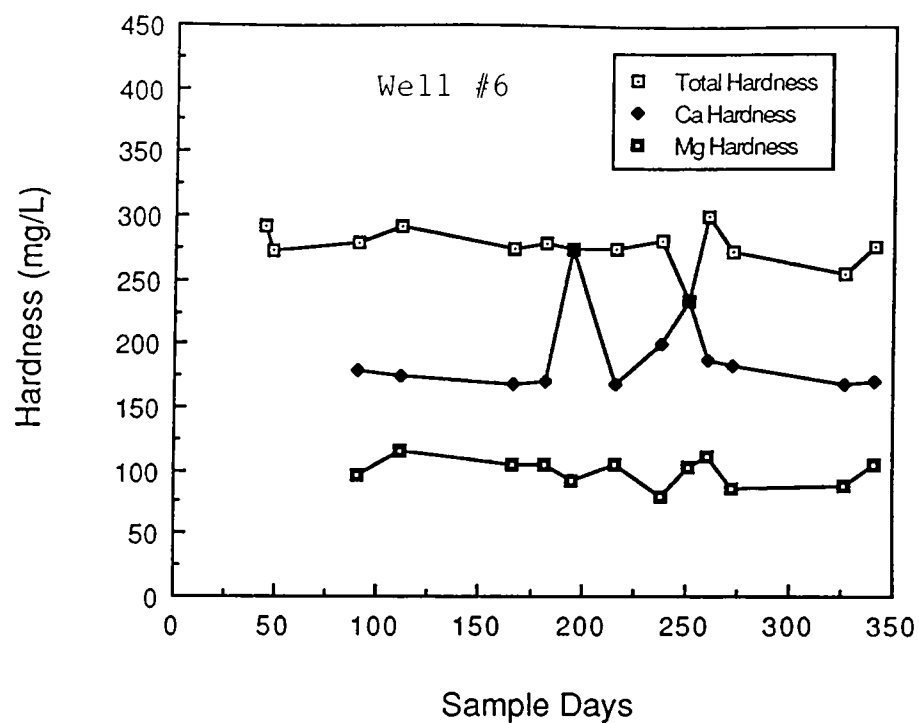


Fig. 24. Non-contaminated wells-hardness (mg/L) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

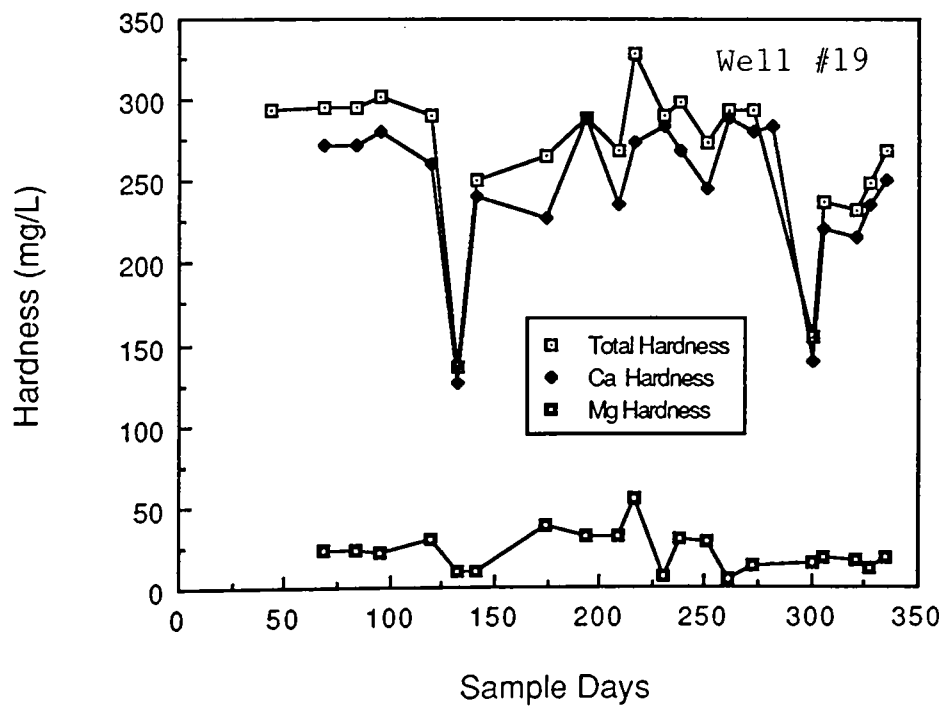
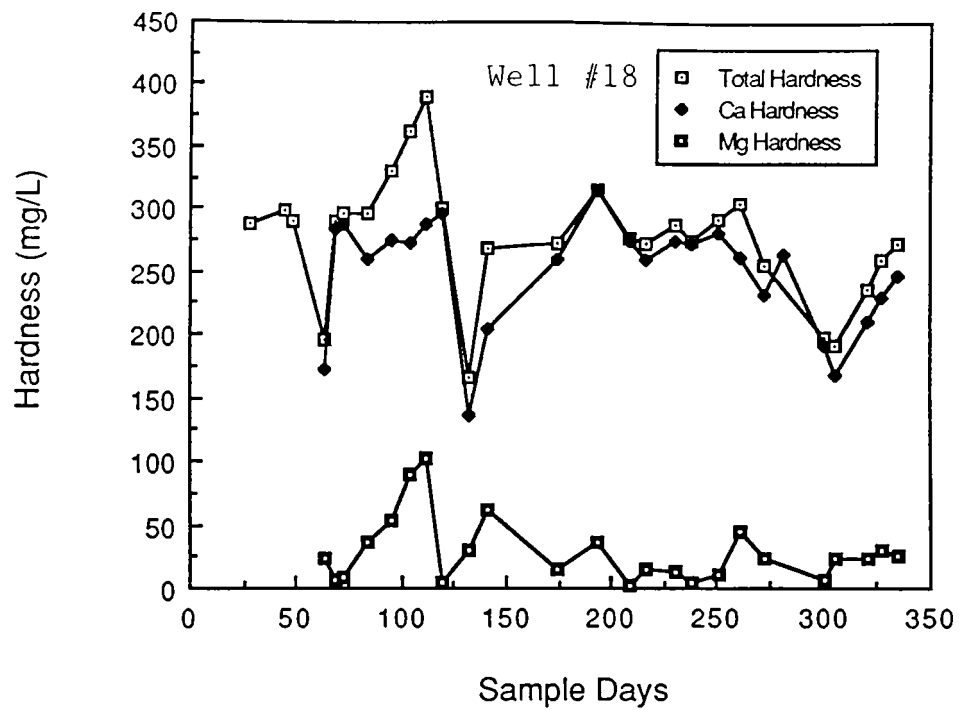


Fig. 25. Contaminated wells-hardness (mg/L) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

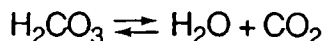
Table 9. Monthly calcium and magnesium hardness values for the Sink Creek drainage basin, Hays County, Texas (7/85-6/86).

Ca Hardness (mg/L)	1	2	3	4	5	6	7	8	9	10	11	12
<u>Sample Months</u>												
September 85	212	236	-	-	-	-	209	246	175	243	243	272
October 85	200	224	228	231	220	180	191	224	196	324	288	277
November 85	223	228	216	240	206	176	209	219	154	239	284	261
December 85	208	196	204	204	204	168	186	212	228	244	168	196
January 86	227	261	252	262	277	223	252	271	209	282	286	288
February 86	200	249	220	216	208	168	210	232	144	286	272	260
March 86	214	243	250	231	237	217	192	235	206	270	304	274
April 86	230	253	241	248	229	186	218	260	197	294	296	252
May 86	-	-	259	-	220	-	200	216	158	234	184	240
June 86	200	184	222	216	204	170	191	175	232	233	171	205

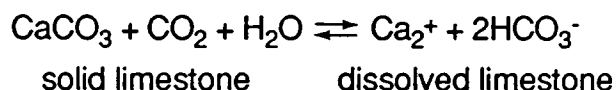
Mg Hardness (mg/L)												
September 85	60	56	-	-	-	-	96	45	84	23	55	17
October 85	76	74	70	71	60	98	140	87	72	118	28	91
November 85	61	50	66	30	81	116	85	89	69	81	24	53
December 85	60	84	44	46	90	106	53	82	28	12	26	50
January 86	78	58	56	58	50	100	67	89	99	32	12	47
February 86	76	51.7	68	88	78	106	87	66	109	13	40	22
March 86	62	57	56	79	55	92	100	75	53	28	14	18
April 86	52	55.9	41	68	65	100	90	50	77	15	19	18
May 86	-	-	37	-	50	-	55	52	31	16.4	122	8
June 86	68	92	53	48	76	97	69	90	20	39	63	60

Table 9. Monthly calcium and magnesium hardness values for the Sink Creek drainage basin, Hays County, Texas (7/85-6/86).

Ca Hardness (mg/L)	13	14	15	16	17	18	19	20	21	22
Sample Months										
September 85	257	-	304	316	-	248	272	296	-	233
October 85	244	340	288	268	308	269	276	332	240	238
November 85	213	304	292	268	-	240	193	-	262	208
December 85	230	288	224	216	22.4	204	240	256	208	236
January 86	254	325	294	312	276	288	258	287	254	265
February 86	275	268	293	300	292	268	255	288	256	246
March 86	253	324	300	302	297	276	266	295	254	242
April 86	245	302	293	284	292	253	584	300	263	261
May 86	172	319	232	249	257	179	180	-	273	180
June 86	228	304	270	227	255	230	234	240	224	216
Mg Hardness (mg/L)										
September 85	21	-	24	18	-	13	24	10	-	57
October 85	34	18	134	56	20	61	23	76	56	47
November 85	10	34	26	108	-	48	20	-	40	23
December 85	22	12	75	30	78	62	10	26	68	20
January 86	27	7	41	25	50	25	35	20	72	43
February 86	12	6	6	24	16	8	44	4	38	162
March 86	18	11	19	33	15	9	22	12	45	45
April 86	23	10	27	43	21	34	10	20	45	46
May 86	17	0	63	55	43	15	16	-	40	27
June 86	36	8	33	95	48	26	15	85	77	23



As the concentration of carbonates in water increases so does the solubility of CO_2 . After an equilibrium has been reached between HCO_3^- , CO_3^{2-} , Ca^{+2} and undissociated CaCO_3 there is an excess amount of free CO_2 remaining in solution. This excess is required to maintain the stability of $\text{Ca}(\text{HCO}_3)_2$ and increases rapidly with an increase of bicarbonate in the water due to carbonate. Additional CaCO_3 will dissolve when the amount of free CO_2 is increased above the amount required to keep CaCO_3 in solution at equilibrium (Wetzel, 1983; Bögli, 1980). The dissolution of limestone is commonly described by the equation:



Alkalinity and pH

Alkalinity is a measure of the acid-neutralizing capacity of water. Bicarbonate, carbonate and hydroxide are the primary cause of alkalinity in natural waters and are expressed as milligrams per liter as CaCO_3 . The forms of alkalinity were calculated and the major constituent was bicarbonate alkalinity with much lesser amounts of carbonate alkalinity and minute amounts of hydroxide alkalinity (APHA, 1985). These components are a function of pH, temperature and other dissolved solids. The components of alkalinity are common in natural waters due to the abundance of carbonate minerals and carbon dioxide. In natural waters alkalinity normally varies, but never exceeds 400 to 500 mg/L as CaCO_3 (Brown, et. al, 1974; USEPA, 1976) (Table 6).

Alkalinity values in Hays County ranged from 216 to 334 mg/L as CaCO_3 (Ozuna, et. al, 1987). Average monthly values at the study site ranged from 177 to 346 mg/L as CaCO_3 with the majority between 200 and 300 mg/L (Table 8). The values varied throughout the study period, but the wells with

high levels of bacterial contamination again exhibited decreases following the rainfalls in November 1985 and May 1986 (Figs. 26 & 27).

The pH or hydrogen-ion activity of water is caused by the dissociation of water molecules and the presence of dissolved acids and bases. The pH of water is actually a measure of its reactive characteristics. Low pH values indicate corrosive conditions and the dissolution of limestone (CaCO_3).

High pH values are associated with alkaline or deposition of calcium carbonate (CaCO_3) (Table 5). A carbon dioxide-bicarbonate-carbonate equilibrium exists in water which is easily disturbed by the loss of carbon dioxide. The pH of groundwater is often controlled by dissolved carbon dioxide gas and carbonates/bicarbonates. Changes in pH can occur in groundwater samples when exposed to the atmosphere. The high levels of carbon dioxide existing under confined pressure of an aquifer will be lost until the concentration equals that which can exist under the partial pressure of the atmosphere and a new equilibrium is established. For this reason pH was determined at the time of sampling (USEPA, 1984 & 1985; Hem, 1959; UOP, Inc., 1975).

The groundwater found in the United States normally falls within a range of 5.5 to 8.0 (Hem, 1959). From October 1982 to June 1985 pH values for Hays County were greater than 7.0 with few exceptions (Ogden, et. al, 1986; Ozuna, et. al, 1987). The average monthly pH of the groundwater during the study ranged from 6.12 to 7.44 (Table 10). The pH values did not show the same changes seen in chemical concentrations following rainfall events and did not appear to be affected by individual rainfall (Figs. 28 & 29). In general, pH values ranged from 6.8 to 7.44 with the majority remaining above 7.0. Minor fluctuations in pH were seen throughout the study period until a major decrease occurred in February. Values from February to June ranged from 6.12 to 6.87. The pH of rain is naturally acidic (less than 7) and slightly corrosive (the degree of acidity and corrosiveness vary with the geographic location and mans influence). As rainwater combines with dissolved gases present in the atmosphere (carbon dioxide, oxygen, nitrogen and sulfur dioxide) the pH decreases. In the soil, rainwater can

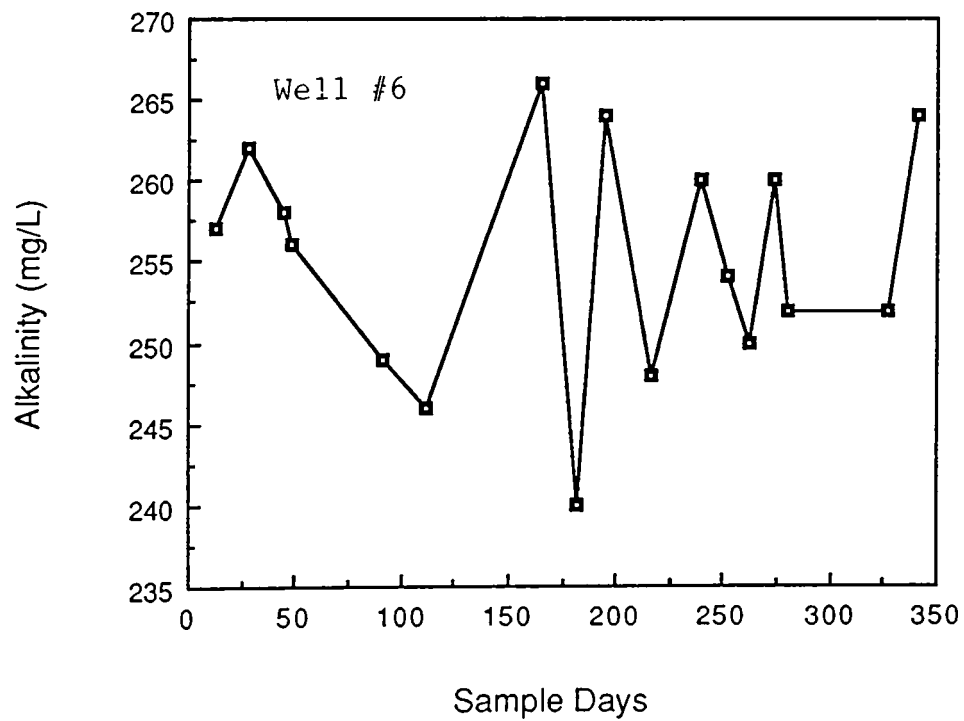
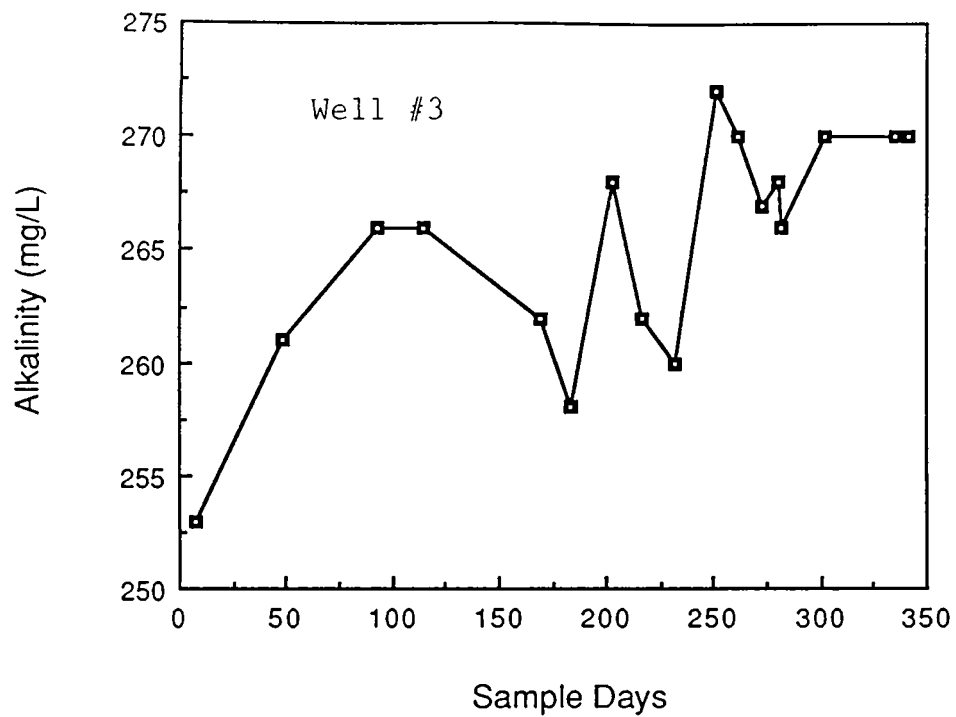


