Conceptual Model: Northern Segment of the Edwards (Balcones Fault Zone) and Associated Trinity Aquifers of Texas

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EXECUTIVE SUMMARY

The northern segment of the Edwards (Balcones Fault Zone) Aquifer is the part of the Edwards (Balcones Fault Zone) Aquifer located north of the Colorado River in northern Travis, central Williamson, and southern Bell counties. The aquifer is an important source of water for municipalities, industry, and landowners in central Texas. Rapid population growth in this part of Texas has increased interest in the northern segment of the Edwards (Balcones Fault Zone) Aquifer and heightened concerns about groundwater availability in the aquifer. This portion of the aquifer underlies several large cities in the region, including parts of Austin, Cedar Park, Pflugerville, Round Rock, Georgetown, Jarrell, Salado, and Belton. This report documents the development of a conceptual model of the northern segment of the Edwards (Balcones Fault Zone) Aquifer and adjacent parts of the underlying Trinity Aquifer. A conceptual model describes the hydrogeologic environment and the groundwater flow regime within a model study area. In other words, it describes a simplified representation of the hydrogeological features—hydrostratigraphy, hydraulic properties, hydrologic boundaries, recharge, and discharge—that influence groundwater flow through the aquifer. It forms the basis for a numerical groundwater flow model.

The northern segment of the Edwards (Balcones Fault Zone) Aquifer consists of the following stratigraphic units: the Comanche Peak Limestone, Edwards Limestone, and Georgetown Formation. Adjacent parts of the Trinity Aquifer are composed of the Glen Rose and Travis Peak formations. These aquifers dip—tilts downward—towards the east and are exposed at land surface (outcrops) along their western margins.

Available water-level data show that groundwater in the northern segment of the Edwards (Balcones Fault Zone) and Trinity aquifers generally flows from aquifer outcrop recharge zones towards deeper parts of the respective aquifers with most flow occurring in the aquifer outcrop. Groundwater in these aquifers naturally discharges along the major rivers and streams that cross the respective outcrops—the Colorado, San Gabriel, and Lampasas rivers, and Salado Creek—and to a lesser extent by cross-formational flow through overlying stratigraphic units.

Groundwater in the northern segment of the Edwards (Balcones Fault Zone) Aquifer is used primarily for municipal uses (87 percent), but is also used locally for manufacturing, mining, and rural domestic uses. In the Bell County portion of the aquifer, rural domestic pumpage accounts for almost a quarter of pumping from the Edwards (Balcones Fault Zone) Aquifer, while in Williamson and Travis counties there is significant pumping for mining and manufacturing, respectively.

Hydraulic property data—a measure of how easily groundwater flows through the system—for the northern segment of the Edwards (Balcones Fault Zone) Aquifer is mostly
available in the confined portion of the aquifer—the parts of the aquifer that are below land surface. The data available show significant variability in the aquifer properties resulting from structural complexity within the basin, lithologic variability, and the effects of post-depositional processes including karstification. Hydraulic conductivity values for the northern segment of the Edwards (Balcones Fault Zone) Aquifer range from less than 1 foot per day to more than 1,000 feet per day and display no apparent spatial trends.

Water quality in the northern segment of the Edwards (Balcones Fault Zone) Aquifer is generally fresh, becoming slightly saline with depth and is generally slightly fresher than groundwater in the underlying Trinity Aquifer. In the northern segment of the Edwards (Balcones Fault Zone) Aquifer, groundwater compositions range from calcium-bicarbonate compositions to calcium-magnesium-bicarbonate compositions to sodium-bicarbonate and sodium-chloride compositions with increasing depth.

Groundwater isotope compositions in the northern segment of the Edwards (Balcones Fault Zone) Aquifer indicate: (1) the relative ages of groundwater within the aquifer with implications to the spatial distribution of groundwater flow, and (2) the seasonality of recharge to the aquifer. The data suggest that: (1) the groundwater flow system in the northern segment of the Edwards (Balcones Fault Zone) Aquifer is primarily restricted to the aquifer outcrop, (2) the confined portion of the aquifer is stagnant, and (3) most recharge occurs during fall and winter months despite the fact that highest monthly precipitation occurs during the spring.

