technical paper

Defining Groundwater Flow Characteristics in the Northern Segment of the Edwards Aquifer Based on Groundwater Chemistry

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Abstract

Chemical and isotopic compositions along two groundwater flow paths were used to characterize groundwater flow system in the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Groundwater compositions reflect geochemical processes that the groundwater encounters along a flow path, for example, interaction with aquifer rock or soil, groundwater mixing, and recharge processes. Recharge processes can be investigated by comparison of conservative constituents in both precipitation and groundwater.

Results of this study support groundwater flow model results that indicate that (1) groundwater circulation is most active in the unconfined part of the aquifer where most of the recharge occurs by infiltration through soil and intermittent streams and natural discharge occurs through perennial streams and (2) little groundwater flow enters the confined part of aquifer. The spatial distribution of groundwater flow in the aquifer produces compositional differences between groundwater in the unconfined and confined parts of the aquifer. Additionally, this study suggests that recharge to the aquifer occurs mostly during fall and winter months. This observation is based on stable hydrogen and oxygen isotopic compositions of groundwater and precipitation.

Introduction

The northern segment of the Edwards (Balcones Fault Zone) Aquifer is an important source of water for municipalities, industries, and landowners in central Texas. Of the three segments of the Edwards (Balcones Fault Zone) Aquifer, the San Antonio and Barton Springs segments have historically received greater attention due to conflicts over groundwater demand for municipal, agricultural, recreational, and ecological uses (Figure 1). The northern segment has received lower priority largely because the largest city in the region, Austin, does not rely on the northern segment for groundwater to meet its water demands. However, other smaller municipalities in the area, such as Georgetown, Pflugerville, and Round Rock, use groundwater from the Edwards (Balcones Fault Zone) Aquifer. Rapid population growth in these and adjacent municipalities is likely to be accompanied by rapid growth in demand for groundwater from the northern segment of the Edwards (Balcones Fault Zone) Aquifer. This growth necessitates our gaining a better understanding of the hydrology and potential effects of future population growth on this segment of the aquifer. This understanding can be achieved through groundwater modeling and evaluation of geochemical tracers in the groundwater.

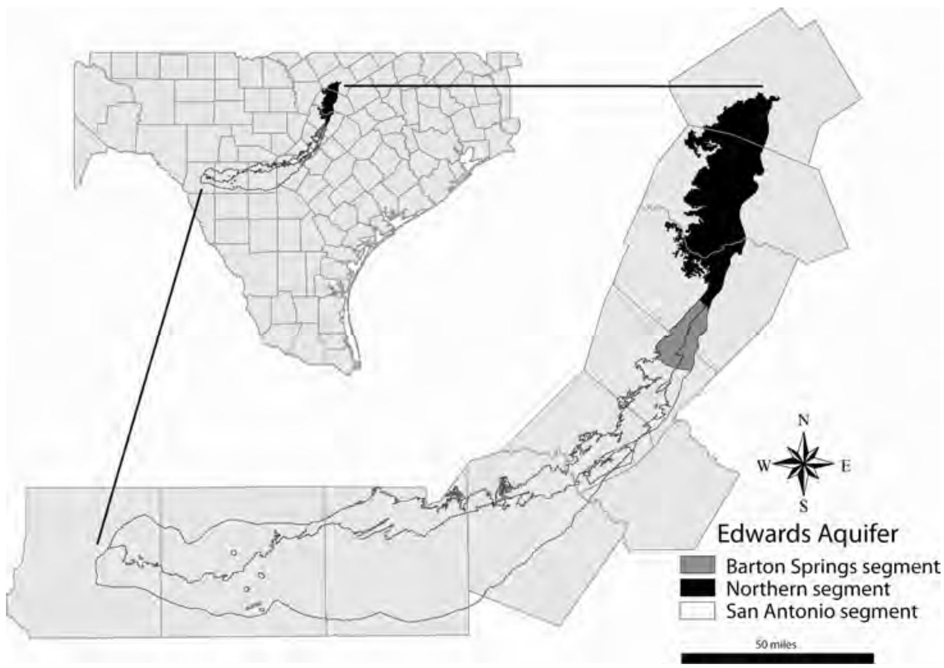

Figure 1. The Edwards (Balcones Fault Zone) Aquifer is divided into three segments: Northern, Barton Springs, and San Antonio, each separated by hydrologic divides.

Study Area

The northern segment of the Edwards (Balcones Fault Zone) Aquifer is located in central Texas (Figure 2). It is the northernmost of the three segments that make up the Edwards (Balcones Fault Zone) Aquifer, underlying parts of Bell, Travis, and Williamson counties (Figure 1). The northern segment of the Edwards (Balcones Fault Zone) Aquifer extends from the Colorado River in Travis County to the Lampasas River in southern Bell County. This segment of the Edwards (Balcones Fault Zone) Aquifer is bounded by the Colorado River to the south, the western margin of the Edwards and associated limestones outcrop to the west and north, and the easternmost extent of fresh groundwater, referred to as the bad-water line.

Central Texas has a sub-humid climate. At weather stations located within the study area, median annual precipitation ranges from 20 to 30 inches. Approximately 60 percent of annual precipitation falls in April through June and September through October (Figure 3). Some of this precipitation takes the form of severe thunderstorms. These thunderstorms frequently produce major flash floods that have the potential to generate recharge to the underlying aquifer (Senger and others, 1990). Monthly precipitation is typically lowest during July and August.

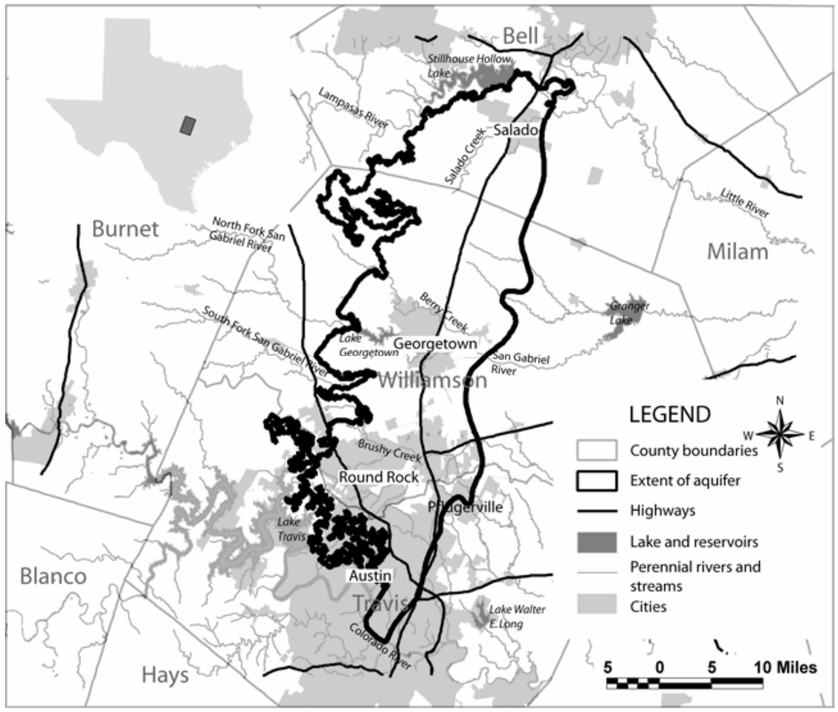

Figure 2. Location of study area.