Fig. 26. Non-contaminated wells-alkalinity (mg/L) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

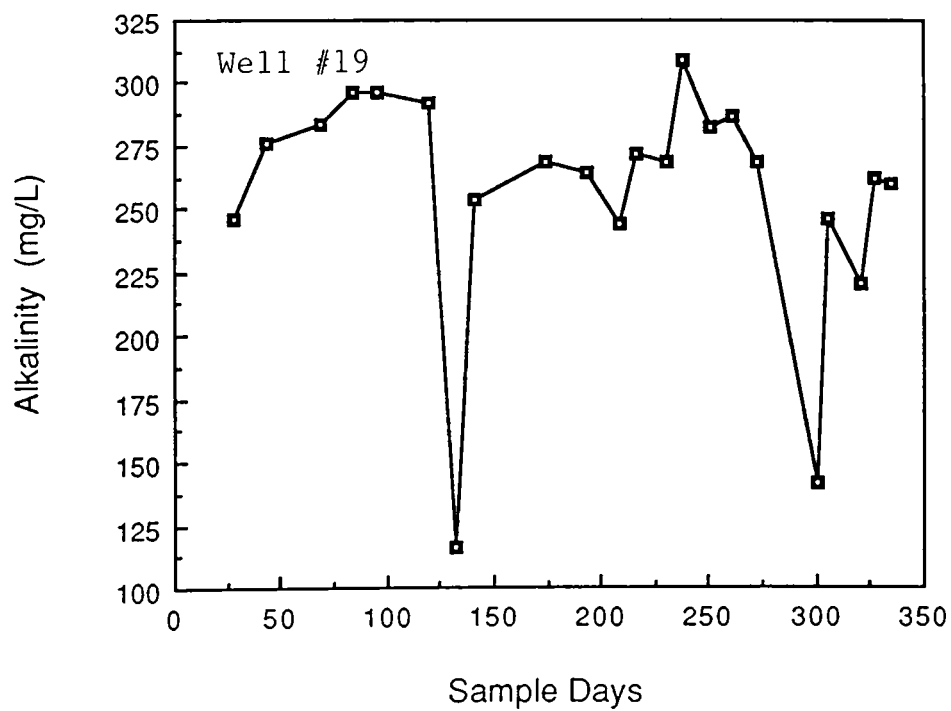
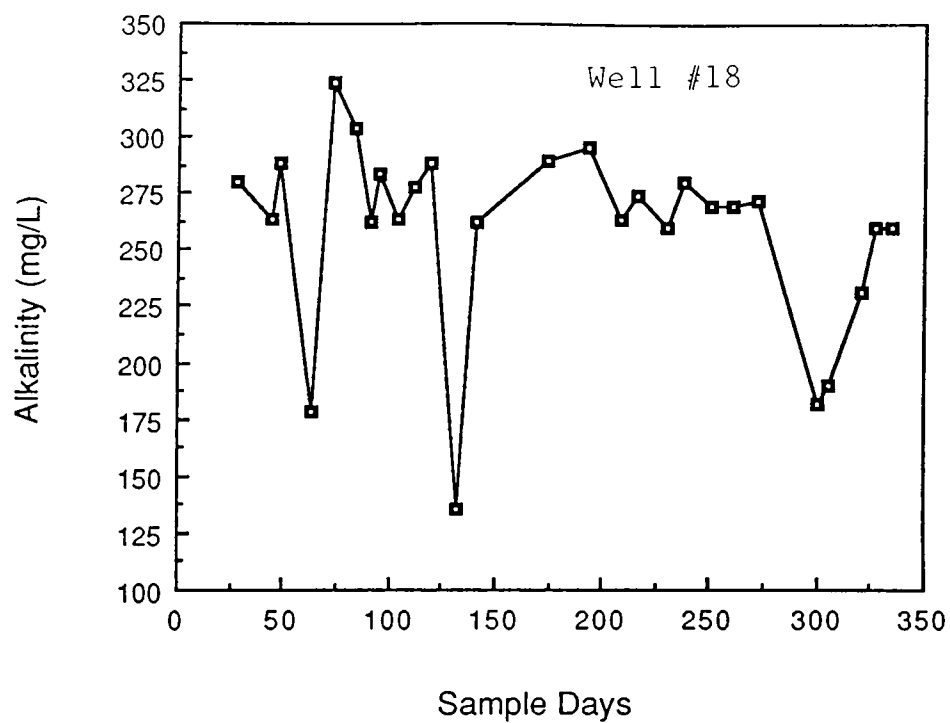


Fig. 27. Contaminated wells-alkalinity (mg/L) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

Table 10. Monthly pH and water temperature values for the Sink Creek drainage basin, Hays County, Texas (7/85-6/86).

pH (Units)	1	2	3	4	5	6	7	8	9	10	11	12
<u>Sample Months</u>												
July 85	7.32	7.22	7.25	7.34	7.16	7.24	7.12	7.26	7.12	7.19	7.32	7.12
August 85	7.41	7.25	7.3	7.28	7.16	7.34	7.28	7.12	7.34	7.04	7.15	7.12
September 85	7.31	7.14	7.23	7.14	7.16	7.4	7.21	7.12	7.23	6.96	7.01	7.05
October 85	7.21	7.29	7.15	7.1	7.11	7.31	7.24	7.08	7.27	7.06	7.01	6.96
November 85	7.19	7.21	7.16	7.19	7.09	7.37	7.24	7.13	7.15	6.95	7.11	7.01
December 85	7.2	7.11	7.14	7.11	7.1	7.16	7.15	7.14	7.07	7.1	7.1	7.1
January 86	7.18	7.02	7.16	7.22	7.19	7.17	7.22	7.14	7.26	7.15	7.16	7.14
February 86	6.8	6.87	6.75	6.74	6.65	6.84	6.64	6.68	6.72	6.43	6.76	6.53
March 86	6.7	6.66	6.82	6.72	6.63	6.84	6.7	6.51	6.7	6.52	-	6.53
April 86	6.58	6.42	6.21	6.65	6.25	6.48	6.6	6.63	6.61	6.47	6.51	6.47
May 86	6.69	6.67	6.66	6.58	6.64	6.63	6.51	6.39	6.74	6.5	6.61	6.63
June 86	6.72	6.63	6.72	6.51	6.61	6.61	6.64	6.61	6.5	6.65	6.63	6.5
<u>Temperature</u>												
(°C)												
July 85	25	24	26	25	25	25	26	25	24	25	24	24
August 85	24.2	24.7	26	25.2	23.8	25.9	25.5	23.8	23.3	24	24.4	24.8
September 85	24.1	24.1	25.5	24.9	24.7	25.7	25.1	23.6	23.2	23.7	23.6	24
October 85	23.1	22.4	22.4	22.4	21.9	23.2	23.2	22.2	21.6	22.4	22.7	22.5
November 85	21.6	19.8	18.6	19.5	20.9	19.3	21.3	20.8	20.3	21.9	21.7	20.5
December 85	19.2	12.1	12.2	16.7	17.4	12	21.2	18.2	18.6	18.5	18.3	18.1
January 86	16.4	14.2	11.9	16.1	17.7	11.6	19.7	17.2	18.6	18.4	18.8	18.7
February 86	21.4	19	17.1	18.8	20.6	17.3	22.2	19.9	18.6	19.6	21	22.3
March 86	20.9	18.7	17.6	19.7	21.9	17.9	23.4	20.3	22.1	22.4	21.4	21.7
April 86	21.1	21.7	20.3	21.8	21	19.4	22.2	21.9	21.7	22.5	22.6	21.2
May 86	21.6	23.1	23.1	23.8	22.3	23.1	23.3	22.1	22	22.8	22.4	22.6
June 86	23.5	23.9	24.3	23.5	23.1	25.1	23.5	23.1	23.1	24.4	23.3	23.4

Table 10. Monthly pH and water temperature values for the Sink Creek drainage basin, Hays County, Texas (7/85-6/86).

pH (Units)	13	14	Sample		Well	Number				
			15	16	17	18	19	20	21	22
<u>Sample Months</u>										
July 85	7.04	6.92	6.95	7.13	7.02	6.99	6.95	7.14	7.12	7.08
August 85	7.14	6.97	7.07	7.01	7.04	7.03	7.14	6.97	7.29	7.44
September 85	7.05	6.8	6.91	6.91	6.83	6.96	6.98	7.01	7.14	7.17
October 85	7.01	6.85	6.84	6.99	6.92	6.9	7.11	7.05	7.09	7.1
November 85	7.03	6.89	6.9	7	6.89	7.01	7.13	7.01	7.08	7.11
December 85	7.1	6.84	7	7.08	7.05	7.04	7.04	7.12	7.09	7.12
January 86	7.19	6.96	7.06	7.07	7.12	7.08	7.04	7.16	7.06	7.19
February 86	6.55	6.54	6.47	6.58	6.53	6.58	6.71	6.66	6.64	6.6
March 86	6.56	6.44	6.49	6.48	6.47	6.51	6.6	6.61	6.53	6.47
April 86	6.55	6.45	6.5	6.12	6.48	6.53	6.57	6.53	6.58	6.36
May 86	6.43	6.48	6.41	6.46	6.39	6.44	6.51	6.45	6.39	6.53
June 86	6.5	6.59	6.38	6.49	6.37	6.5	6.54	6.37	6.36	6.6
<u>Temperature</u>										
(°C)										
July 85	24	27	24	23	25	26	24	24	25	27
August 85	23.7	24.3	23.6	23.5	24.4	26.4	23.9	25.2	25	26.5
September 85	22.7	25.2	23.2	22.7	24.2	24.2	23.8	23.6	25.7	26.7
October 85	21.7	23.1	21.8	22.5	22	22	22.1	21.3	22.1	22.3
November 85	20.3	18.1	19.7	21	19.6	20.2	19	18.3	19.9	20.4
December 85	17.7	12.7	17.6	16.6	15.5	17.1	13.5	15.5	12.9	13.7
January 86	17.7	13.4	17.4	17.4	15	17.8	13.1	15.1	13.9	19.4
February 86	20.1	18	19	21.1	20	18	15.2	16.8	17	19.7
March 86	20.6	19.5	19.8	19.9	19.3	19.8	18.2	16.5	18.4	22.1
April 86	21.7	21.5	22.1	21.5	22.3	20.4	21	21.1	21.8	22
May 86	21.6	22.5	21.8	21.8	22.3	21.8	22.9	21.8	22.8	22.8
June 86	22.4	24.6	23	22.3	23.8	23.2	24.6	23.2	23.9	22.7

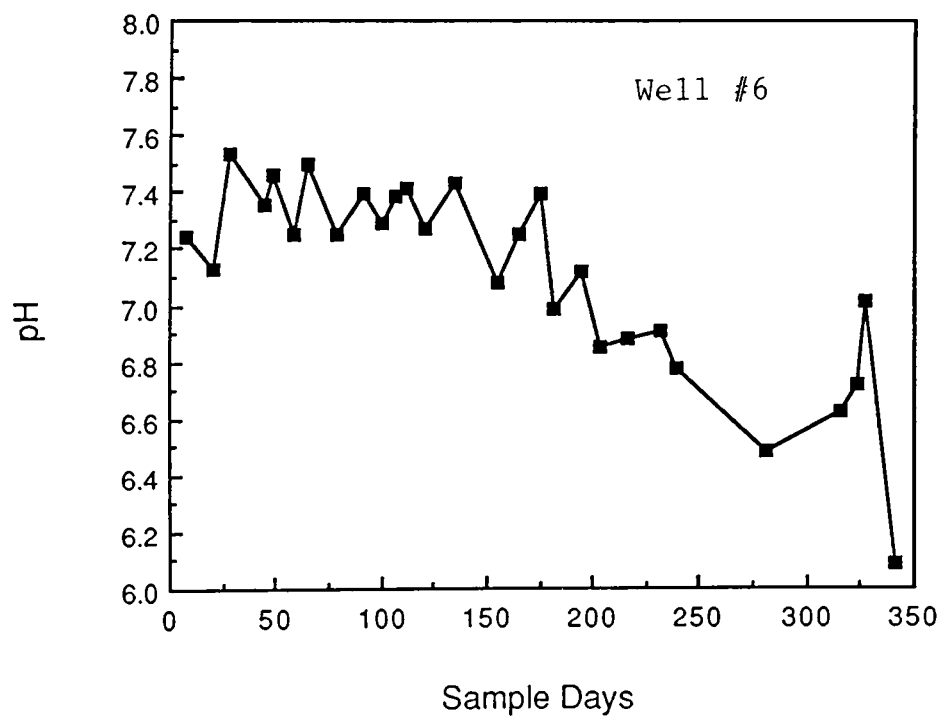
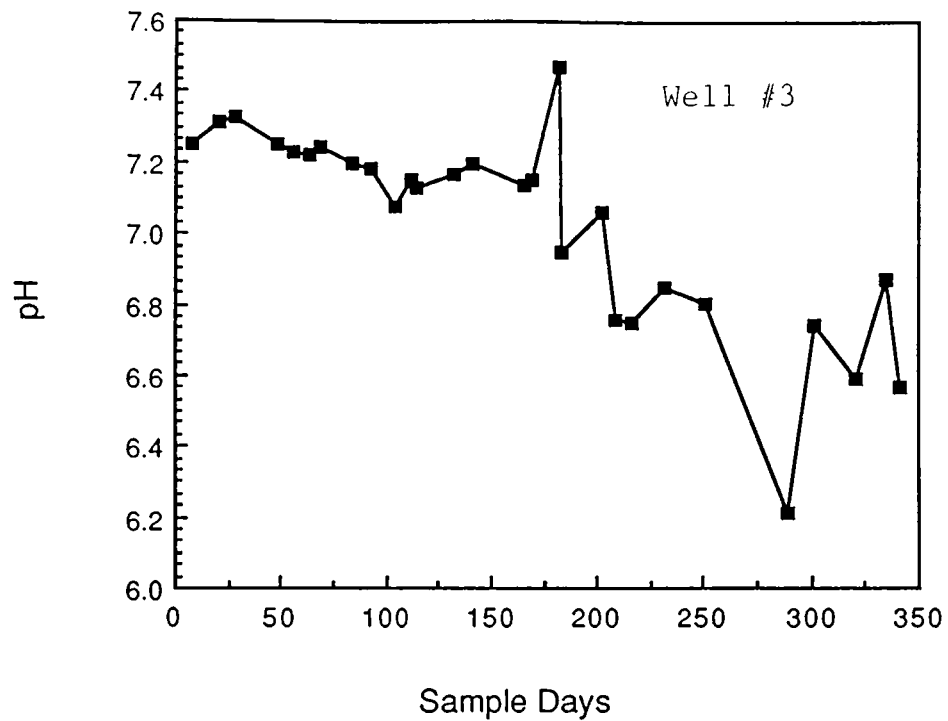