The conceptual model for the northern segment of the Edwards (Balcones Fault Zone) Aquifer and adjacent parts of the Trinity Aquifer—the basis used to construct a numerical groundwater flow model—is composed of up to three model layers simulating groundwater flow through the Edwards (Balcones Fault Zone) Aquifer, the underlying Walnut Formation confining unit and the Trinity Aquifer. A three-layer model would accommodate the processes of recharge to the aquifer outcrop(s), groundwater flow into confined parts of the northern segment of the Edwards (Balcones Fault Zone) and Trinity aquifers, groundwater flow between the Edwards (Balcones Fault Zone) and Trinity aquifers, and discharge to streams and by upward flow through overlying stratigraphic units.

1.0 INTRODUCTION
The northern segment of the Edwards (Balcones Fault Zone) Aquifer is the northern extent of the Edwards (Balcones Fault Zone) Aquifer, a major aquifer—one of nine major and 22 minor aquifers in Texas (Figures 1.0.1 and 1.0.2). The Texas Water Development Board defines a major aquifer as an aquifer that produces large amounts of water over a large area, and minor aquifers as aquifers that produce minor amounts of water over large areas
or large amounts of water over small areas (George and others, 2011). Total pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer has ranged from a high of more than 25,000 acre-feet per year to about 10,000 acre-feet per year during the period 1980 through 2015. This aquifer is important as a source of water—in addition to surface water—to provide for the needs of a rapidly growing population along the Interstate Highway 35 corridor.

This report describes the aquifer data used to develop an updated conceptual model for the northern segment of the Edwards (Balcones Fault Zone) Aquifer. This conceptual model will be the basis for the updating for the groundwater availability model for that portion of the Edwards (Balcones Fault Zone) Aquifer including the addition of the underlying Trinity Aquifer. Once the groundwater availability model is calibrated, it can be used as a quantitative tool to evaluate the effects of pumping, drought, and different water management scenarios on the groundwater flow system. This report includes descriptions of (1) the study area, (2) previous investigations of the northern segment of the Edwards (Balcones Fault Zone) Aquifer, (3) the hydrologic setting including hydrostratigraphy, geologic framework, groundwater hydrology, recharge, discharge, surface water, hydraulic properties of the rocks, and water quality, and (4) the resultant conceptual model.
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2.0 STUDY AREA
The northern segment of the Edwards (Balcones Fault Zone) Aquifer occurs at land surface (outcrop) and buried under other geologic units (subcrop) in a relatively narrow band in central Texas (Figure 2.0.1). The outcrops are located on the western side of the aquifer and it dips to the east (Figure 2.0.2). The northern segment of the Edwards (Balcones Fault Zone) Aquifer is defined as the portion of the aquifer that lies north of the Colorado River. The eastern—downdip—boundary of the aquifer is defined by the occurrence of groundwater containing total dissolved solids more than 1,000 milligrams per liter. The study area in this report includes the northern segment of the Edwards (Balcones Fault Zone) Aquifer and adjacent and underlying portions of the Trinity Aquifer (Figure 2.0.3). The Trinity Aquifer is defined as having groundwater with total dissolved solids less than 3,000 milligrams per liter.

Figure 2.0.4 shows the counties, major roadways, and cities in the study area. The northern segment of the Edwards (Balcones Fault Zone) Aquifer underlies parts of three counties—Travis, Williamson, and Bell counties. Cities overlying the northern segment of the Edwards (Balcones Fault Zone) Aquifer include Austin, Cedar Park, Pflugerville, Round Rock, Georgetown, Jarrell, Salado, and Belton. The locations of rivers, streams, lakes, and reservoirs in the study area are shown on Figure 2.0.5. The major perennial streams in the study area include the Lampasas and Colorado rivers that form the northern and southern boundaries of the aquifer, respectively, as well as the San Gabriel River and the Salado and Brushy creeks.