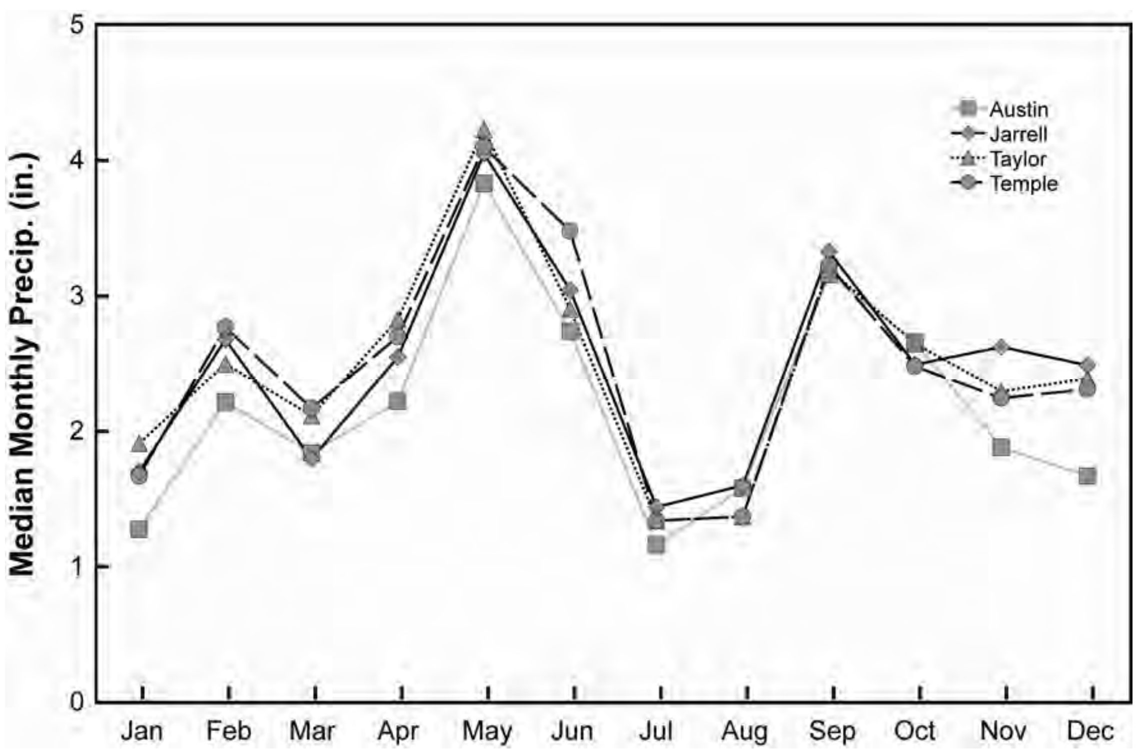

Figure 3. Median monthly precipitation at selected stations in the study area (data from National Climate Data Center).

Geology

Stratigraphic units underlying the study area range in age from the Paleozoic Ellenburger Group to Recent alluvium (Brune and Duffin, 1983). Only Cretaceous and younger rocks are exposed at the surface (Figure 4). The most important aquifer units in the study area occur in the Cretaceous Trinity, Fredericksburg, and Washita groups (Figure 4). These Cretaceous units are up to 2,000 feet thick and dip gently toward the southeast (Trippet and Garner, 1976).

The Trinity Group is divided into the Travis Peak, Glen Rose, and Paluxy formations (Figure 5; Brune and Duffin, 1983). Of these three formations, only the Glen Rose Formation occurs throughout the study area, the other two formations only occur as isolated outcrops. The Glen Rose Formation is predominantly composed of alternating layers of limestone and dolomite at the top and massive layers of limestone and dolomite at the base.

The Fredericksburg Group is divided into the Walnut Formation, Comanche Peak Limestone, and Edwards Limestone (Figure 5; Brune and Duffin, 1983). The Walnut and Comanche Peak formations are composed of fine-grained limestone and shale, occurring primarily in the subsurface in the northern part of the study area. The Edwards Limestone is composed of massive vuggy limestone with fine-grained marl at the top of the formation. This marl is very thin in the study area and tends to become thicker toward the north.

The Washita Group is divided into the Georgetown Formation, Del Rio Clay, and Buda Limestone (Figure 5; Brune and Duffin, 1983). The Georgetown Formation thins southward and is composed of fine-grained limestone that in places is hydraulically connected to the Edwards Limestone. The Del Rio Clay and Buda Limestone are composed of shale and fine-grained limestone, respectively (Brune and Duffin, 1983).

Hydrogeology

The northern segment of the Edwards (Balcones Fault Zone) Aquifer generally consists of the Comanche Peak Limestone, Edwards Limestone, and Georgetown Formation (Figures 5 and 6). These stratigraphic units constitute the upper Fredericksburg and lower Washita groups and are collectively referred to as the Edwards and associated limestones (Brune and Duffin, 1983). The aquifer overlies older Cretaceous rock of the Walnut Formation and is overlain by the Del Rio Clay (Figures 5 and 6). The Walnut Formation and Del Rio Clay are recognized as confining units (Brune and Duffin, 1983; Baker and others, 1986). The base of the aquifer is defined as the base of rocks having greater water-yielding capabilities (Baker and others, 1986). In most areas, this excludes the Walnut Formation; however, in some areas beds in the Walnut Formation are composed of potentially permeable shell beds and may thus be included in the Edwards (Balcones Fault Zone) Aquifer.

The unconfined portion of the aquifer, consisting of the outcrop of the Edwards and associated limestones, becomes narrow in the south, near the Colorado River (Figure 4). This narrowing of the outcrop occurs as a result of the combined effects of intense faulting and large topographic variations (Baker and others, 1986). Fracturing of the limestone also enhances the porosity of the limestone and plays a role in the development of karst features. Normal faulting, common in the

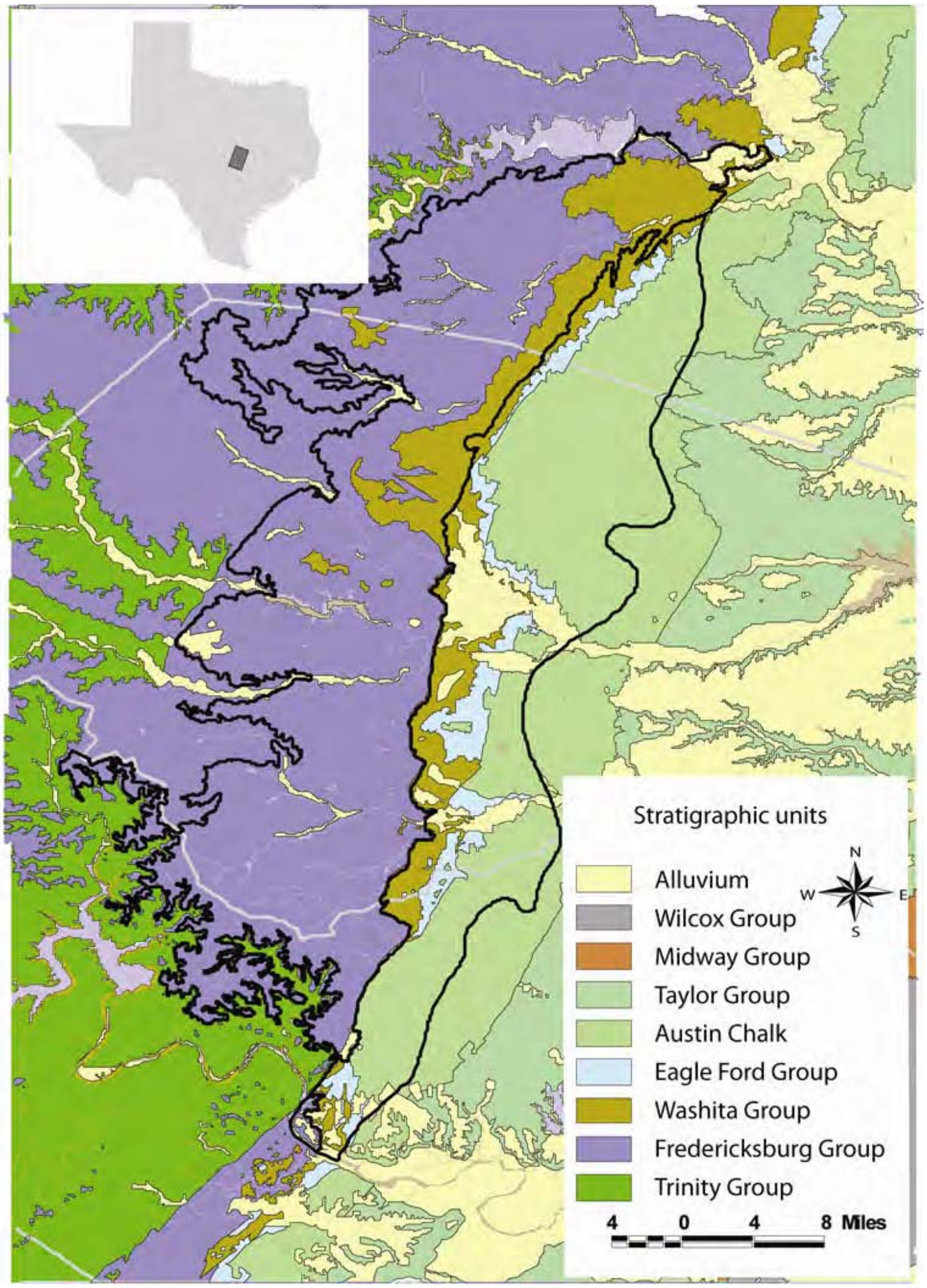

Figure 4. Surface geology in the study area (modified from Proctor and others, 1981).