Fig. 28. Non-contaminated wells-pH ($-\log_{10} [H^+]$) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

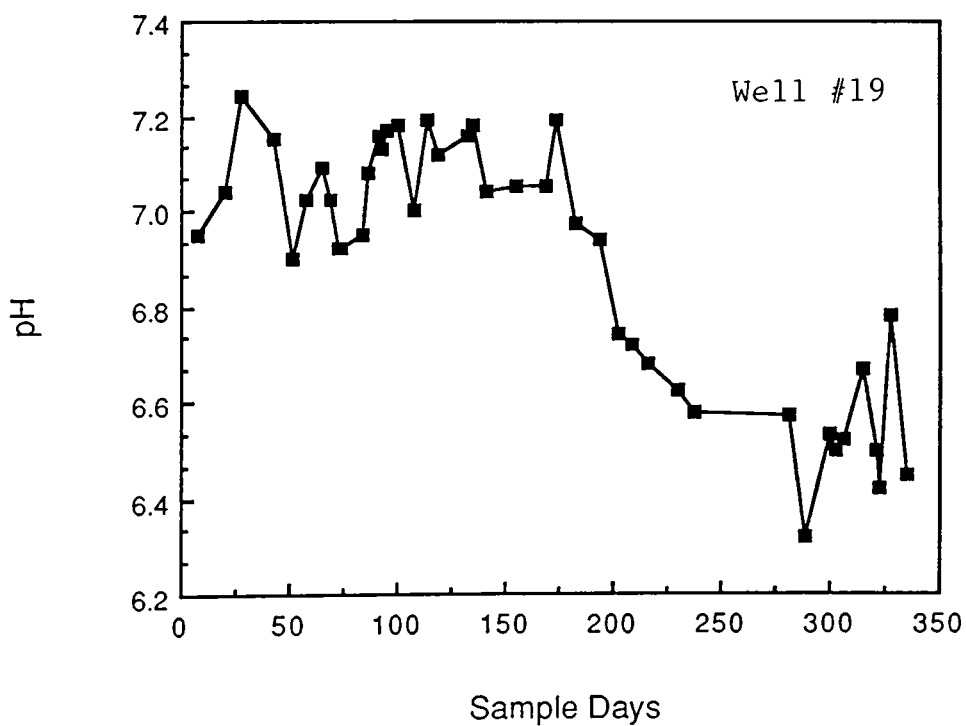
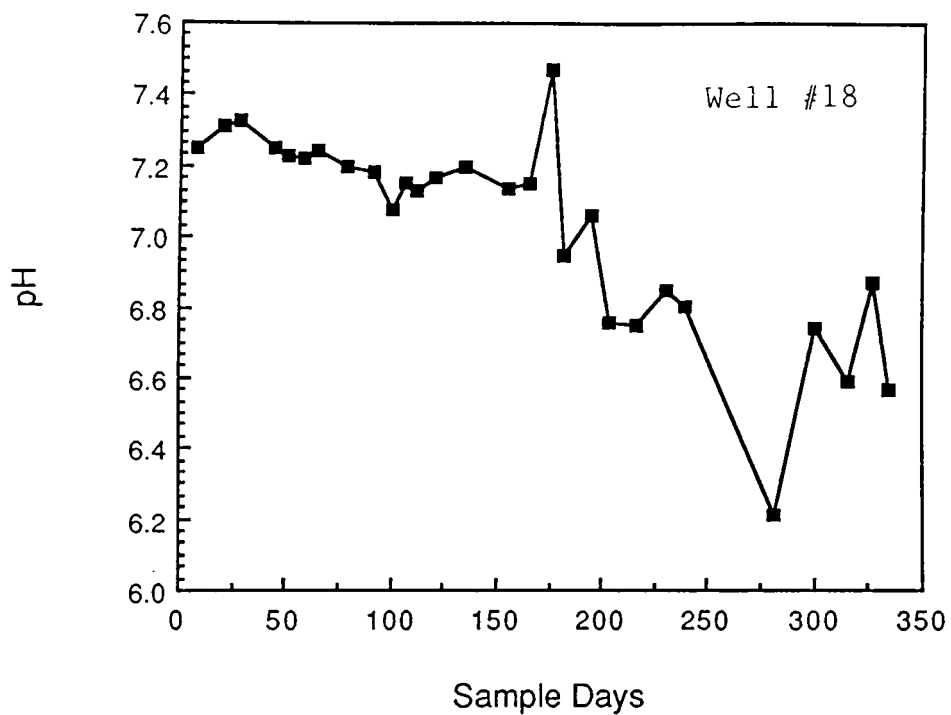


Fig. 29. Contaminated wells-pH ($-\log_{10} [H^+]$) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

also pick up CO₂ forming a weak carbonic acid. Increased levels of CO₂ formed from organic matter entering the system through sinkholes and caves in the Sink Creek drainage can also contribute to the lowering of pH (Underground Resource Management,1981; Ogden, et. al,1986).

Water Temperature

Water temperature was taken at each sampling. The average monthly temperatures of the groundwater ranged from 11.6°C in January 1986 to 27°C in July 1986 (Table 10). Temperatures fluctuated greatly throughout the study period from the normal range of groundwater in the Edwards aquifer, 21-22 °C (69.8 - 71.6°F). Sample sites with exposed storage tanks had temperatures that fluctuated over running time. The usual running time for each site was 10 min. After a 20 min running time the temperature of water from an exposed tank ranged from 27.8°C (82.0°F) to 24.8°C (76.6°F). The temperature in a storage tank covered by a shed the temperature remained constant after a 2 min running time. The water temperature was not obviously affected by rainfall events as were the other parameters, but more by air temperature (Figs. 30 & 31).

Calcium Carbonate Saturation

The value known as the pH of saturation (pH_s) is defined as the pH at which water containing bicarbonate and calcium is saturated with calcium carbonate. The pH_s was calculated using several elements of the samples- temperature, total dissolved solids (TDS), calcium (Ca⁺²) and alkalinity (as CaCO₃). These components are used in the following calculation (APHA,1985):

$$\text{pH}_s = \text{temp.constant} + \text{TDS constant} - \log[\text{Ca}^{+2}] - \log[\text{alk.}]$$

Total dissolved solids estimates were used in the calculation and

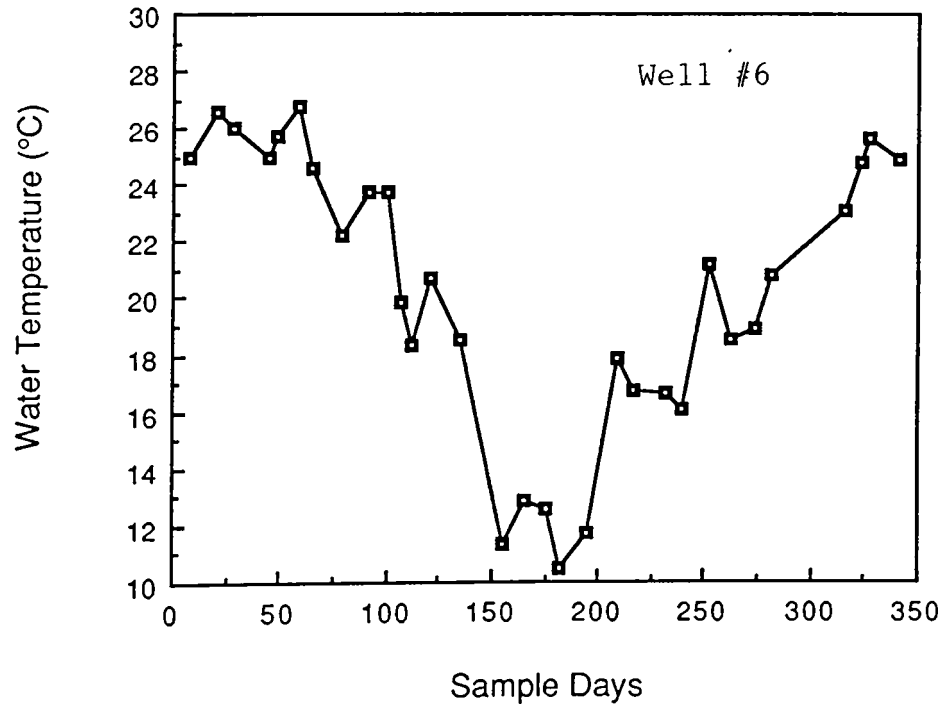
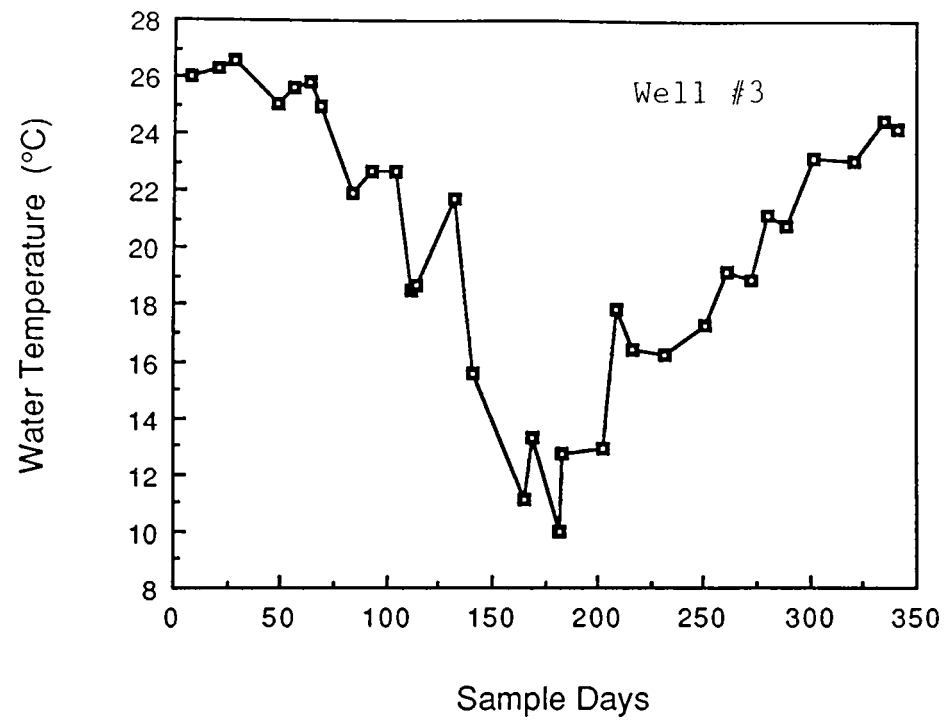


Fig. 30. Non-contaminated wells-water temperature (°C) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

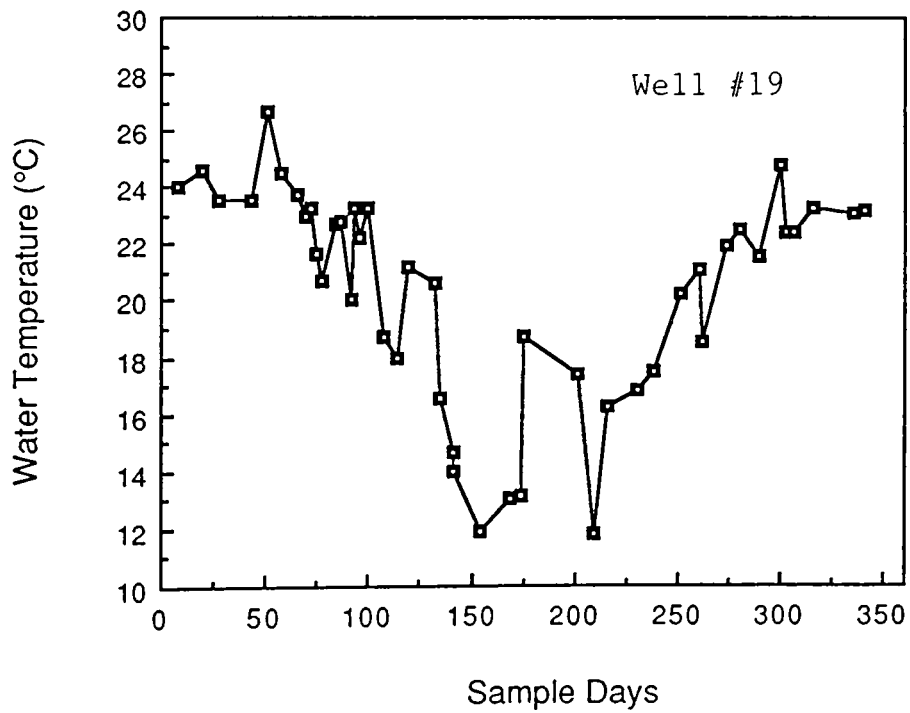
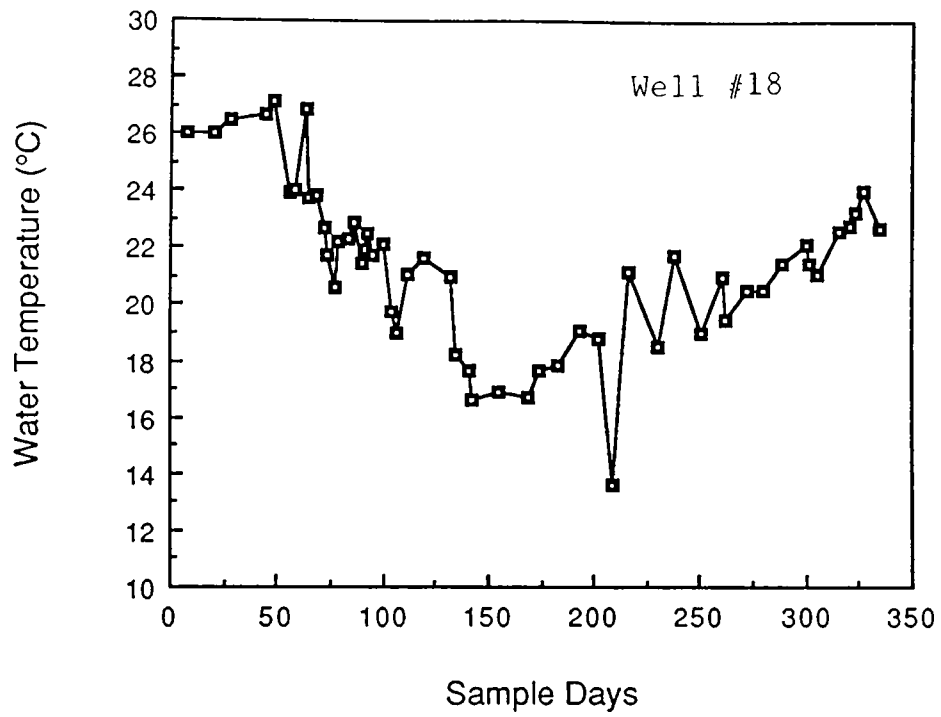


Fig. 31. Contaminated wells-water temperature (°C) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

were derived by multiplying conductivity by 0.65 (Brown, et. al,1974).

From the pHs value the Langelier Saturation Index (SI) can be calculated. SI is equal to the actual pH minus the calculated pH_s. A negative index value indicates the tendency for the CaCO₃ to be dissolved. A positive index is an indicator of the tendency for CaCO₃ deposition (APHA,1985).

In general the SI values for the sample wells remained negative indicating a corrosive tendency. There was no pattern indicating the influence of surface runoff on these values. Wells experiencing contamination and those not both exhibited negative values. The positive values seen were not dominant and were intermixed with negative values. During the second half of the sample period as the pH of the water dropped below seven, the SI values followed.

A second measure of CaCO₃ saturation using the Langelier Saturation Index (SI) is called the Driving Force Index (DFI). An approximate DFI value can be calculated by the following equation (APHA,1985):

$$DFI = 10^{(SI)}$$

The Driving Force Index is a simple ratio between the existing ions and ions which would exist at equilibrium. If the system is at equilibrium the DFI index is 1.0, values greater than 1.0 indicate the possibility of CaCO₃ deposition with values less than 1.0 indicating the tendency for corrosion and the dissolution of CaCO₃ (APHA,1985). The majority of calculated DFI values were less than one indicating a corrosive tendency and CaCO₃ dissolution (Figs. 32 & 33).