Figures 2.0.6 and 2.0.7 show the major and minor aquifers that occur within the study area. The major aquifers occurring in the study area are the Edwards (Balcones Fault Zone) Aquifer and the underlying Trinity Aquifer. Minor aquifers—the Marble Falls, Ellenburger-San Saba, and Hickory aquifers—mainly occur at depth in the study area although small outcrops of the Marble Falls and Ellenburger-San Saba aquifers occur along the western boundary of the study area.

The northern segment of the Edwards (Balcones Fault Zone) Aquifer underlies part of the Lower Colorado Regional Water Planning Area and the Brazos G Regional Water Planning Area (Figure 2.0.8). The aquifer also underlies parts of the Clearwater Underground Water Conservation District (Figure 2.0.9). Additionally, parts of other groundwater conservation districts—Central Texas, Lost Pines, and Post Oak groundwater conservation districts, and Saratoga Underground Water Conservation District—cover parts of the study area. The northern segment of the Edwards (Balcones Fault Zone) Aquifer lies within Groundwater Management Areas 8 (Figure 2.0.10). The northern segment of the Edwards (Balcones Fault Zone) Aquifer underlies parts of the Brazos and Lower Colorado river authorities.
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2.1 Physiography and Climate

The study area for the northern segment of the Edwards (Balcones Fault Zone) Aquifer includes parts of the Central Texas Uplift, Edwards Plateau, Blackland Prairies, and Interior Coastal Plains physiographic provinces (Wermund, 1996; Figure 2.1.1). The Central Texas Uplift occurs along the western margin of the study area. It is made up of Precambrian intrusive and early Paleozoic sedimentary rocks that form a rolling landscape with hills up to 600 feet high (Wermund, 1996). The Edwards Plateau physiographic province includes the Jollyville Plateau and Lampasas Cutplains (Senger and others, 1990). The Jollyville Plateau has been separated from the Hill Country by erosion that resulted in the formation of the Colorado River valley. The Hill Country and Jollyville Plateau are characterized by highly dissected canyonland, while the Lampasas Cutplains is characterized by gently rolling terrain. The Blackland Prairie occurs where limestones are overlain by younger alluvial units that occur along the margin of the Interior Coastal Plains (Senger and others, 1990). The most prominent topographic feature is the Balcones Escarpment, a product of normal faulting in this region. This escarpment forms the boundary between the Jollyville...
Plateau and Hill Country parts of the Edwards Plateau and the Blackland Prairie (Trippet and Garner, 1976). This boundary becomes more subdued to the north in the Lampasas Cutplains. The Interior Coastal Plains, along with the Blackland Prairie are subprovinces of the Gulf Coastal Plains. The Interior Coastal Plains is made up of alternating belts of resistant uncemented sands and weaker shales that erode forming long, sandy ridges.

The northern segment of the Edwards (Balcones Fault Zone) Aquifer is located among the Cross Timbers, Edwards Plateau, and Blackland Prairies Level III ecological regions (United States Environmental Protection Agency, 2013; 2017; Figure 2.1.2). A small portion of the East Central Texas Plains Level III ecological region is also located along the eastern boundary of the study area. A wide variety of plant and animal life can be found in the study area.

The Cross Timbers ecoregion is a transition area between the formerly prairie regions to the west, and the forested hills to the east (United States Environmental Protection Agency, 2013; 2017). Rainfall is highly variable, ranging from 25 inches in the west to 35 inches in the east (Texas Parks and Wildlife Department, 2017). The predominant land cover in this ecoregion is rangeland and pastureland, with some areas of woodland, primarily in the east. The native vegetation includes various types of grass—little and big bluestem and indiangrass—with alternating bands of trees—Texas mulberry, American elm, live oak and post oak trees.