Series	Group		Stratigraphic Unit	Hydrologic Unit	Maximum Thickness (feet)
Gulf	Navarro			Navarro and Taylor Group	850
	Taylor				
	Austin			Austin Chalk	450
Comanche	Eagle Ford				50
	Washita		Buda Limestone		50
			Del Rio Clay		60
			Georgetown Formation	Edwards aquifer	100
	Fredericksburg		Edwards Limestone		200
			Comanche Peak Limestone		50
			Walnut Formation		150
	Trinity		Paluxy Formation	Upper Trinity	10
		Glen Rose	Upper Member		450
			Lower Member	Middle Trinity	450
		Travis Peak	Hensell Sand Member		100
			Cow Cr. Limestone Member		100
			Hammett Shale Member		50
			Sligo Member	Lower Trinity	150
			Hosston Member		850

Figure 5. Stratigraphic and hydrostratigraphic units in the study area (modified from Brune and Duffin, 1983).

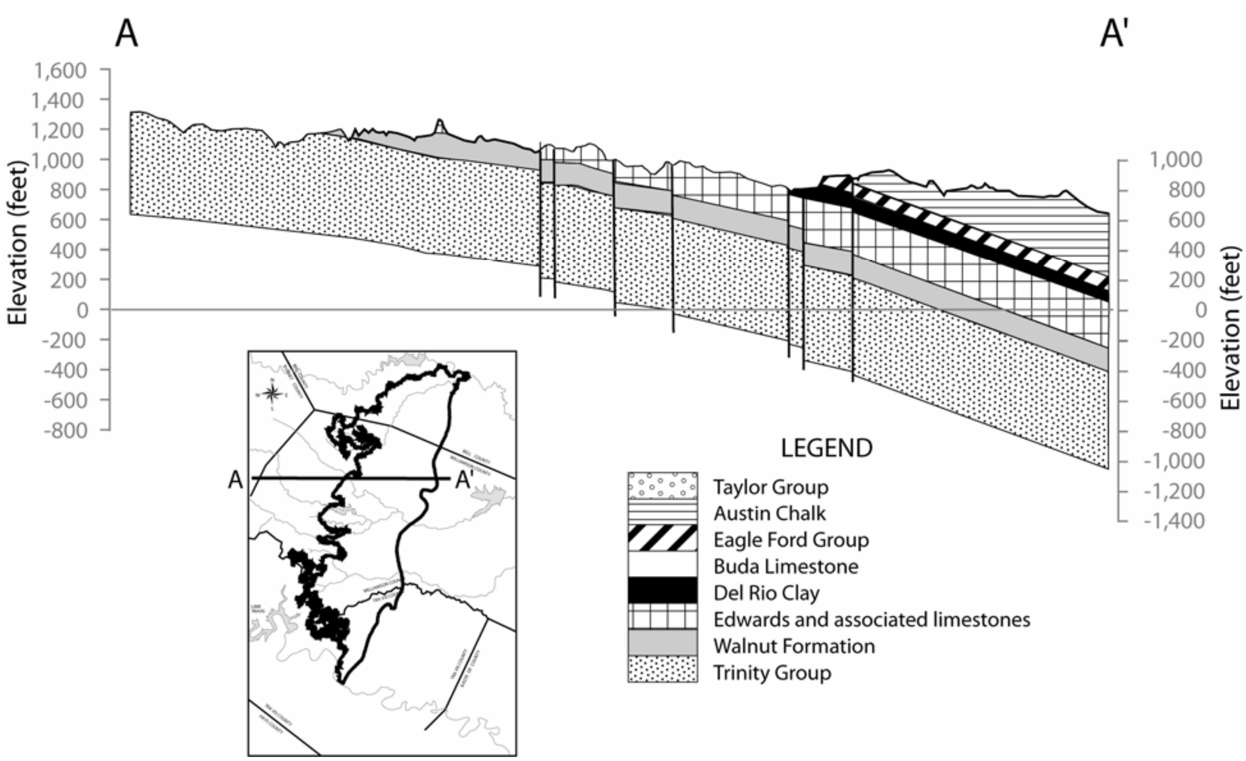

Figure 6. Geologic cross sections of the northern segment of the Edwards (Balcones Fault Zone) Aquifer (modified from Jones, 2003).

southern portion of the study area, generally decreases toward the north (Baker and others, 1986). It is associated with the Balcones Fault Zone, a zone of faults about six to eight miles wide that extends from Del Rio in south-central Texas to Dallas. This zone is characterized by major faults that strike north-south to northeast-southwest and dip 40 to 80 degrees to the east, with a net displacement of 600 to 1,000 feet (Brune and Duffin, 1983; Collins, 1987). Cross faults, sub-perpendicular to major faults, are also common (Collins, 1987). These faults influence groundwater flow in two ways: (1) faults provide preferential flow paths and (2) fault displacement in some cases produces barriers to groundwater flow (Brune and Duffin, 1983). Preferential groundwater flow along faults and joints in this aquifer often results in formation of solution cavities such as caves (Brune and Duffin, 1983).

Water Levels

In the northern segment of the Edwards (Balcones Fault Zone) Aquifer, the potentiometric surface slopes generally toward the east although adjacent to the Colorado River it slopes toward the south (Figure 7). Groundwater flow along fractures is responsible for the southward flow in the southern part of the study area, where fracturing is most intense. Senger and others (1990) suggested that some of the major faults, especially in the south, also act as hydraulic barriers, restricting west-to-east groundwater flow. In the central and northern parts of the aquifer, where faulting is less intense, the influence of fractures on regional groundwater flow is less apparent (Senger and others, 1990).

In the unconfined part of the aquifer, the water table occurs less than 100 feet below land surface and may approach land surface along incised streams (Senger and others, 1990). In the confined part of the aquifer, water levels approach or may, in some cases, exceed land surface, resulting in flowing wells. Water-level fluctuations observed in this aquifer are in response to changes in recharge and discharge rates associated with rapid recharge during wet periods (Baker and others, 1986). Adjacent to the Colorado River, water-level fluctuations are muted due to the stabilizing effect of Lake Austin and Town Lake.

Recharge

Recharge to the Edwards (Balcones Fault Zone) Aquifer takes the form of infiltration of precipitation that falls on the outcrop or infiltration of runoff derived from watershed areas upstream from the aquifer outcrop (Dahl, 1990; Slade and others, 2002). The primary mechanism for recharge to the aquifer is infiltration along intermittent streams and by infiltration of precipitation on the outcrop. The recharge zone is characterized by the occurrence of (1) numerous scattered karst features, such as dissolution-enhanced fractures, sinkholes, and caves and (2) faults and joints that intersect losing segments of perennial and intermittent streams that cross the study area. Karst features and fractures are potential recharge sites capable of transmitting large amounts of water to the aquifer following heavy rainfall events (Brune and Duffin, 1983; Kreitler and others, 1987).