Nitrate

Nitrogen exists in four primary forms - organic nitrogen, ammonia nitrogen (NH₄⁺), nitrites (NO₂⁻) and nitrates (NO₃⁻). Nitrate is the predominant end product of nitrification (NH₄⁺→NO₂⁻→NO₃⁻). Nitrates are of primary

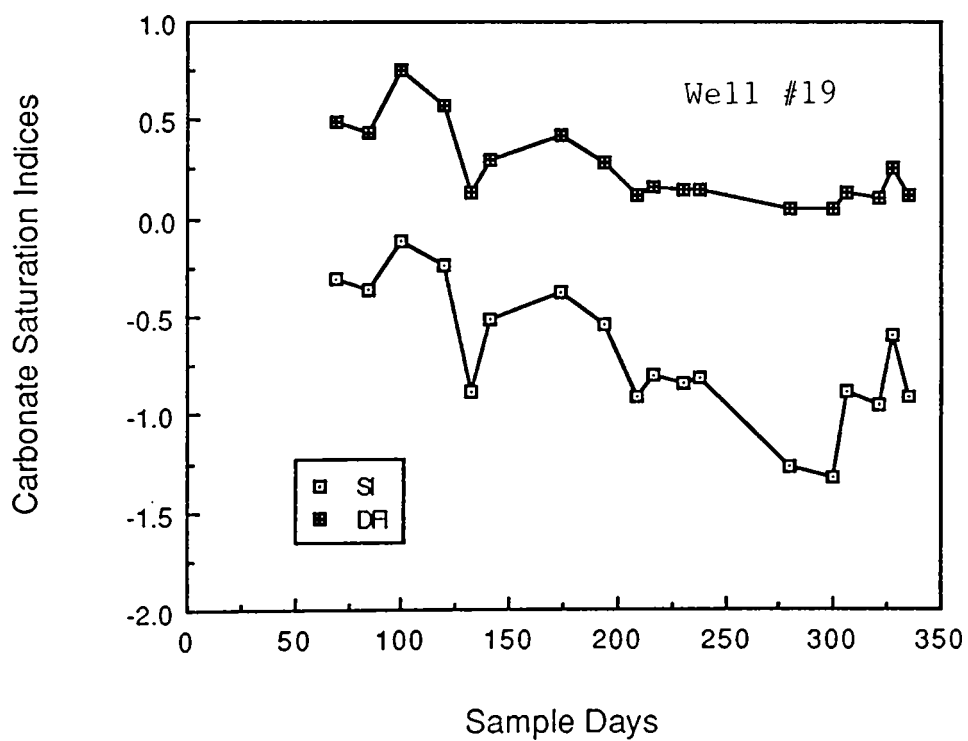
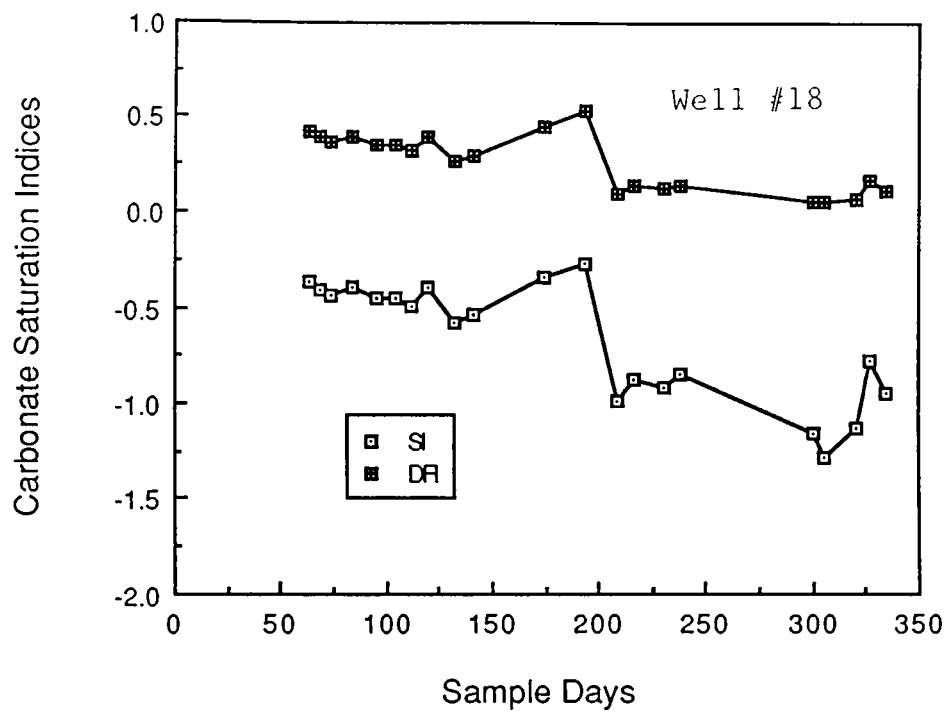


Fig. 32. Carbonate saturation indices (driving forces index and saturation index) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

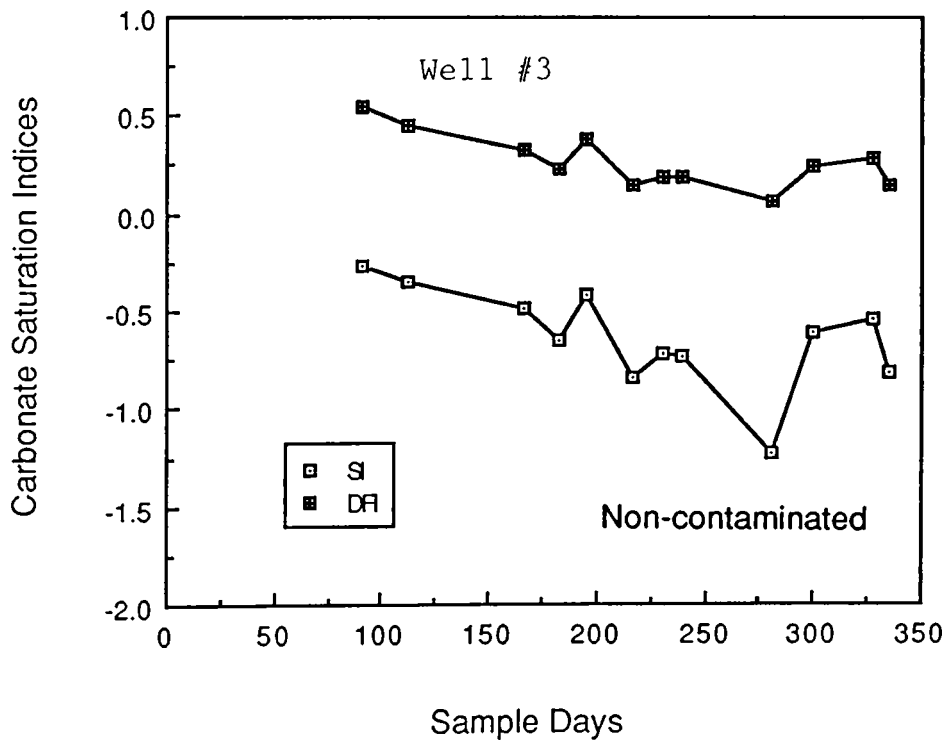
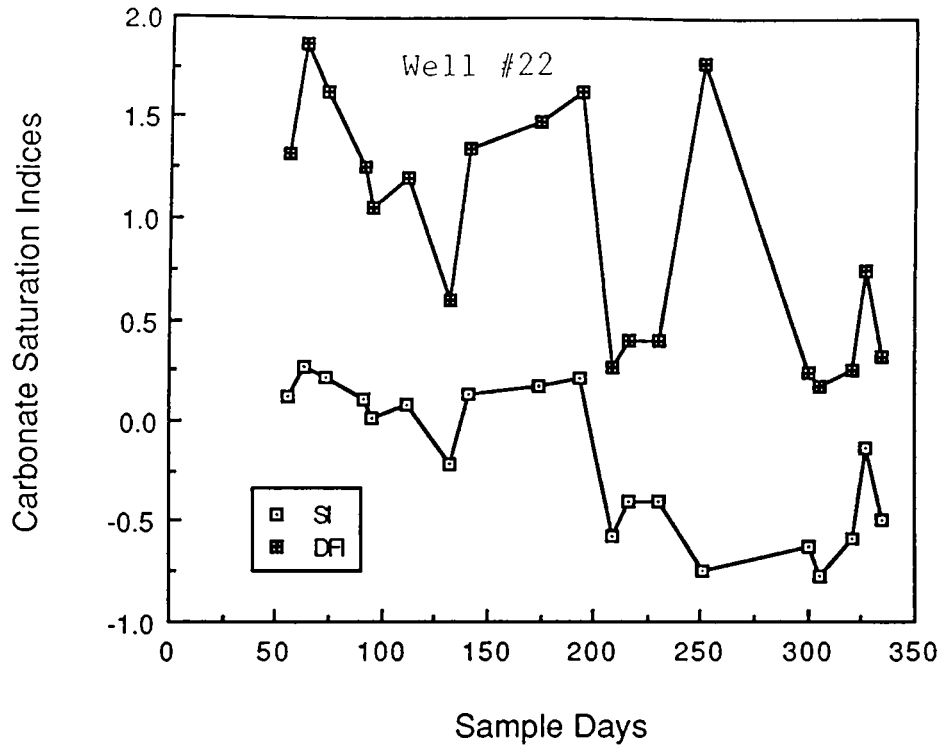


Fig. 33. Carbonate saturation indices (driving forces index and saturation index) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

concern in groundwater and are recognized as posing a significant health hazard to humans in concentrations of 10 mg/L or more (Table 6). The reduction of nitrates to nitrites in the intestine of humans causes methemoglobinemia (blue babies), a reduction of the oxygen carrying capacity of the blood (Canter, Knox and Fairchild, 1987; APHA, 1985). Monthly nitrate concentrations ranged from <0.05 to 4.52 mg/L (Table 11). Again nitrates followed the same patterns as the other dissolved solids by decreasing in contaminated wells and increasing in non-contaminated wells following the largest rainfalls (Figs. 34 & 35). The nitrate concentrations were below the those causing health risks. More nitrogen enters groundwater from fertilizers than animal wastes (Canter, et. al, 1987). The low levels of nitrate and orthophosphate in the groundwater samples can be attributed to the limited use of fertilizers containing phosphorus and nitrates, in the watershed.

Orthophosphate

Phosphorous exists in water as nearly all phosphate (orthophosphate, condensed and organically bound phosphates). The most important form of inorganic phosphorous is orthophosphate (PO_4^{3-}), making up 90%. Orthophosphate, the only form of soluble inorganic phosphorous that can be directly utilized, is the least abundant of any nutrient and is commonly a limiting factor (Wetzel, 1983; APHA, 1985) (Table 6). Orthophosphate was analyzed for as an indicator of contamination by waste products or fertilizers. Monthly orthophosphate values ranged from < 0.01 to 1.94 mg/L (Table 11). Orthophosphate showed the same trend as the other dissolved substances by decreasing in contaminated wells and increasing in non-contaminated wells following heavy rainfalls (Figs. 34 & 35). Phosphorous does not create any health risks and is usually absorbed in the soil profile before reaching groundwater (D'Itri and Wolfson, 1987).

Table 11. Monthly nitrate and orthophosphate values for the Sink Creek drainage basin, Hays County, Texas (7/85-6/86).

Nitrate (mg/L)	1	2	3	4	5	6	7	8	9	10	11	12	13
<u>Sample Months</u>													
July 85	0.95	-	-	-	1.42	-	1.08	-	-	0.2	-	-	-
August 85	1.94	1.85	0.78	2.31	1.94	2.38	2.47	2.12	1.02	1.25	0.69	1.42	2.03
September 85	1.19	1.94	-	1.42	1.25	-	2.33	1.12	0.517	1.98	1.5	2.12	2.29
October 85	1.08	1.42	1.25	3.13	1.94	2.11	1.6	2.59	0.47	1.68	0.95	1.68	2
November 85	1.08	1.25	4.32	4.52	2.63	3.13	2	2.3	0.61	1.22	0.95	1.55	1.54
December 85	0.78	1.08	1.08	2.29	1.42	2.29	1.08	2.29	0.95	1.1	0	0.78	1.34
January 86	1.1	1.51	1.02	2.66	2.12	2.38	2.05	2.21	< 0.05	1.63	0.54	1.12	1.51
February 86	1.25	1.77	0.95	2.11	1.77	1.77	2.12	2.11	0.95	2.62	1.25	1.59	2.29
March 86	1.42	2.03	1.94	3.34	2.38	2.66	2.12	2.46	1.21	2.29	1.42	1.82	2.46
April 86	1.31	2.23	1.71	3.88	2.91	2.68	2.02	3.52	1.5	2.46	1.32	2.36	1.94
May 86	-	-	1.59	-	-	2.47	1.86	1.08	1.51	1.85	0.05	1.42	1.68
June 86	1.45	1.68	1.6	2.47	3.15	3.34	1.08	1.65	0.88	1.25	< 0.05	1.25	0.99
<u>Orthophosphate (mg/L)</u>													
July 85	< 0.01	-	-	-	0.4	-	< 0.01	-	-	0.017	-	-	-
August 85	0.72	0.57	0.545	0.42	0.605	0.39	0.6	0.55	0.355	0.47	0.41	0.187	0.39
September 85	0.623	-	-	-	0.38	-	0.662	0.5	1	0.896	0.477	0.09	0.95
October 85	0.43	0.4	0.19	0.445	0.22	0.28	0.75	0.617	0.29	0.275	0.3	0.45	0.533
November 85	0.317	0.24	0.42	0.42	0.4	0.26	0.307	0.25	0.29	0.283	0.185	0.287	0.27
December 85	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.15	< 0.01	0.29	0.01	0	0	0.005
January 86	0.29	0.43	0.395	0.695	0.465	0.235	0.385	0.405	0.55	0.355	0.205	0.225	0.4
February 86	< 0.09	2.13	0.33	0.41	0.35	0.41	0.375	0.43	0.49	0.3	0.33	0.38	0.4
March 86	0.3	0.265	0.123	0.3	0.12	0.22	0.135	0.177	0.17	0.125	0.09	0.127	0.113
April 86	0.09	0.53	0.077	0.2	0.493	0.16	0.163	0.15	0.15	0.217	0.2	0.077	0.117
May 86	-	-	0.09	-	-	0.51	0.32	0.25	0.38	0.145	0.2	0.38	0.67
June 86	0.31	0.34	0.34	0.47	0.47	0.52	0.395	0.36	0.37	0.397	0.27	0.355	0.417

Table 11. Monthly nitrate and orthophosphate values for the Sink Creek drainage basin, Hays County, Texas (7/85-6/86).