The Edwards Plateau ecoregion is largely a dissected limestone plateau that is hillier in the south and east where it is easily distinguished from bordering ecological regions by sharp fault lines (United States Environmental Protection Agency, 2013; 2017; Texas Parks and Wildlife Department, 2017). This semiarid region contains a sparse network of perennial streams. Originally covered by juniper-oak savanna and mesquite-oak savanna.

The Texas Blackland Prairies form an ecological region, distinguished from surrounding regions by its fine-textured, clayey soils and predominantly prairie natural vegetation (United States Environmental Protection Agency, 2013; 2017; Texas Parks and Wildlife Department, 2017). This ecoregion includes scattered woodlands made up of pecan, cedar elm, oak, and hackberry trees, with some mesquite. The predominant natural vegetation is grasses—little bluestem grass with lesser amounts of big bluestem, indiangrass, eastern gamagrass, switchgrass, and side oats grama. However, this ecoregion is now almost entirely cultivated.

Figure 2.1.3 is a topographic map of the study area (Gesch and others, 2002). Land-surface elevation is greatest—up to 1,600 feet above mean sea level—along the western margin of the study area and generally decreases to the east to elevations of 200 to 400 feet above mean sea level.
The study area includes three climatic divisions, the Edwards Plateau, North Central, and South Central divisions (Figure 2.1.4). The Climate divisions represent regions with similar characteristics such as vegetation, temperature, humidity, rainfall, and seasonal weather changes. Climate data collected at locations throughout the state are averaged within each of the divisions. These divisions are commonly used to assess climate characteristics across the state (NCDC, 2011). In the study area, the climate is generally subtropical and subhumid to semi-arid. The Edwards Plateau division is characterized by subtropical steppe or semi-arid brushland and savanna. The North Central division is subtropical subhumid mixed savanna and woodlands, and the South Central division is subtropical subhumid mixed prairie, savanna, and woodlands.

The average annual maximum air temperature in the study area ranges from about 77 degrees Fahrenheit in Burnet County to about 79 degrees Fahrenheit in central Williamson County (Figure 2.1.5). Figure 2.1.6 shows average annual precipitation for the period 1981 through 2010 (NCDC, 2020). The annual average precipitation generally increases from west to east across the study area, from a high of 34 to 37 inches per year in eastern Bell, Travis and Williamson counties to a low of 31 to 32 inches per year in northern Burnet County.

Precipitation data are available at four stations within the study area—Camp Mabry, Jarrell, Stillhouse Hollow Dam, and Taylor (Figure 2.1.7). Annual precipitation data recorded at these stations over the period 1930 through 2016 is shown in Figure 2.1.8. Figure 2.1.8 indicates wide interannual variation of precipitation, ranging from lows of about 11 inches to highs of 60 inches per year. Figure 2.1.9 shows monthly precipitation for the four stations averaged over the period 1986 through 2016. In the study area, highest monthly precipitation—exceeding 4 inches—occurs in May. Most precipitation occurs during spring and fall months—April through June and September through December—with least precipitation occurring in July and August. Median monthly precipitation at Camp Mabry is more evenly distributed than at the other stations with more precipitation during the dry summer months and less during the fall months.