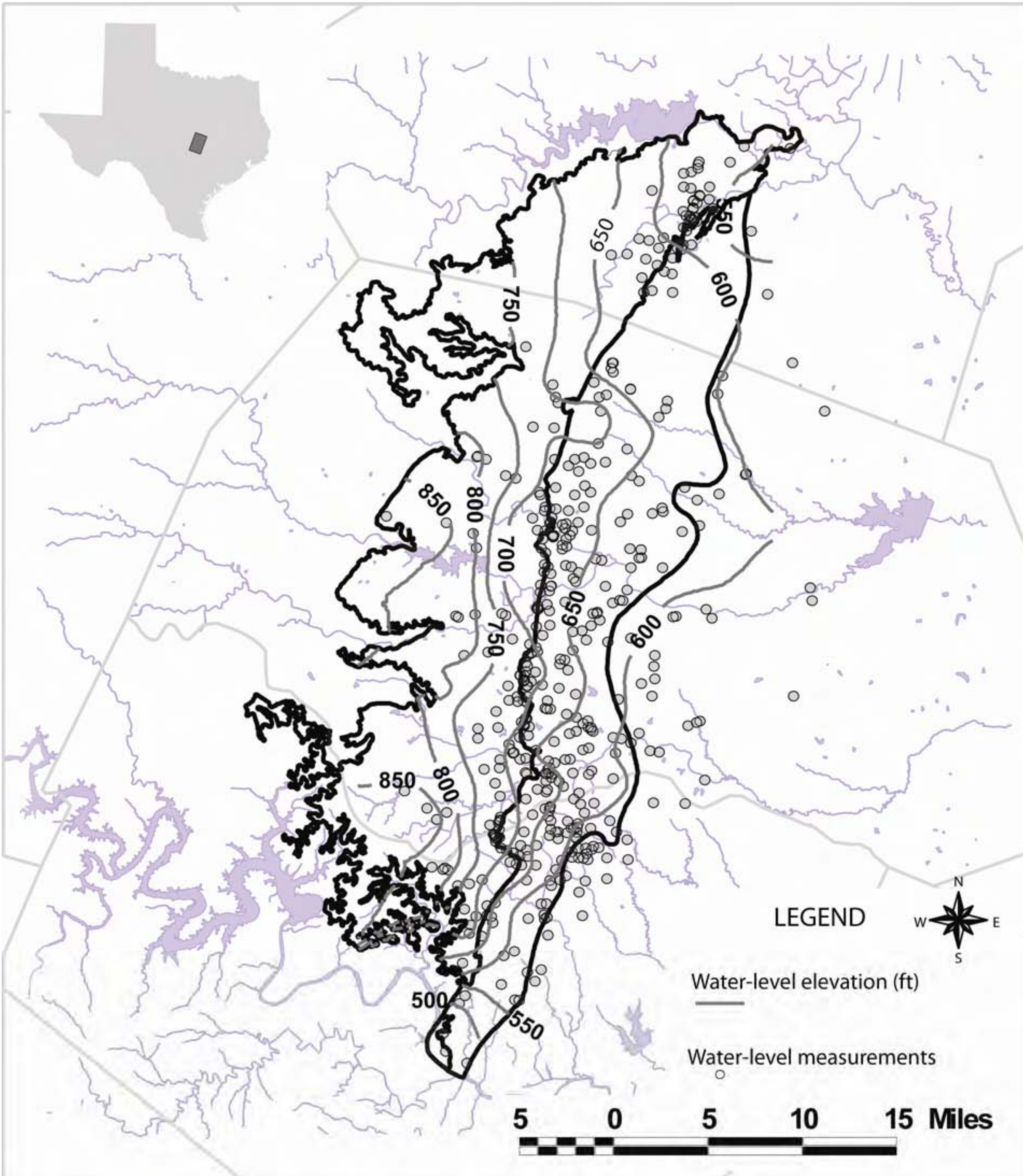

Figure 7. Water-level elevations in the northern segment of the Edwards (Balcones Fault Zone) Aquifer for 1980.

Discharge

The northern segment of the Edwards (Balcones Fault Zone) Aquifer is only slightly to moderately developed. Consequently, natural discharge through springs and seeps is thought to be much larger than well pumping (Duffin and Musick, 1991). TWDB pumping estimates indicate that municipal and rural domestic pumping together account for almost 90 percent of the groundwater withdrawn from the aquifer.

The Lampasas and Colorado rivers that form the northern and southern boundaries of the study area are the largest rivers in the area. Together with smaller rivers and creeks, such as Brushy Creek, Berry Creek, Salado Creek, and San Gabriel River that cross the outcrop of the aquifer, they are likely recipients of groundwater discharge as indicated by their perennial flow (Figure 2). Springs and seeps in the western part of the aquifer discharge mostly from fractures or cavities in the Edwards Limestone or along the contact between the Edwards and Comanche Peak limestones (Figure 8; Kreitler and others, 1987). In the east, major springs are associated with major faults and generally occur some distance east (down-gradient) of these faults. Faulting frequently results in the juxtaposition of relatively impermeable Del Rio Clay and Buda Limestone and Edwards aquifer rock. This juxtaposition restricts groundwater flow across faults and often results in upward flow along the fault and discharge through springs (Brune and Duffin, 1983; Land and Dorsey, 1988; Senger and others, 1990). Hence the occurrence of several major springs, for example, Mount Bonnell, Salado, San Gabriel, and Berry springs, adjacent to the boundary between unconfined and confined parts of the aquifer (Figure 8). Other major springs occurring in the study area include Childers Springs in Bell County; Deep Eddy, Mormon, Power House, and Seiders springs in Travis County; and Berry, Knight, San Gabriel, and Manske springs in Williamson County (Brune, 1975). Along the southern margin of the study area, discharge from the aquifer often takes the form of numerous small springs or seeps located along the southern margin of the Jollyville Plateau (Senger and others, 1990). Discharge in the confined part of the aquifer takes the form of cross-formational flow from the Edwards (Balcones Fault Zone) Aquifer, through the Del Rio Clay, into overlying aquifer units such as the Austin Chalk.

Precipitation over the recharge zone and the upstream contributing zone results in rapid increases in spring discharge. The lag time between precipitation events and spring response varies from almost immediate to more than one week (Brune and Duffin, 1983).

Groundwater Geochemistry

Geochemical compositions of groundwater in the Edwards (Balcones Fault Zone) Aquifer are used to define the down-dip margin of the aquifer. This boundary, referred to as the bad-water line, is defined as the easternmost extent of freshwater in the aquifer. Freshwater is defined as water with total dissolved solids less than 1,000 milligrams per liter. The bad-water line is considered as the eastern boundary of the aquifer because high groundwater salinity is often associated with restricted groundwater circulation (Ridgeway and Petrini, 1999).

Groundwater in the study area becomes progressively more saline from the outcrop recharge zone in the west to down-dip parts of the aquifer in the east (Figure 9). Total dissolved solids in groundwater varies from 200 to 400 milligrams per liter in the recharge zone and increases to

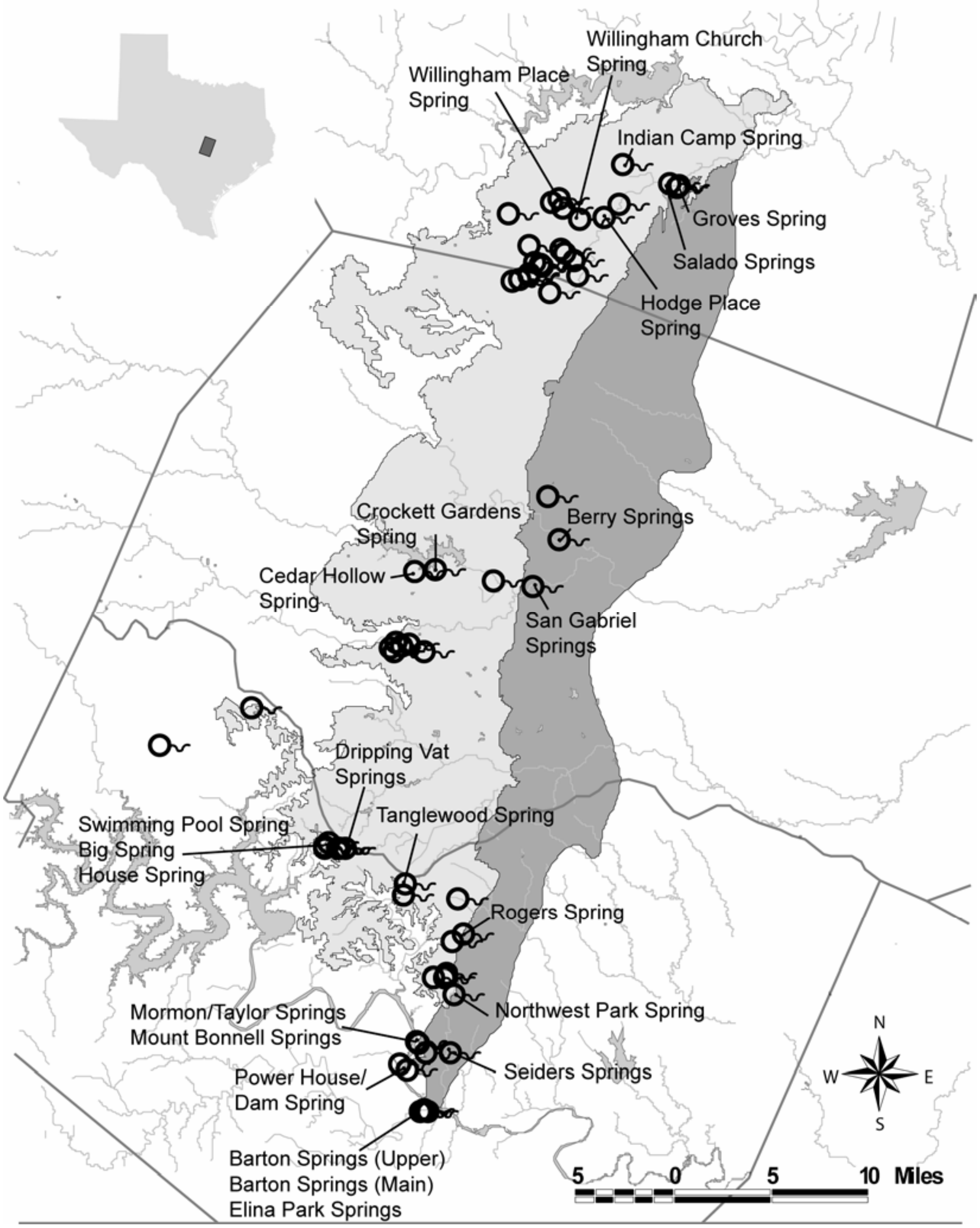

Figure 8. Location of major springs discharging from the Edwards (Balcones Fault Zone) Aquifer in the study area.