Nitrate (mg/L)	14	15	16	Sample 17	Well 18	Number 19	20	21	22
<u>Sample Months</u>									
July 85	-	-	1.59	-	-	-	< 0.05	1.25	-
August 85	3.56	1.51	1.42	1.77	1.94	1.6	1.94	1.25	1.68
September 85	3.88	1.25	1.68	-	1.81	1.94	1.59	1.77	1.94
October 85	3.44	1.77	2.47	1.77	1.94	2.11	2.11	1.25	1.94
November 85	3.23	1.45	1.77	-	1.28	0.98	-	2.12	2.06
December 85	2.84	1.08	1.25	1.42	1.08	1.42	1.08	1.59	1.59
January 86	2.7	0.073	1.6	1.86	1.42	1.77	1.59	1.51	1.86
February 86	3.65	1.77	1.94	0.95	1.6	1.51	1.08	0.95	1.6
March 86	4.2	1.82	1.59	1.36	1.71	1.83	1.83	1.77	2.38
April 86	3.88	1.59	1.77	1.54	3.06	1.88	1.55	1.88	2.33
May 86	3.44	1.77	1.59	1.59	1.68	1.54	-	1.94	1.68
June 86	2.63	1.89	1.25	1.17	0.84	1.11	< 0.05	1.77	1.25
<u>Orthophosphate</u>									
(mg/L)									
July 85	-	-	< 0.01	-	-	-	< 0.01	< 0.01	-
August 85	0.305	0.425	0.68	0.59	0.34	0.625	1.23	0.38	0.495
September 85	1	0.75	0.585	-	0.712	0.43	0.56	0.62	0.513
October 85	0.28	0.33	0.58	1.3	0.47	0.455	0.36	0.22	0.27
November 85	0.27	0.245	0.265	-	0.287	0.19	-	0.235	0.21
December 85	0	0	0	< 0.01	0.09	0	< 0.012	< 0.01	0
January 86	0.2	0.105	0.195	0.26	0.255	0.275	0.325	0.48	0.21
February 86	0.33	0.355	0.36	0.45	0.605	0.4	0.29	0.51	0.45
March 86	0.205	0.1	0.173	0.187	0.157	0.093	0.057	0.14	0.11
April 86	0.153	0.25	0.193	0.11	0.233	0.127	0.15	0.123	0.127
May 86	0.24	0.12	1.04	0.36	0.93	0.38	-	1.94	1.26
June 86	0.53	0.437	0.165	0.35	0.247	0.353	0.193	0.44	0.31

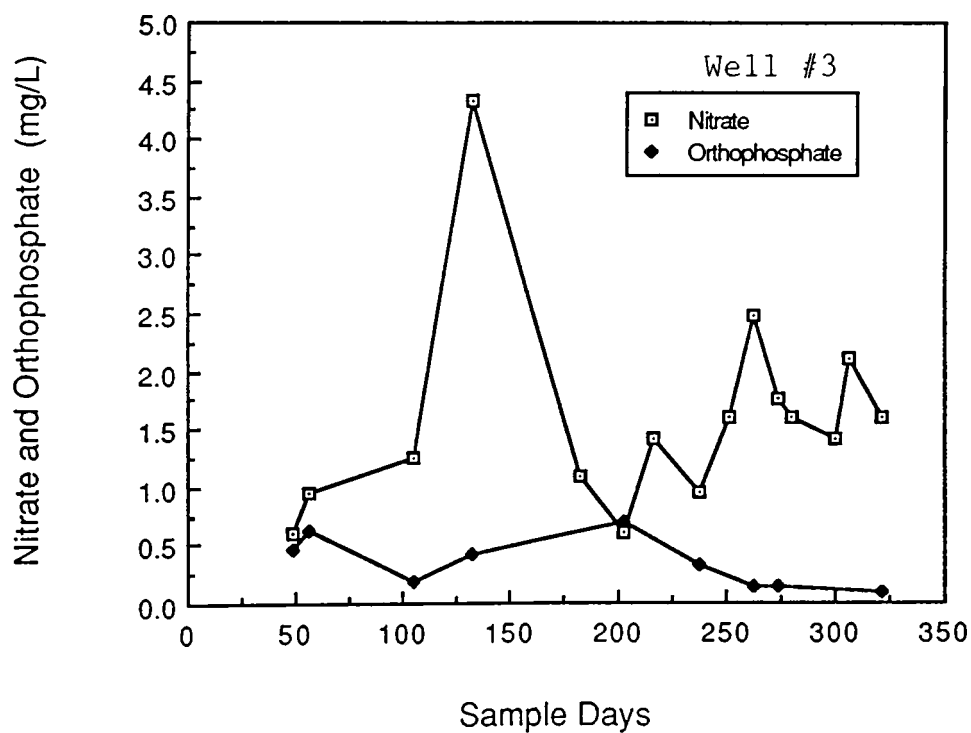
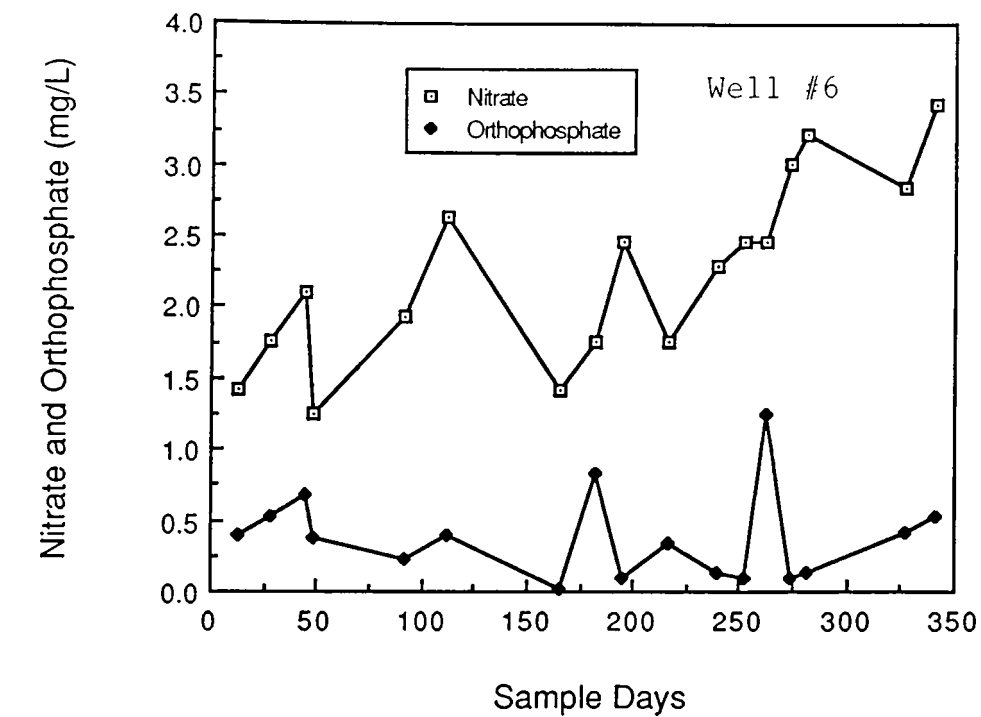


Fig. 34. Non-contaminated wells-nitrate and orthophosphate (mg/L) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

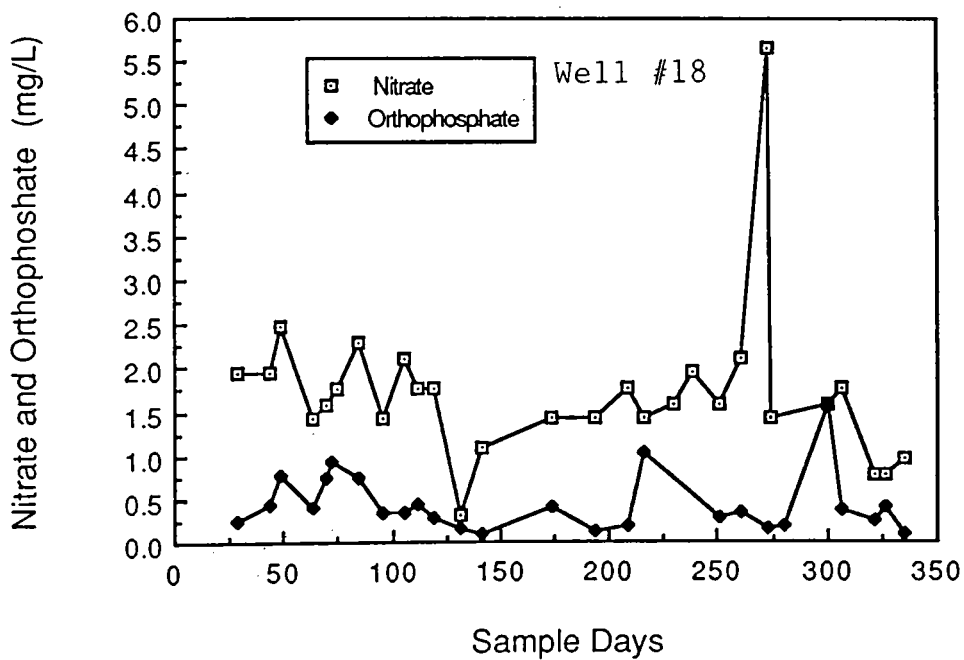
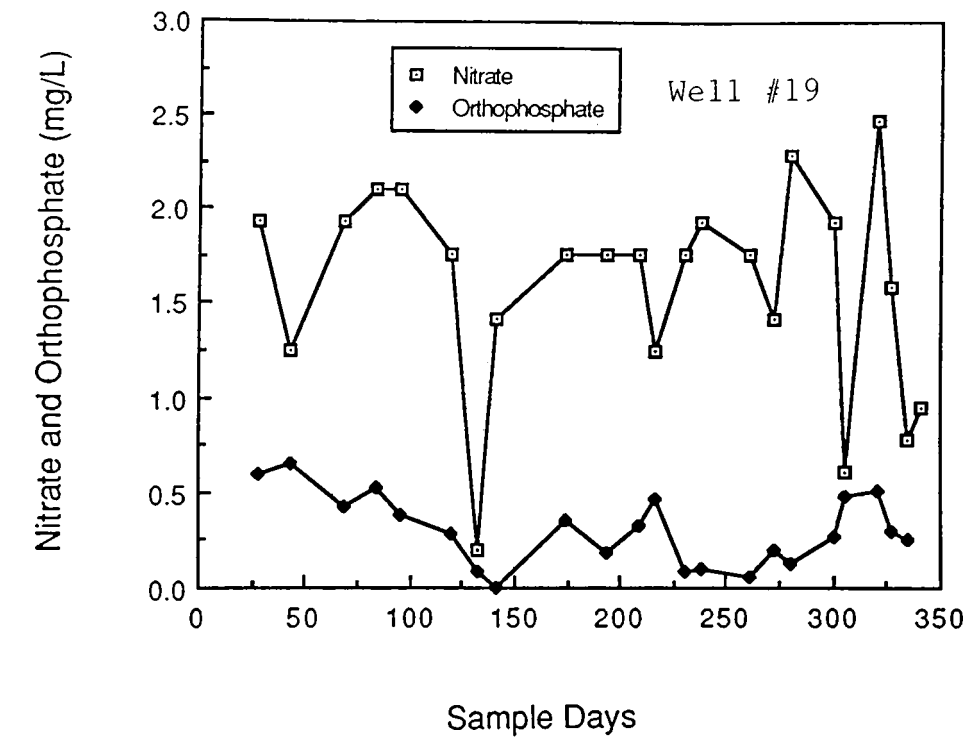


Fig. 35. Contaminated wells-nitrate and orthophosphate (mg/L) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

Chloride

Chloride (Cl^-), one of the major anions in water, is derived primarily from rocks and soils (Table 6). When chloride combines with sodium it creates a salty taste to water and can increase the corrosiveness. Chloride concentrations in the recharge zone range from 10 to 30 mg/L. Moving east toward the "bad water" line values increase from 200 to 500 mg/L at the extreme edge of the aquifer (Baker, et. al, 1986; APHA, 1985; UOP, Inc., 1975). Monthly chloride values ranged from 2.67 to 20.75 mg/L (Table 12). These concentrations mirrored values from previous studies and showed the same patterns as the other dissolved solids following the largest rainfalls (Figs. 36 & 37) (Ogden, et.al, 1986; Ozuna, et.al, 1987). The low levels of chloride found in the samples had little effect on the quality of water. The USEPA (1985) recommends chloride levels not exceed 250 mg/L.

Sulfate

Sulfates are derived from rocks and soils containing gypsum, iron sulfides and other sulfur compounds. Levels in excess of 300 mg/L can have a laxative effect on humans (600-1,000 mg/L) and in combination with other ions create a bitter taste (300-400mg/L) (Table 6) (USEPA, 1985). Sulfate concentrations in the recharge zone typically range from 10 to 30 mg/L. Sulfate, like chloride values increase in the vicinity of the "bad water" line from 200 to 800 mg/L (Baker, et.al, 1986). Levels found in the samples ranged from 2.91 to 22.53 mg/L were well below the recommended levels (Table 12). From June to December 1985 sulfate values were reported as <10 mg/L and no patterns could be determined. From January to July 1986 the values showed the same pattern as the other dissolved substances following the May/June 1986 rainfall (Figs. 36 & 37).

Table 12. Monthly chloride and sulfate values for the Sink Creek drainage basin, Hays County, Texas (7/85-6/86).

Chloride (mg/L)	1	2	3	4	5	6	7	8	9	10	11	12
Sample Months												
July 85	6	-	-	-	-	6.25	6	-	-	6	-	-
August 85	6	10.7	10.25	20.75	8.25	3.4	8.5	10.75	6.75	7	10.5	6.5
September 85	6.38	11.5	-	-	-	12	10.45	8.5	10.42	8.3	10.63	5.88
October 85	6.5	7	12.5	11.5	8.5	6	11	8.67	8	7.25	10	7.25
November 85	6.33	6.5	12.5	13	8.5	6.5	9.67	7.67	8.75	6.5	9.25	6.33
December 85	5.5	7.5	7	9	8.5	5.5	6	9.5	6	5.5	7	6
January 86	4.5	10	8.75	17.25	9.25	6.25	7.25	8.25	6	7.88	9.75	6.88
February 86	8	10.25	10.5	15	9.5	6.5	10.25	9.5	7.25	8	11.5	7
March 86	9	6.25	8.35	13.5	9	6	10	7.67	9	8.25	10	5.5
April 86	6	7.33	11.17	15.5	9.17	6.33	10.33	8.5	12.83	8.17	10.33	6.5
May 86	-	-	12.45	-	5	-	9.85	7.5	4.65	5	7.5	6
June 86	6.9	6.43	12.65	8.18	8.03	6.9	5.63	6.92	6.02	5.4	6.53	5.78
Sulfate (mg/L)												
July 85	< 10	-	-	-	-	< 10	< 10	-	-	< 10	-	-
August 85	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
September 85	< 10	< 10	-	-	-	< 10	< 10	< 10	< 10	< 10	< 10	< 10
October 85	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
November 85	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	11.65	< 10
December 85	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	26.6	< 10
January 86	7.76	8.45	8.16	7.62	7.63	6.54	7.3	7.65	9.44	6.58	7.7	7.33
February 86	5.4	5.82	5.72	4.93	4.56	3.06	4.69	4.53	8.36	3.22	5.56	4.56
March 86	14.4	13.87	11.32	12.9	12.14	7.89	9.94	9.8	14.91	7.31	21.4	8.34
April 86	6.02	5.57	5.61	4.93	5.77	3.84	3.72	5.21	7.19	2.9	5.33	3.69
May 86	-	-	4.28	-	4.43	-	4.58	11.73	4.03	4.22	21.4	4.19
June 86	3.92	4.52	5.15	4.02	3.44	2.7	4.89	7.96	5.05	4.91	22.2	3.96

Table 12. Monthly chloride and sulfate values for the Sink Creek drainage basin, Hays County, Texas (7/85-6/86).

Chloride (mg/L)	13	14	15	Sample 16	Well 17	Number 18	19	20	21	22
<u>Sample Months</u>										
July 85	-	-	-	7.25	-	-	-	5.5	5.55	-
August 85	8.25	6.5	7.5	7.5	6.5	6.25	12.5	3	6	8
September 85	7.7	8	8	8.13	-	5.69	6.5	3	6.5	7.3
October 85	7	8	7.5	7.5	7	5.92	7.25	2.5	7	7.5
November 85	5.17	9	6.75	7.25	-	4.67	4.25	-	6.5	5
December 85	6.38	6.5	6	6	7	5.5	5.5	4.5	7.5	6
January 86	7.13	7.75	6.88	9.5	7.25	7.75	6	3.75	6.25	8.5
February 86	6.75	9.5	7.5	8	6.5	3.55	6.75	4	7	7.25
March 86	5.5	9.75	6	6.83	6	4.83	5.33	2.67	7	6.33
April 86	5.5	9.33	7.17	7.67	7.17	5.67	5.67	3	7.17	7
May 86	3.63	9.7	6.03	6.83	6.3	4.9	7.05	4	7.4	4.03
June 86	6.13	6.85	7.22	7.18	6.55	5.87	5.57	4.05	7.73	5.87
<u>Sulfate</u>										
(mg/L)										
July 85	-	-	-	< 10	-	-	-	< 10	< 10	-
August 85	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
September 85	< 10	< 10	< 10	< 10	-	< 10	< 10	< 10	< 10	< 10
October 85	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
November 85	< 10	< 10	< 10	< 10	-	< 10	< 10	-	< 10	< 10
December 85	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
January 86	8.55	7.42	6.54	6.85	7.15	10.03	7.15	7.86	7.91	12.25
February 86	6.55	5.22	2.84	3.83	4.11	5.19	5.5	5.22	5.09	3.89
March 86	22.53	13.46	5.96	7.14	8.77	9.77	10.17	8.78	12.2	9.06
April 86	6.12	5.11	2.91	3.73	3.72	4.18	4.49	7.27	4.84	4.28
May 86	4.1	3.78	3.23	4.11	3.74	3.7	4.3	-	4.74	4.03
June 86	5.72	2.59	3.44	4.22	3.55	5.77	6.75	22.7	4.63	4.88

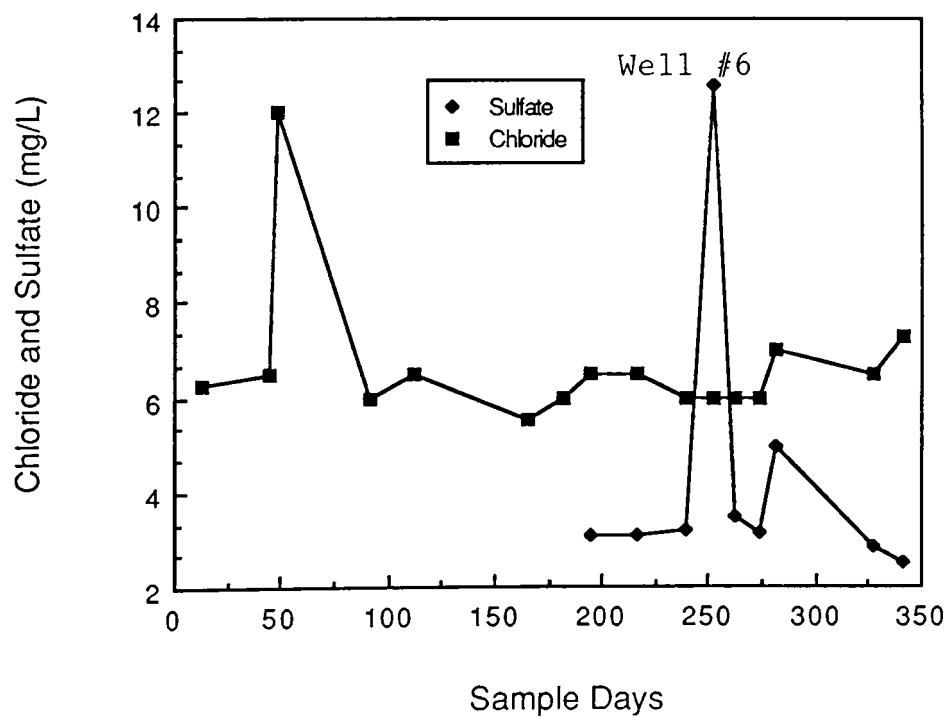
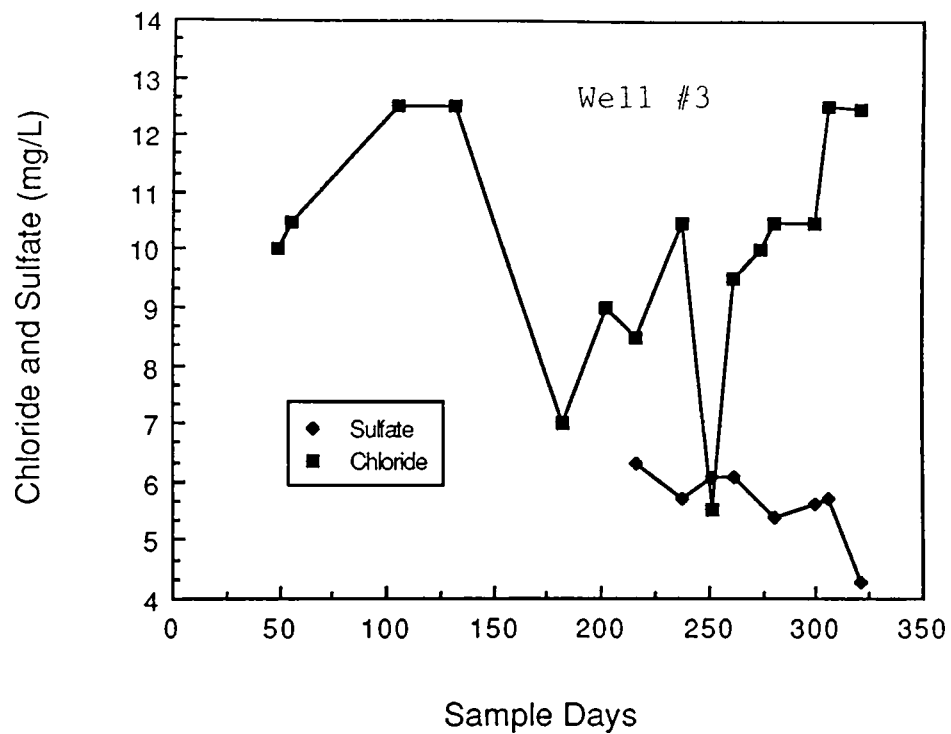


Fig. 36. Non-contaminated wells-chloride and sulfate (mg/L) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

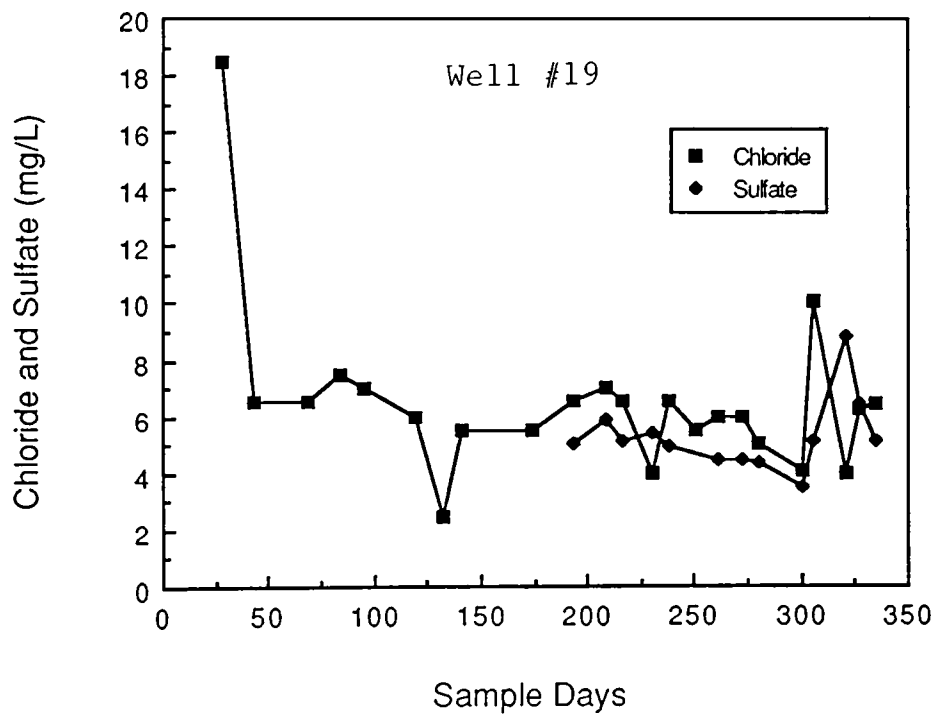
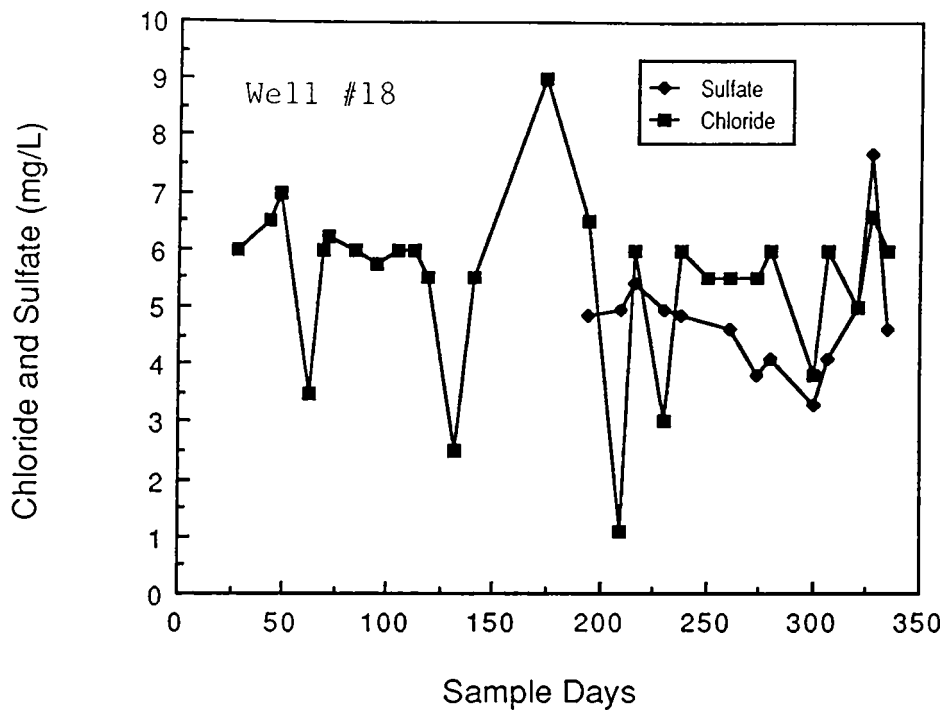


Fig. 37. Contaminated wells-chloride and sulfate (mg/L) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

Microbial Contamination of Groundwater

In the late nineteenth century the microbial contamination of ground water was responsible for epidemics of cholera and typhoid. Today the problems still exist only on a larger scale. There is an estimated 800 billion gallons of domestic waste released into ground water annually. This does not include the additional 268 billion gallons from leaky municipal sewage systems and treatment lagoons. Bacteria and viruses exist in almost all domestic sewage. Approximately half of the outbreaks of waterborne diseases are caused by the microbial contamination of ground water (Gerba,1985). With increased urbanization and the use of ground water the bacteriological contamination of groundwater will increase and become a major environmental concern.

Survival and Transport of Microorganisms

The three key factors affecting the survival and retention time of enteric bacteria in soil are climate, the nature of the soil and the nature of the microorganisms. Temperature and rainfall are the two important climatic factors influencing viral and bacterial survival. The warmer the temperature the faster they die off. The rate is doubled with every 10°C rise in temperature between 5 and 30°C. Temperature becomes the controlling factor above 30°C. During periods of high rainfall and saturated soils enteric organisms have the highest survival rates (Canter and Knox,1985; Gerba,1985). During this study the highest levels of coliforms occurred following the heaviest rainfall events and when the soils were saturated. Temperatures during the majority of the study period were not optimal for bacterial survival (Table 2).

The most important factor in survival is soil moisture. Soil properties such as pH and organic content are also important in determining survival rates. Enteric organisms have a longer survival time in alkaline soils than in acidic soils (pH 3-5). Organic material in the soil can also increase the survival rate (Canter and Knox,1985; Gerba,1985). The soils in the study area were thin, well drained and prone to rapid drying (Fig.9) (Table 2).

Moisture content of the soil was high only following rainfall events and drying was rapid. The pH was high, but the organic content was low. The conditions of the soil during and shortly after rainfall events was adequate to allow for the survival of coliforms. Within 4-5 days of rainfall coliform organisms in contaminated wells dropped off due to inadequate environmental conditions.

Coliform Bacteria

Indicator organisms were used to determine the possible presence of waterborne pathogens. Coliforms, a group which comprises all aerobic and facultative anaerobic, gram-negative, nonspore-forming, rod shaped bacteria that ferment lactose with gas formation, are the most commonly used indicator organisms (APHA, 1985). Total coliform testing produces colonies with a metallic sheen within 24 h at 35°C. Fecal coliform testing is done to differentiate between coliforms from warm-blooded animals and those from other sources. Fecal coliform organisms form blue colonies within 24 h at 44.5 ± 0.2 °C (APHA, 1985). The presence of coliform organisms in water indicate the "possible" presence of waterborne pathogens such as typhoid, dysentery, hepatitis, cholera, viruses, parasites and minor intestinal disorders (Slade, et. al, 1986). The primary source of coliform organisms are the feces of warm blooded animals. The health limits set by the Texas Department of Health (1985) are 0 colonies/100 ml for drinking water and 200 colonies/100 ml in swimming waters (Table 5).

During the study total coliform numbers ranged from 0 to 1880 colonies/100 ml (Table 13). Seventeen of the 22 wells showed total coliform contamination. Twelve of these wells had counts greater than 100, where the highest colony counts occurred in November and May following significant rainfall (Figs. 38 & 39). Contamination following other rainfall events occurred, but with lower colony counts. Fecal coliform counts ranged from 0 to 1436 colonies/100ml showing the same pattern as total coliform (Table 13) (Figs. 40 & 41).

Table 13. Monthly fecal and total coliform counts for the Sink Creek drainage basin, Hays County, Texas (7/85-6/86).

Fecal Collform (colonies/100ml)	1	2	3	4	Sample 5	Well 6	Number 7	8	9	10	11	12
<u>Sample Months</u>												
July 85	0	0	0	0	0	0	2	6	0	0	0	2
August 85	0	0	0	0	0	0	0	0	1	11	0	0
September 85	0	0	0	0	0	0	0	2	0	0	0	0
October 85	0	0	0	0	0	0	0	0	0	4	0	0
November 85	0	0	0	0	0	0	50	3	215	780	14	10
December 85	0	0	0	0	0	0	1	0	2	2	0	1
January 86	0	0	0	0	0	0	0	0	0	0	0	0
February 86	0	0	0	0	0	0	0	0	0	0	0	0
March 86	0	0	0	0	0	0	0	0	0	0	0	0
April 86	0	0	0	0	0	0	0	0	0	0	0	0
May 86	0	0	0	5	0	0	37	119	108	149	20	84
June 86	0	0	0	0	0	0	7	18	62	53	12	7
<u>Total Collform (colonies/100ml)</u>												
September 85	1	2	0	0	0	0	57	123	1	1	1	31
October 85	6	0	0	3	0	0	19	30	0	20	1	50
November 85	8	0	0	7	0	0	37	48	630	139	37	31
December 85	10	0	1	0	1	1	10	10	33	20	13	18
January 86	4	0	0	0	0	0	11	9	2	4	3	1
February 86	3	1	0	0	0	0	66	19	1	1	0	0
March 86	169	0	0	1	0	0	8	21	3	0	0	4
April 86	5	0	0	110	2	0	13	2	0	0	0	0
May 86	92	0	0	-	0	0	61	37	114	17	40	120

Table 13. Monthly fecal and total coliform counts for the Sink Creek drainage basin, Hays County, Texas (7/85-6/86).