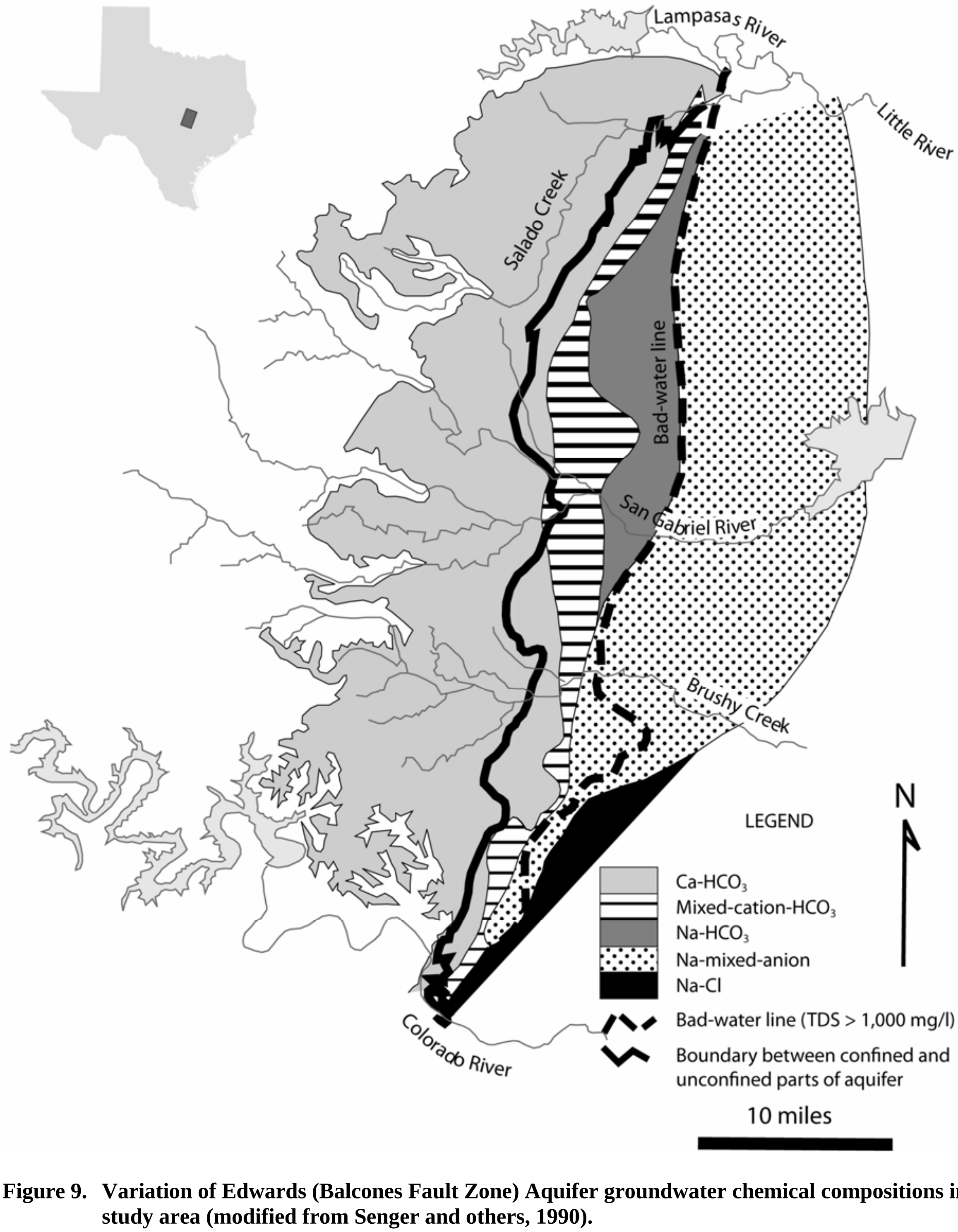

Figure 9. Variation of Edwards (Balcones Fault Zone) Aquifer groundwater chemical compositions in the study area (modified from Senger and others, 1990).

more than 3,000 milligrams per liter down-dip (Baker and others, 1986). Intense faulting in the south creates barriers to eastward groundwater flow and results in the occurrence of saline groundwater within one to two miles of the recharge zone compared to more than 10 miles further north. In addition to variations of total dissolved solids across the aquifer, groundwater geochemical compositions also vary down-dip from calcium-bicarbonate to sodium-sulfate type waters and sodium-chloride type water (Figure 9; Brune and Duffin, 1983). These hydrochemical patterns indicate hydrochemical evolution of groundwater along flow paths. In the south, where faults are more abundant, hydrochemical zones are much narrower than in the north suggesting that the large faults that disrupt fresh groundwater flow may also provide pathways for an influx of deep saline groundwater (Senger and others, 1990).

Groundwater Sampling

We collected ten water samples from springs and wells located along two groundwater flow paths in the aquifer (Figure 10). Six of the samples were collected from a groundwater flow path parallel to the San Gabriel River and the other four samples were collected along Salado Creek. The San Gabriel River and Salado Creek are major discharge zones in the central and northern parts of the study area, respectively. The San Gabriel River flow path lies parallel to the dip of the Edwards (Balcones Fault Zone) Aquifer and extends into the confined part of the aquifer, while the Salado Creek flow paths lies approximately parallel to strike and is solely within the unconfined part of the aquifer. All water samples were collected from springs except for two samples that we collected from wells located in the confined part of the aquifer. Water samples were analyzed for major elements; stable oxygen, hydrogen, and carbon isotopes; and tritium. Analytical precision, based on analyses of laboratory standards and duplicate samples is ±0.2 ‰, ±3 ‰, ±0.2 ‰, and up to 0.27 tritium units (TU) for stable oxygen, hydrogen, carbon, and tritium isotopes, respectively.

Results

Results of major element and isotopic analyses appear in Table 1. Sampling indicates generally increasing sodium, sulfate, and chloride concentrations along flow paths (Figure 11). Water samples collected from the unconfined part of the aquifer have similar major element compositions clustering close together on a Piper Diagram. The Piper Diagram indicates calcium-bicarbonate type water compositions. Water samples from wells located in the confined part of aquifer have higher sodium, sulfate, and chloride, characteristic of down-gradient groundwater compositions in the aquifer. Groundwater isotopic compositions lie mostly within narrow ranges. Stable oxygen ($\delta^{18}O_{SMOW}$) and hydrogen (δD_{SMOW}) isotopic compositions lie within the range -5.0 to -4.4 ‰ and -31 to -26 ‰, respectively (Figure 12). However, stable carbon ($\delta^{13}C_{PDB}$) and tritium compositions differ in the unconfined and confined parts of the aquifer (Figure 13). Groundwater $\delta^{13}C$ values are -12.3 to -8.7 ‰ in the unconfined part of the aquifer and -4.8 to -3.7 ‰ in the confined part of the aquifer (Figure 13). Groundwater tritium is only measurable in the unconfined part of the aquifer where concentrations range from 1.8 to 3.2 TU.