Fecal Collform (colonies/100ml)	13	14	15	Sample 16	Well 17	Number 18	19	20	21	22
<u>Sample Months</u>										
July 85	2	2	0	0	0	3	2	0	0	30
August 85	0	0	0	0	0	0	0	0	0	4
September 85	3	0	2	0	0	64	2	0	0	0
October 85	1	0	0	0	0	0	0	0	0	0
November 85	535	0	128	32	2	535	838	0	0	635
December 85	3	0	0	0	0	6	0	1	0	3
January 86	0	0	0	0	0	0	1	0	0	0
February 86	1	0	0	0	0	0	1	0	0	0
March 86	0	0	0	0	0	0	0	0	0	0
April 86	0	0	0	0	0	0	0	0	0	0
May 86	110	10	55	23	7	249	285	2	0	119
June 86	97	2	25	5	2	63	20	30	0	40
<u>Total Collform (colonies/100ml)</u>										
September 85	5	0	13	1	0	19	7	3	0	2
October 85	5	0	4	2	1	11	4	2	0	1
November 85	974	82	230	140	39	940	1210	0	1	1030
December 85	35	9	45	11	5	44	48	5	0	33
January 86	1	0	4	2	0	6	2	1	0	1
February 86	6	0	11	5	2	6	13	2	0	3
March 86	21	0	3	0	0	0	7	0	0	0
April 86	26	0	1	4	0	0	6	0	0	0
May 86	107	55	55	85	31	117	71	0	0	130

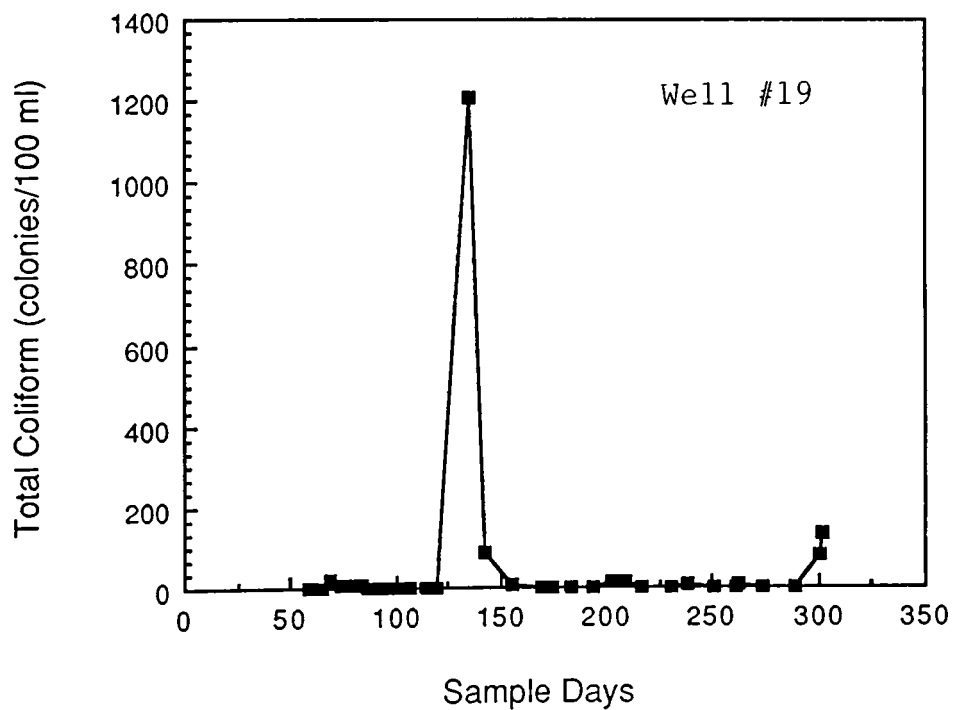
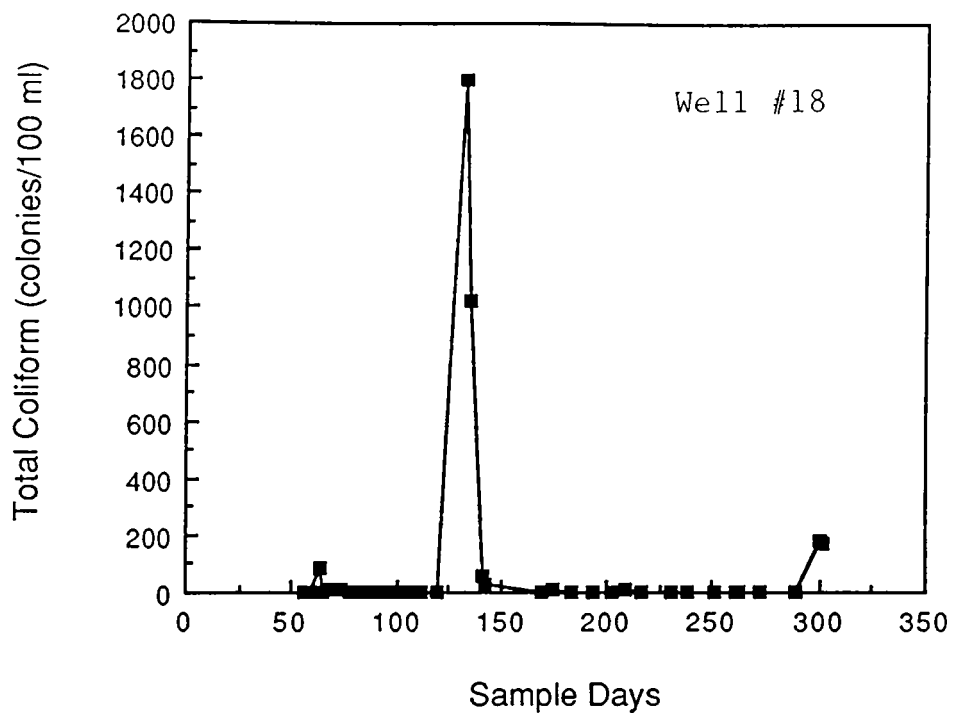


Fig. 38. Total coliform (colonies/100 ml) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

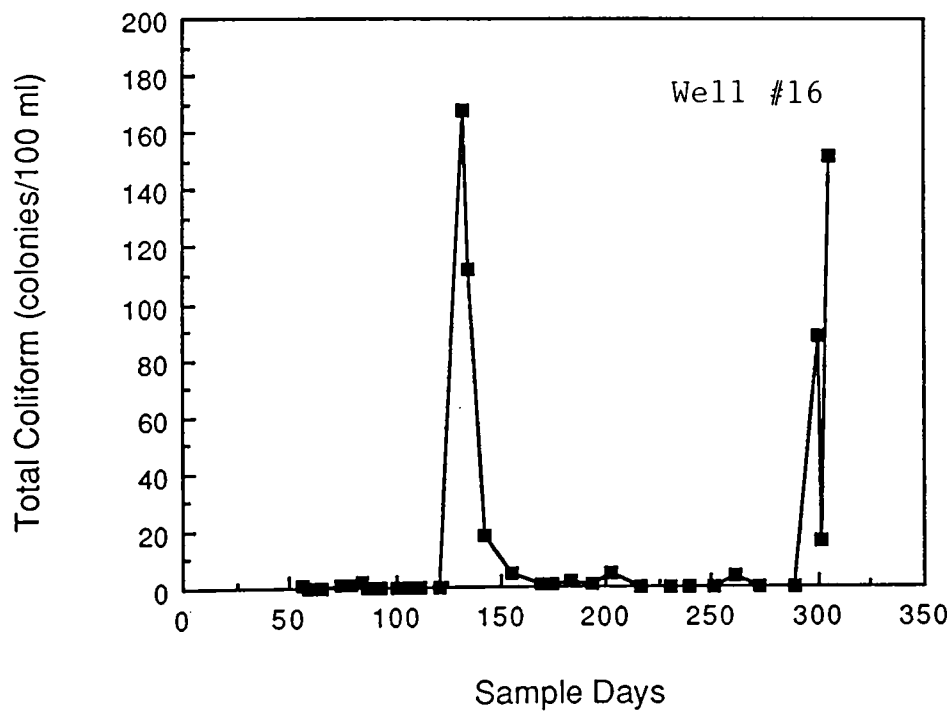
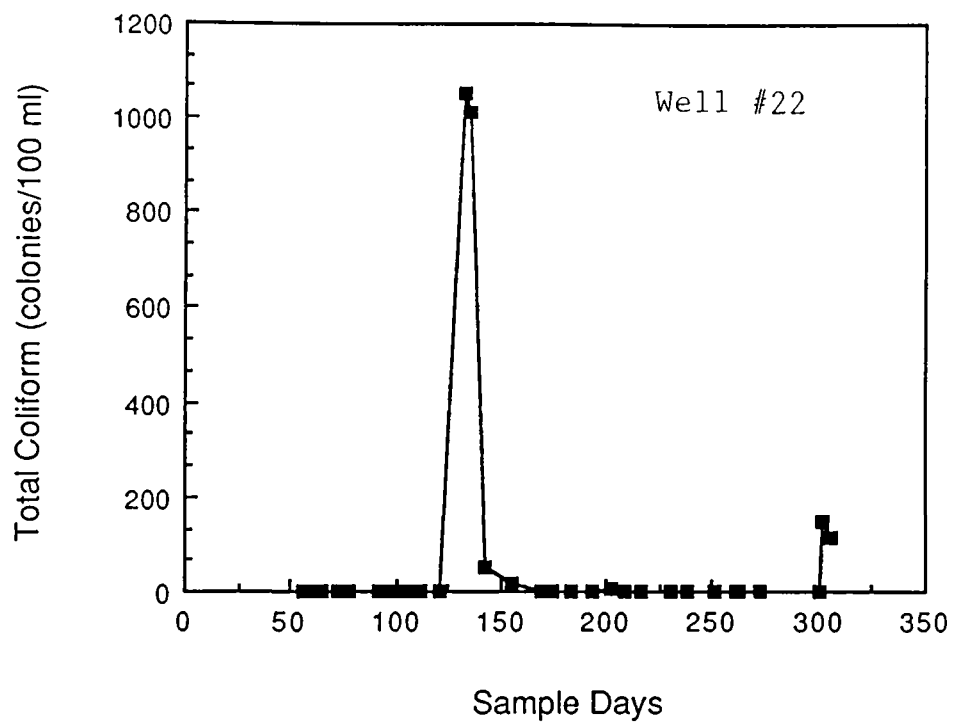


Fig. 39. Total coliform (colonies/100 ml) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

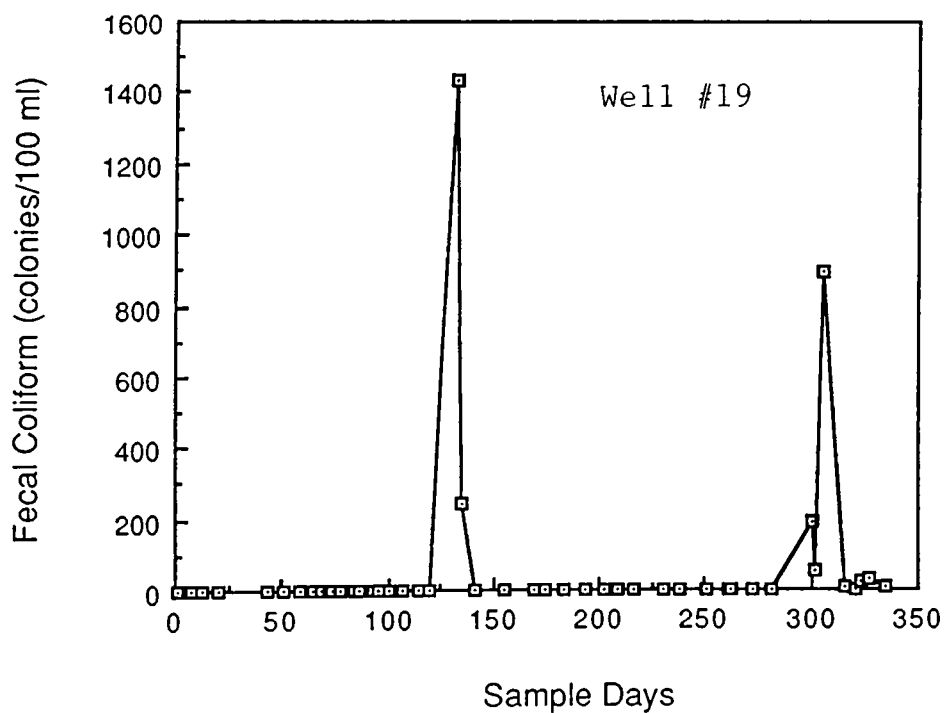
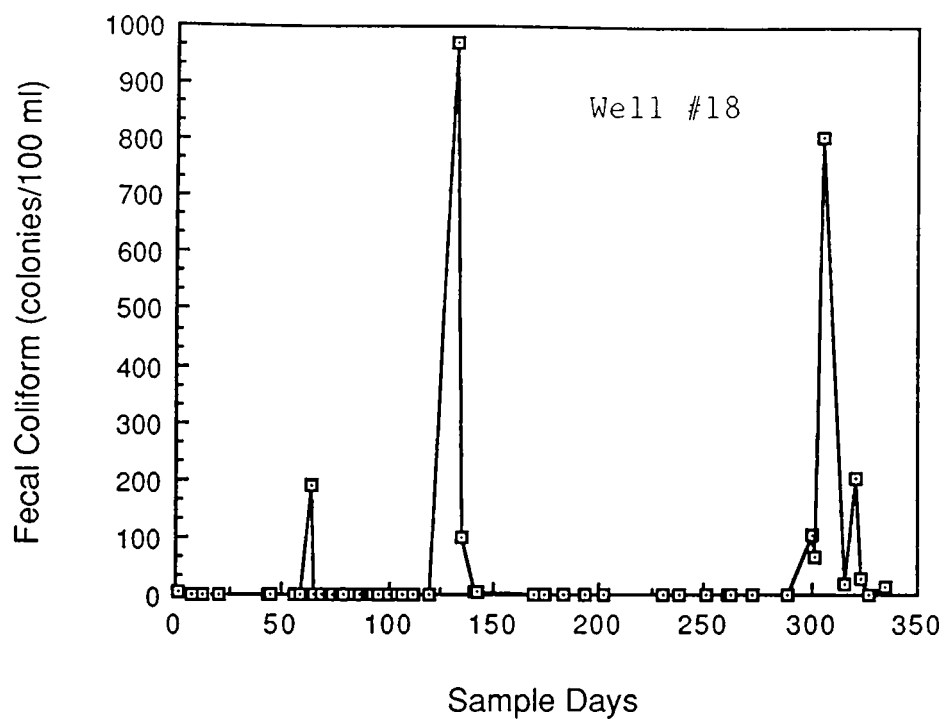


Fig. 40. Fecal coliform (colonies/100 ml) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

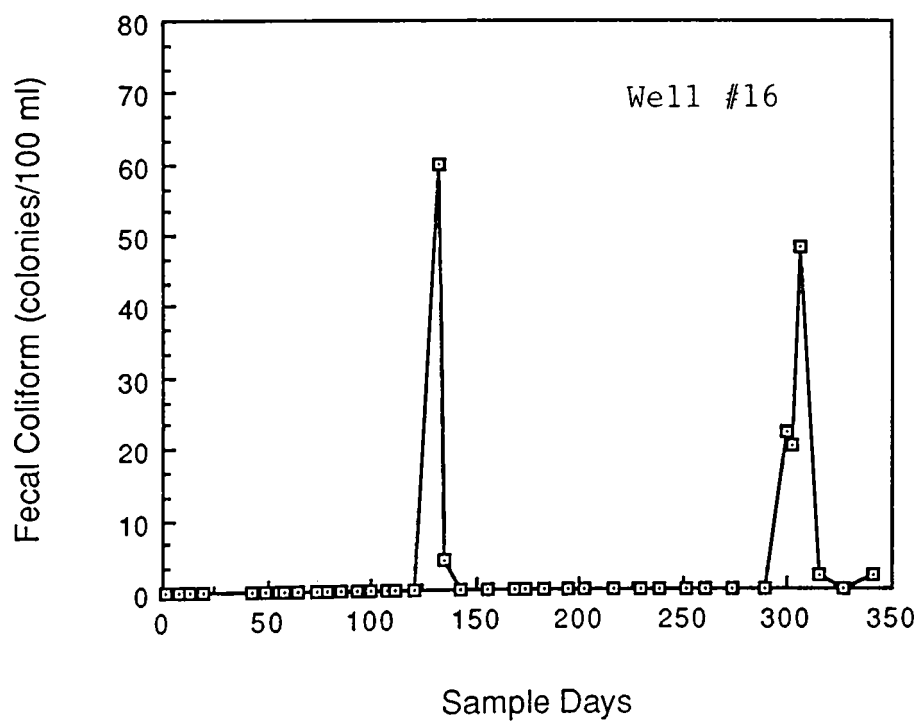
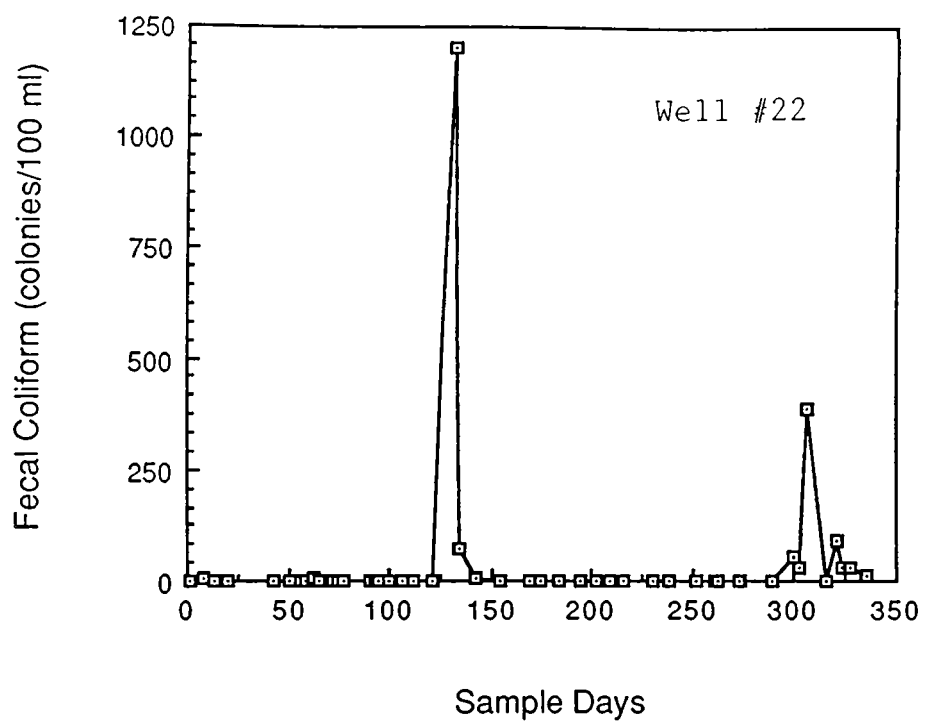


Fig. 41. Fecal coliform (colonies/100 ml) from July 17, 1985 (day 1) to June 23, 1986 (day 341).

Fecal Coliform/Fecal Streptococcus Ratios

Fecal coliform/fecal streptococcus ratios (FC/FS) were used in determining the sources of bacteriological pollution. FC/FS ratios greater than 4.1 are indicators of domestic and human wastes. If FC/FS ratios are less than 0.7 the pollution is derived from a nonhuman source. Mixed human and animal wastes are indicated by ratios between 0.7 and 4.4 (APHA,1985).

The FC/FS ratios were calculated on samples collected on November 26, 1985. Densities of fecal streptococcus must be greater than 100 colonies/100 ml to ensure the accuracy of the ratios (APHA, 1985). Ten wells had densities greater than 100 colonies/100 ml. Although these ratios are not conclusive they do indicate the possible sources of contamination. There are two possible sources for the bacterial contamination, local septic tanks and the cattle and wildlife grazing in the watershed of the flood control/recharge structure. Area septic systems consist of tanks and soil absorption fields. An estimated 40 % of the existing septic tanks in the United States do not function properly. Poor location, management and construction of septic systems can be the cause or potential cause of pollution in groundwater (Canter and Knox,1985). The degree to which the study area was suitable for a septic system is classified as severe. Severe defines the soil properties and area features as significantly unfavorable and require the special maintenance and design of septic systems (Table 2) (US Soil Conservation Service,1984). One of the 10 wells mentioned had a FC/FS ratio indicating the possibility of contamination from mixed human and animal wastes. In this case a septic system could have played a role in the contamination (Fig. 42).

The nine other wells had values ranging from 0.19 to 0.678, which indicated nonhuman sources of contamination (Fig.42). The water draining off the flood plain appeared to be the prime source for the contamination of drinking water wells. Cattle graze on the flood plain of the flood

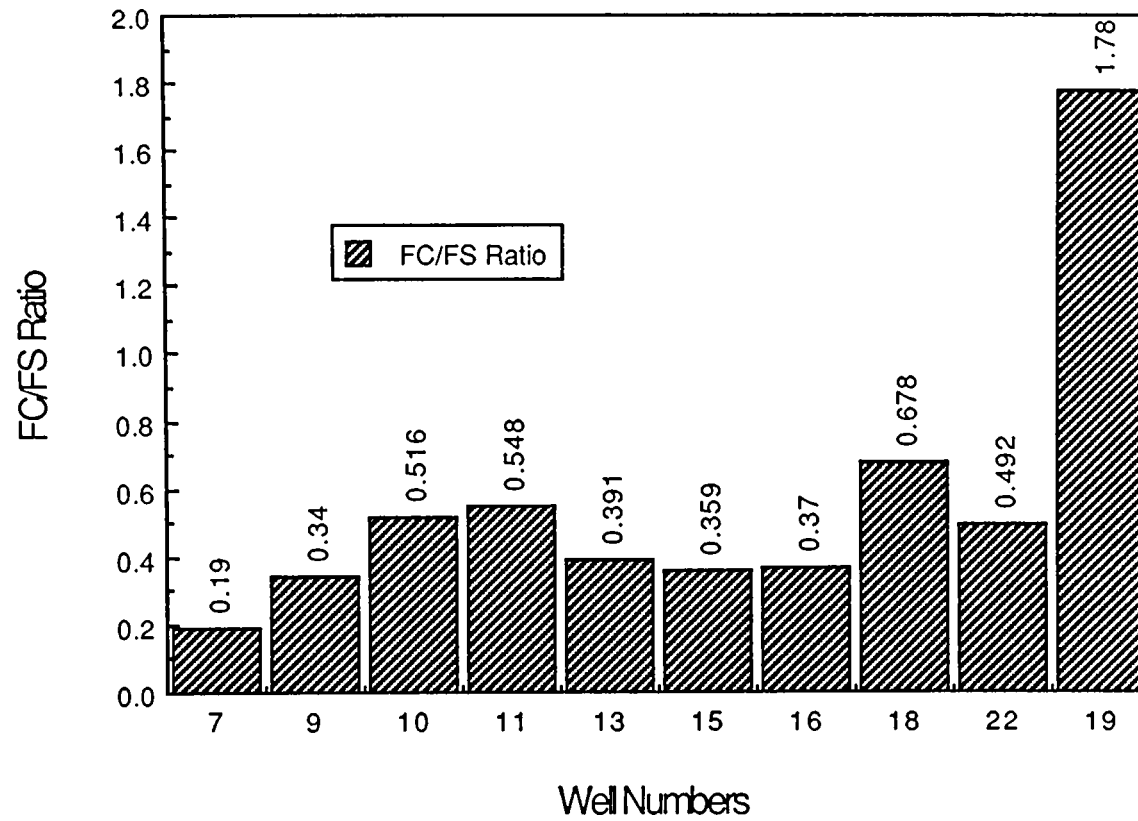


Fig. 42. Fecal coliform/fecal streptococcus ratios (FC/FS) for samples collected November 26, 1985.

control/recharge structure adjacent to the study area. After very fast and heavy rainfalls water crossed the flood plain picking up fecal material before entering faults and fractures in the ground. The contamination of wells did not occur immediately and there was a lag time of approximately six to 12 hrs. Turbidity was associated with the presence of coliform bacteria. Turbidity varied from amounts detectable on the bacteriological filter paper to water filled with bright orange sediment (Table 14). Turbidity and bacteria decreased within four to five days following rainfall to pre-rainfall conditions.

In addition to using the FC/FS ratio to determine the source(s) of bacteriological contamination, various other factors were used to find patterns between contaminated and non-contaminated wells. Several previous studies showed that rainfall and well depth are related to the bacterial contamination of ground water. Studies done in east Texas have shown that higher levels of bacterial contamination occurred in shallower wells with depths of 15 m (50 ft) or less. Contamination occurred at deeper depths, but with less frequency (Gerba, 1985). Study wells had depths that ranged from 58 m (190 ft) to 107 m (350 ft). There was no correlation between the depth of sample wells and bacterial contamination.

By using the well depth, land elevation and line of equal water table elevation the approximate depth to which a well penetrated the water table and the depth to the top of the water table was determined (Figs. 43). Contaminated wells ranged in penetration depth from 13 m (43 ft) to 184 m (56 m) and depth to the top of the water table at each sample site ranged from 130 ft (40 m) to 245 ft (75 m) (Table 15). From this information no definite conclusions could be drawn from these relationships. Wells which had fecal or total coliform contamination had penetration depths ranging from 17 m (55 ft) to 56 m (184 ft). Those with counts higher than 200 colonies/100 ml had penetration depths ranging from 43 ft (13 m) to 30 m (100 ft), but wells not experiencing coliform contamination were also found at the same depths. When values for the depth to the top of the water table were plotted on a map with isolines the majority of contaminated wells were located in the vicinity of Sink Creek (Fig. 43).

Table 14. Comparison of bacteriological contamination and turbidity in the Sink Creek drainage basin.

Well Number	Total Coliform*	Fecal Coliform*	Fecal Strep*	FC/FS Ratio	Turbidity*
5	26	0	2	-	0.32
7	92	0	24	-	0.98
9	40	0	10	-	1.01
10	144	12	144	0.08	1.91
11	80	8	200	0.04	1.91
13	750	500	2090	0.24	13.7
15	110	10	50	-	0.78
16	54	30	152	0.21	0.65
18	130	10	290	0.35	4.2
19	230	50	180	0.28	0.38
22	120	60	2700	0.02	1.7

* Values obtained on 5/30/87

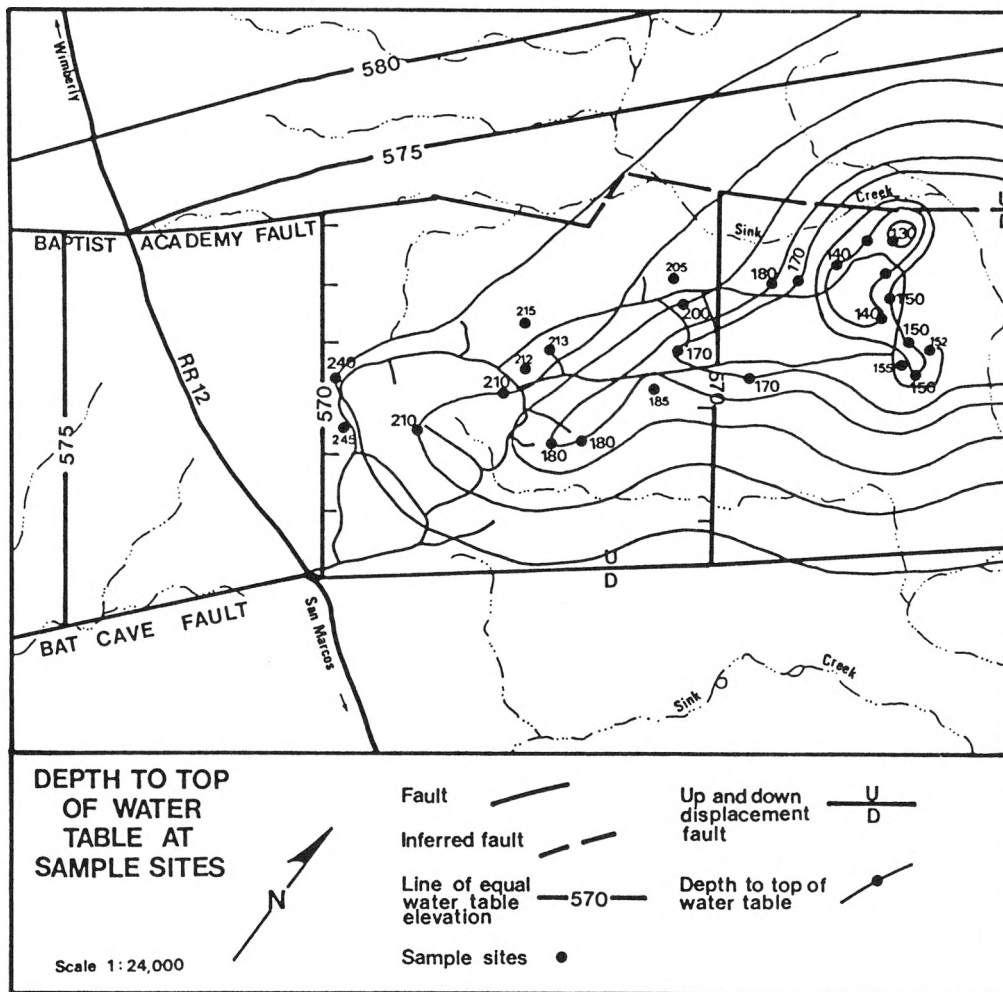


Fig. 43. Sample sites in relation to water table characteristics.

Table 15. Surface, water table and water well characteristics in relation to bacteriological contamination.

Well Number	1	2	3	4	5	6	7	8	9
Land Elevation - ft (m) (approximate)	815 (248)	810 (247)	780 (238)	780 (238)	750 (229)	750 (229)	782 (238)	783 (239)	785 (239)
Line of equal water table elevation - ft(m)	570 (174)	570 (174)	570 (174)	570 (174)	570 (174)	570 (174)	570 (174)	570 (174)	570 (174)
Well Depth - ft(m)	300 (181)	273 (83)	-	350 (107)	-	262 (80)	350 (107)	-	300 (91)
Depth to top of water table - ft(m)	245 (175)	240 (73)	210 (64)	210 (64)	180 (55)	180 (55)	212 (65)	213 (65)	215 (65)
Well penetration of water table - ft(m)	55 (17)	33 (10)	-	140 (43)	-	82 (25)	-	-	85 (26)
Contamination Maximum FC/TC	√ 0/19	- 0/0	- 0/0	√ 8/11	- 0/2	- 0/0	√ 100/144	√ 174/240	√ 340/630

Table 15. Surface, water table and water well characteristics in relation to bacteriological contamination.

Well Number	10	11	12	13	14	15	16	17
Land Elevation - ft(m) (approximate)	775 (236)	750 (229)	740 (225)	710 (216)	700 (213)	710 (216)	720 (219)	710 (216)
Line of equal water table elevation - ft(m)	570 (174)	570 (174)	570 (174)	570 (174)	570 (174)	570 (174)	570 (174)	570 (174)
Well Depth - ft(m)	248 (76)	289 (88)	270 (82)	190 (58)	-	-	210 (64)	190 (58)
Depth to top of water table - ft(m)	205 (62)	180 (55)	170 (52)	140 (43)	130 (40)	140 (43)	150 (46)	140 (43)
Well penetration of water table - ft(m)	43 (13)	109 (33)	100 (30)	100 (30)	-	-	60 (18)	50 (15)
Contamination Maximum FC/TC	√ 1110/530	√ 36/81	√ 84/163	√ 970/1880	√ 18/92	√ 216/570	√ 60/168	√ 8/76

Table 15. Surface, water table and water well characteristics in relation to bacteriological contamination.

Well Number	18	19	20	21	22
Land Elevation - ft(m) (approximate)	725 (221)	720 (219)	722 (220)	740 (225)	755 (230)
Line of equal water table elevation - ft(m)	570 (174)	570 (174)	570 (174)	570 (174)	570 (174)
Well Depth - ft(m)	240 (73)	225 (68)	300 (91)	250 (76)	235 (72)
Depth to top of water table - ft(m)	155 (47)	150 (46)	152 (46)	170 (52)	185 (56)
Well penetration of water table - ft(m)	85 (26)	75 (23)	184 (56)	80 (24)	50 (15)
Contamination Maximum FC/TC	√ 808/1800	√ 1436/1210	√ 32/7	- 0/0	√ 1200/1050

SUMMARY

This project was done because of the growing concern of residents living in the San Marcos area for the quality of water in the Edwards aquifer. Residents of rural subdivisions, in both the Sink and Purgatory Creek drainages, have experienced varying levels of turbidity in their wells following large rainfalls.

A relationship existed between rainfall and the bacterial contamination of groundwater. The two largest rainfalls during the study (November 1985 and May 1986) correspond to significant changes in both the concentration of chemical constituents and numbers of coliforms. Bacterial contamination was found in 68.2% of the wells sampled with 40% of those wells having coliform counts greater than 200 colonies/100ml. The highest levels of fecal and total coliform bacteria were found following two major rainfall events. Turbidity levels found in contaminated wells following rainfalls were also an indicator of contamination, the greater the turbidity the higher the coliform counts. Fecal coliform/fecal streptococcus (FC/FS) ratios indicated a non-human source of contamination.

At the same time wells exhibited bacterial contamination, they also showed distinct changes in water chemistry. Large decreases in the concentration of dissolved solids in the water were associated with the rapid infiltration of surface water. The stormwater runoff, contained lower ionic concentrations than that of the groundwater. This infiltration caused a mixing of the surface and groundwaters, initiating the subsequent chemical changes.

No definite conclusions could be drawn based on well depth because contamination occurred at all depths 58 to 107 m (190 to 350 ft). The majority of the wells experiencing contamination were located in the vicinity

of Sink Creek. The location of a well in relation to the characteristic sink holes, faults and fractures in the study area is the dominant theory as to whether a well became contaminated or not.

The importance of studies dealing with the quality of water in the Edwards aquifer is growing. As development over the aquifer increases so does the threat of contaminants entering groundwater. Historical data can be useful in determining water quality trends that occur in the aquifer. These studies can identify sensitive areas that are susceptible to contamination.

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