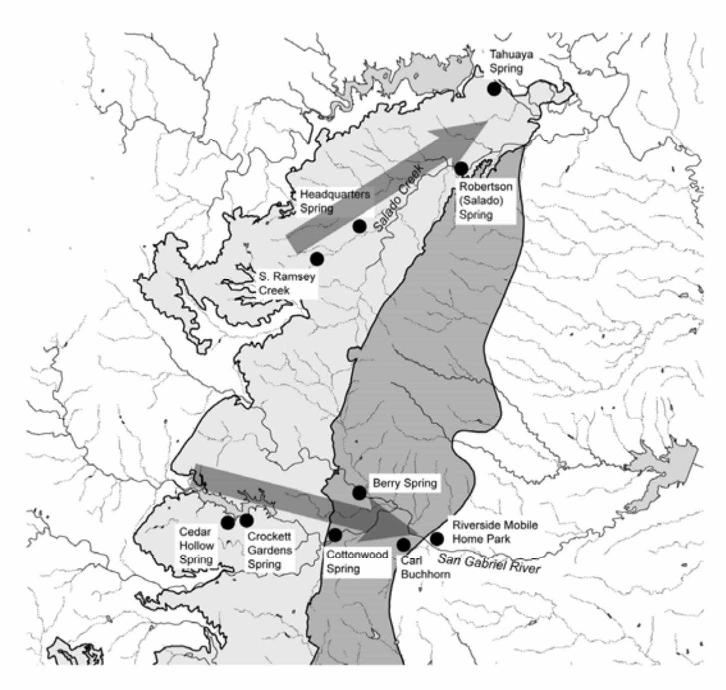

Figure 10. Sampling sites located along flow paths in the San Gabriel River and Salado Creek watersheds.

Discussion

Changes in major element and isotopic compositions along groundwater flow paths give insights into hydrologic and geochemical processes taking place in the aquifer. This information in turn can be used to determine groundwater flow characteristics of the aquifer.

The major element and isotopic compositions of groundwater samples collected in the San Gabriel River and Salado Creek watersheds indicate that compositional changes mainly occur in the down dip areas of the aquifer. Groundwater compositions are relatively uniform in the Salado Creek watershed where groundwater flows parallel to strike (Figures 11 and 13), while in the San Gabriel River watershed, groundwater displays a range of compositions. The range of major element compositions and total dissolved solids suggest mixing between fresh and saline groundwater derived from the unconfined and down-dip areas of the aquifer, respectively (Figures 11 and 13). Differences between groundwater carbon and tritium isotopic compositions in the unconfined and confined parts of the aquifer are apparent. The difference in up-dip and down-dip groundwater tritium compositions indicate different groundwater ages with young, recently recharged, groundwater occurring in the unconfined part of the aquifer and ancient groundwater in the confined part of the aquifer. Related to this, groundwater carbon isotopic compositions in the unconfined and confined parts of the aquifer indicate soil (-8 to -14 ‰) and rock (above -5 ‰) carbon sources, respectively. This is attributable to residence time in the aquifer, where recently recharged groundwater often retains a soil carbon isotopic signature while ancient groundwater adopts a rock carbon isotopic signature over time.

Table 1. **Results of major element and isotopic analyses for water samples collected from the northern segment of the Edwards (Balcones Fault Zone) Aquifer in the San Gabriel River and Salado Creek watersheds (ND indicates constituent was not detected).**

SWN:	58-18-908	58-18-907	58-19-806	58-19-609	58-20-701	58-20-805
Name	Cedar Hollow Spring	Crockett Gardens Spring	Cottonwood Spring (Middle)	Berry Spring	Carl Buchhorn	Riverside Mobile Home Park
Type	Spring	Spring	Spring	Spring	Well	Well
Date	10/31/2002	10/31/2002	10/30/2002	10/31/2002	10/30/2002	10/30/2002
pH	7.38	7.20	7.17	7.08	7.35	7.01
Temp. (°C)	20.6	21.0	21.4	20.9	24.2	25.5
Charge Balance	3%	2%	3%	3%	3%	1%
Ca (mg/l)	90.5	105	98.1	99.6	50.7	35.7
Mg (mg/l)	21.5	21.7	18.9	15.6	31.4	22.7
K (mg/l)	0.56	0.84	1.22	1.40	5.05	7.45
Na (mg/l)	7.89	29.0	12.3	11.4	73.0	189
Cl (mg/l)	13.4	33.6	19.4	17.3	41.9	97.4
NO_3-N (mg/l)	2.13	1.86	3.16	1.98	ND	ND
SO_4 (mg/l)	9.67	28.8	17.4	16.9	84.2	164
Alkalinity (mg/l)	282	320	284	280	250	285
HCO_3 (mg/l)	344	390	346	342	305	348
NO_2+NO_3-N (mg/l)	2.19	1.80	3.00	1.94	ND	ND
TDS (calc.)	490	611	517	506	591	864
Tritium (TU)	2.59	1.80	2.21	2.44	<1	<1
±	0.23	0.23	0.18	0.25		
$\delta^{13}C_{PDB}$ (‰)	-11.8	-13.3	-12.3	-12.1	-4.8	-3.7
±	0.2	0.2	0.2	0.2	0.2	0.2
$\delta^{18}O_{SMOW}$ (‰)	-5.0	-4.9	-4.7	-4.4	-4.9	-4.7
±	0.2	0.2	0.2	0.2	0.2	0.2
δD_{SMOW} (‰)	-31	-31	-29	-26	-30	-30
±	3	3	3	3	3	3

°C = degrees Celcius
mg/l = milligrams per liter
ND = not detected
SWN = state well number
TU = tritium units

Table 1. (cont.)

SWN:	58-11-202	58-03-903	58-04-501	40-60-912
Name	S. Ramsey Creek	Headquarters	Robertson (Salado) Spring	Tahuaya Spring
Type	Spring	Spring	Spring	Spring
Date	4/22/2003	4/22/2003	3/25/2003	3/25/2003
pH	7.13	7.30	7.31	7.35
Temp. (°C)	20.7	20.6	20.0	20.1
Charge Balance	1%	3%	2%	0%
Ca (mg/l)	94.9	88.6	86.8	86.0
Mg (mg/l)	12.7	11.7	12.7	14.8
K (mg/l)	0.51	0.49	1.24	1.17
Na (mg/l)	4.35	3.89	9.62	10.6
Cl (mg/l)	6.65	6.02	12.3	17.8
NO_3-N (mg/l)	1.55	4.22		
SO_4 (mg/l)	8.47	8.89	18.8	13.8
Alkalinity (mg/l)	276	246	241	261
HCO_3 (mg/l)	337	300	294	318
NO_2+NO_3-N (mg/l)	1.54	4.27	4.39	2.41
TDS (calc.)	466	424	435	463
Tritium (TU)	3.23	2.72	2.90	2.58
±	0.26	0.27	0.25	0.26
$\delta^{13}C_{PDB}$ (‰)	-10.2	-10.7	-8.7	-9.6
±	0.2	0.2	0.2	0.2
$\delta^{18}O_{SMOW}$ (‰)	-4.9	-4.9	-4.4	-4.4
±	0.2	0.2	0.2	0.2
δD_{SMOW} (‰)	-30	-31	-27	-27
±	3	3	3	3

°C = degrees Celcius
mg/l = milligrams per liter
ND = not detected
SWN = state well number
TU = tritium units

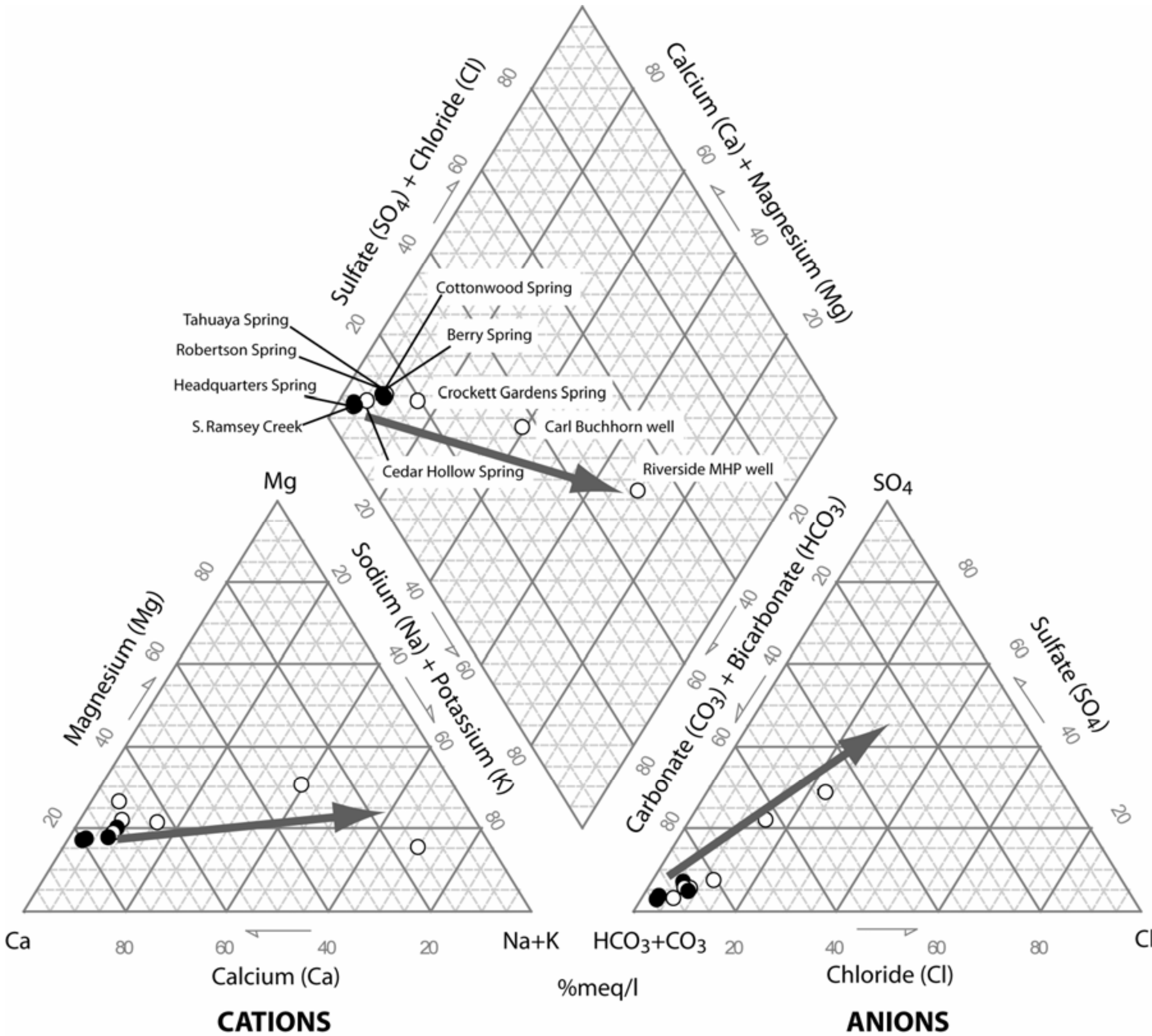

Figure 11. Piper diagram showing groundwater compositions in the San Gabriel River (white) and Salado Creek (black) watersheds. Arrows indicate geochemical evolution of the groundwater along flow paths.

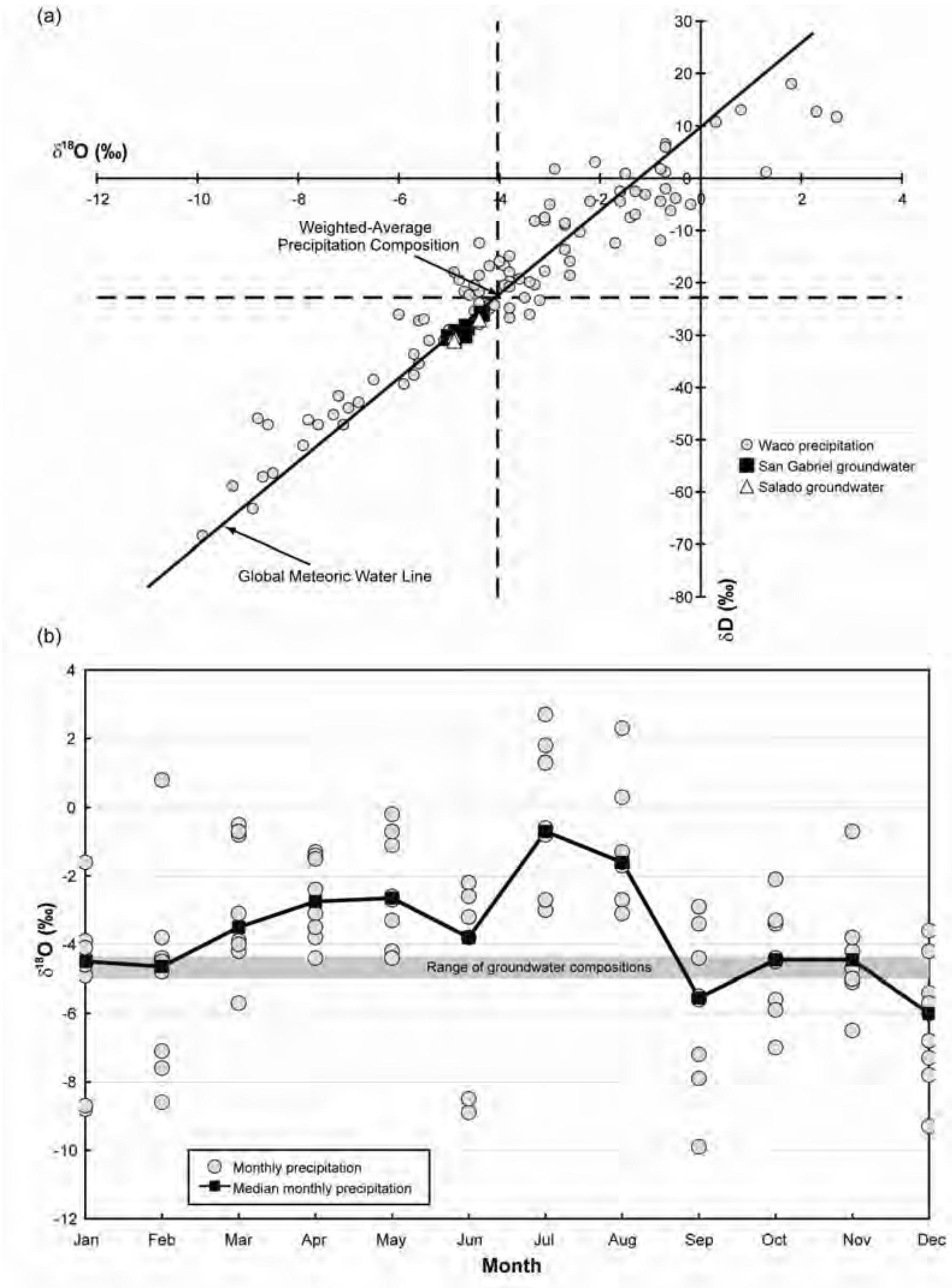

Figure 12. **(a) Plot of hydrogen and oxygen isotope compositions of groundwater along with precipitation collected at Waco (precipitation data from IAEA/WMO, 2004). The dashed lines represent weight-average $\delta^{18}O$ and δD values, respectively. (b) Plot of precipitation oxygen isotopes versus time showing variation in isotopic composition during different months of the year (precipitation data from IAEA/WMO, 2004).**

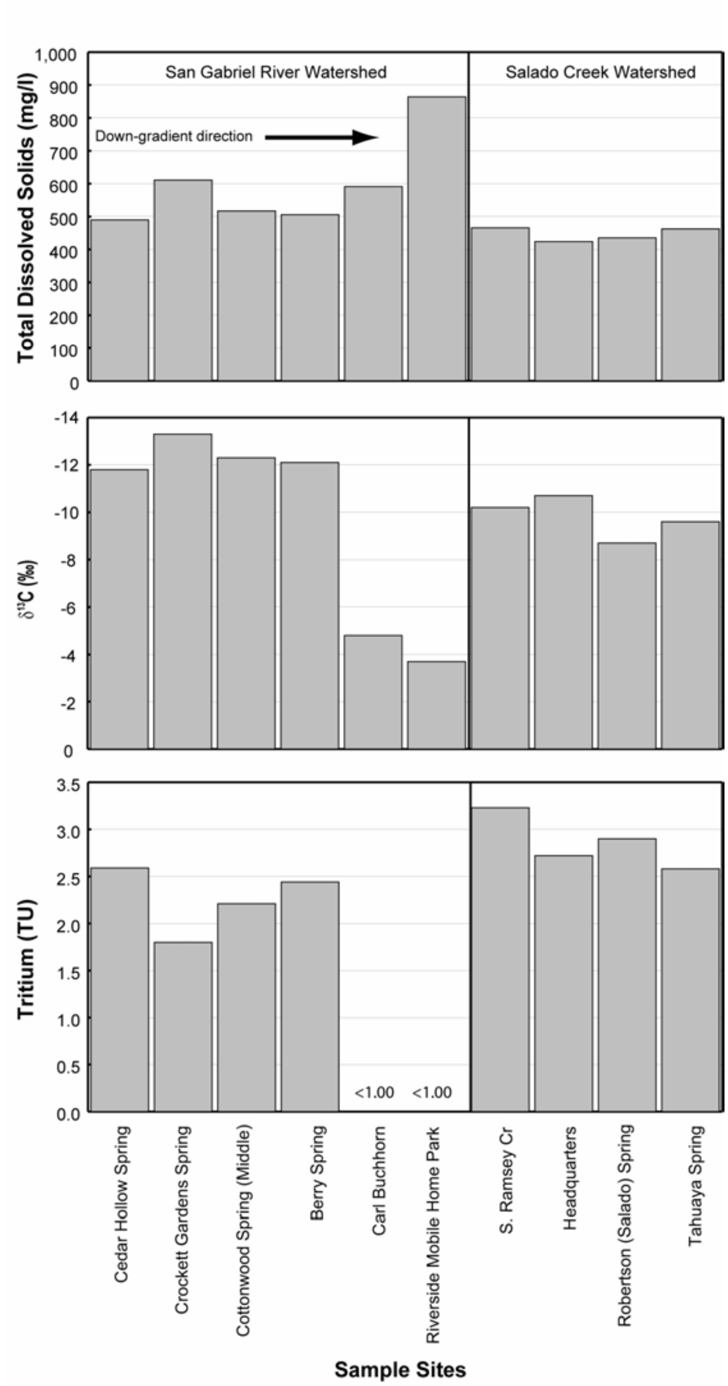

Figure 13. Bar diagrams showing changes in groundwater total dissolved solids, stable carbon isotope, and tritium compositions along flow paths.

The spatial distribution of groundwater characterized by different geochemical compositions reflects the interaction of two main flow systems in the aquifer. These flow systems involve (1) rapid circulation of fresh groundwater from the unconfined part of the aquifer and (2) a slow influx of saline groundwater from down-dip (Senger and others, 1990). The calcium-bicarbonate type water that occurs within or adjacent to the recharge zone is characterized by measurable tritium. The slowly circulating groundwater is characterized by low tritium and mixed-cation-bicarbonate, sodium-bicarbonate, and sodium-mixed-anion-type groundwater with down-dip increasing sodium and chloride concentrations (Figure 9). The contrasting low and high tritium in confined and unconfined parts of the aquifer, respectively, indicate that most groundwater circulation in the aquifer occurs in the unconfined part of the aquifer. This observation is consistent with groundwater flow modeling results which indicate that about 70 to 90 percent of groundwater circulation occurs in the unconfined part of the aquifer where recharge water is discharged as baseflow through stream beds (Jones, 2003). The boundary between low- and high-tritium groundwater coincides approximately with the bad-water line, indicating relatively little circulation of recently recharged groundwater reaching the saline parts of the aquifer. The occurrence of measurable tritium indicates young groundwater in the unconfined part of the aquifer compared to older groundwater in the confined part of the aquifer.

In addition to groundwater samples collected as part of this study, I also evaluated rainwater oxygen and hydrogen isotopic compositions from a station located in Waco, Texas, about 50 miles north of the study area. These data, from the Global Network of Isotopes in Precipitation database, were collected on a monthly basis over the period 1962 through 1986 (IAEA/WMO, 2004). The precipitation δD and $\delta^{18}O$ values lie in the range of -70 to +20 ‰ and -10 to +1 ‰, respectively. These ranges are much wider than the ranges of groundwater δD and $\delta^{18}O$ values in the study area (Figure 12). Stable isotope values of the groundwater are lower than the average precipitation value. Median monthly precipitation $\delta^{18}O$ values approach groundwater $\delta^{18}O$ values during fall and winter months rising to -4 ‰ to -2 ‰ during spring months and peaking at -2 ‰ to 0 ‰ during summer months. This suggests that the probability of recharge occurring is greatest during fall and winter months. This is surprising because highest precipitation occurs during spring months (Figure 3). However, hydrographs of streamflow in Berry Creek and Salado Creek, streams that are dominated by groundwater discharge, support the conclusion that recharge occurs primarily during fall and winter months (Figure 14). These hydrographs indicate generally rising streamflow that is attributable to recharge during fall and winter months and level or declining streamflow rates during spring and summer months.

Conclusions

1. Major element and isotopic compositions indicate young fresh groundwater in the unconfined part of northern segment of the Edwards (Balcones Fault Zone) Aquifer compared to much older groundwater in confined part of aquifer which confirm previous groundwater flow modeling results by Jones (2003) that concluded that most groundwater circulation is in the unconfined part of the aquifer with little flow entering the confined part of the aquifer.

2. Comparison of precipitation and groundwater stable hydrogen and oxygen isotopes suggests that most recharge occurs during fall and winter months.

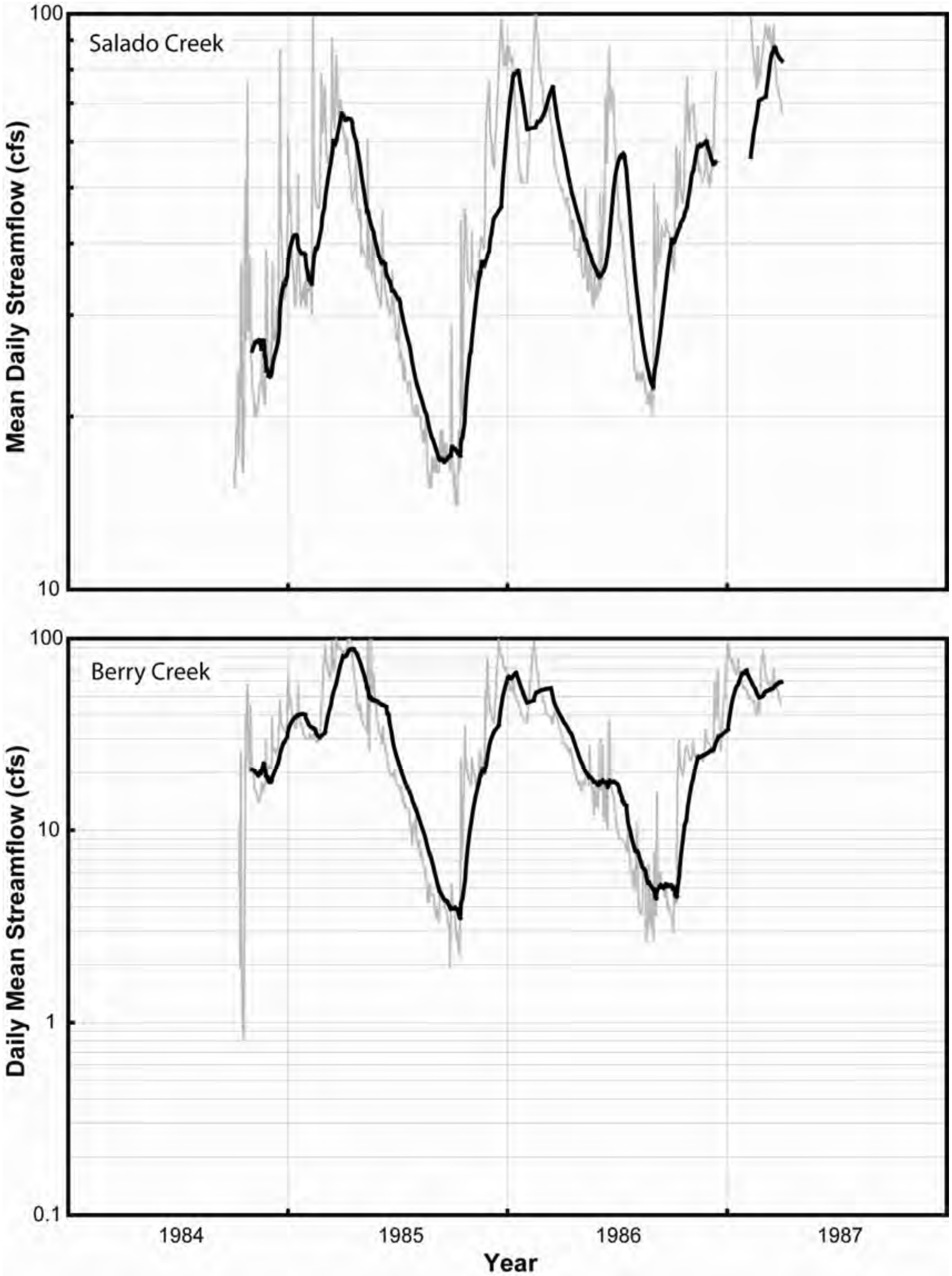

Figure 14. **Hydrographs showing mean daily streamflow in Salado and Berry creeks. The black line represents a 30-day moving average.**

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Honey Creek Cave, Glen Rose Formation (photo taken on January 21, 2006, by Kurt Menking)