The average annual lake evaporation rate in the study area ranges from a high of 59 inches per year to a low of 53 inches per year (Figure 2.1.10; Narasimhan and others, 2005). Average annual lake evaporation is generally lowest in the central and extreme southern parts of the study area, increasing to the west. Lake evaporation rates significantly exceed the annual average precipitation. Monthly variations in lake surface evaporation are shown for two locations in the study area (Figure 2.1.11; Narasimhan and others, 2005). These values represent the average of the monthly lake surface evaporation data from 1971 through 2000. Figure 2.1.11 shows that average lake evaporation peaks in July and August, the driest months in this region.
Figure 2.1.1. Physiographic provinces in the study area (Wermund, 1996).
Figure 2.1.2. Level III ecological regions in the study area (United States Environmental Protection Agency, 2013).
Figure 2.1.3. Topographic map of the study area showing land surface elevation in feet above mean sea level. Based on data from Gesch and others (2002).
Figure 2.1.4. Climate divisions in the study area (modified from NCDC, 2011).
Figure 2.1.5. Average annual air temperature in degrees Fahrenheit in the study area. Based on 1981 to 2010 data (NCDC, 2020).
Figure 2.1.6. Average annual precipitation in inches per year in the study area for the time period 1981 through 2010 (NCDC, 2020).
Figure 2.1.7. Location of precipitation gages in the northern segment of the Edwards (Balcones Fault Zone) Aquifer study area (National Climatic Data Center, 2017).
Figure 2.1.8. Selected time series of annual precipitation in inches per year in the study area (National Climatic Data Center, 2017). Zero values indicate missing data.
Figure 2.1.9. Selected time series of median monthly precipitation in inches per month in the study area for the time period 1986 through 2016 (National Climatic Data Center, 2017).
Figure 2.1.10. Average annual lake evaporation rate in inches per year in the study area for the time period 1941 through 2000 (Narasimhan and others, 2005).
Figure 2.1.11. Average monthly lake surface evaporation in inches in selected weather stations in the study area (Narasimhan and others, 2005).
2.2 Geology
This section provides a brief discussion of the geology of the study area. The discussion is divided into the structural setting, surface geology, and stratigraphy of the northern segment of the Edwards (Balcones Fault Zone) and Trinity aquifers, including a description of geologic structural cross-sections through the study area.

2.2.1 Structural Setting
In the study area, Cretaceous rock units overlie Paleozoic rock units, forming an angular unconformity (Brune and Duffin, 1983), where eastward-dipping Cretaceous rock was deposited on an erosional surface over steeply westward-dipping Paleozoic rock. The Cretaceous rocks that make up the Trinity and Edwards (Balcones Fault Zone) aquifers dip toward the southeast with a slope of 10 to 300 feet per mile. Generally, the dip angle increases with depth (Duffin and Musick, 1991). This dip angle excludes the effects of faulting.

The aquifers in the study area are the Edwards (Balcones Fault Zone) Aquifer that extends from Bell County in the north, south and west to central Kinney County, and the southernmost extent of the northern Trinity Aquifer (Figure 2.2.1). The occurrence of the Edwards (Balcones Fault Zone) Aquifer coincides approximately with the normally faulted Balcones Fault Zone where it cuts through Cretaceous age rocks (Figure 2.2.2). Normal faults occur where tensional stress pulls rocks apart. This results in two blocks, where—in this case—the block east of the fault slides down relative to the western block. The faulting and associated fracturing influence groundwater movement in the limestone rocks thus forming the aquifer (Kreitler and others, 1987; Senger and others, 1990). The normal faulting of the Balcones Fault Zone also cuts through the Trinity Aquifer where it underlies the Edwards (Balcones Fault Zone) Aquifer.

Faults and fractures play a very important role in local and regional groundwater flow patterns within the study area. Karstification of the fractures within the Cretaceous carbonates that make up the aquifers in the study area has produced highly permeable pathways for groundwater flow. In the northern segment of the Edwards (Balcones Fault Zone) Aquifer, the faulting appears to more intense in the south becoming more diffuse to the north (Figure 2.2.3; Senger and others, 1990). Major faults are generally oriented north-south to northeast-southwest and dip or tilt towards the east, although some dip to the west. In the southern part of the study area, the Balcones Fault Zone is generally composed of one large fault—the Mount Bonnell Fault—that with vertical displacement of 715 feet is much larger than any of the adjacent faults that mostly have displacements less than 50 feet (Trippet and Garner, 1976; Senger and others, 1990; Figure 2.2.3). To the north, maximum fault displacement decreases to about 150 feet (Senger and others, 1990). The Trinity Aquifer overlies and is likely unaffected by the Paleozoic faults that are apparent immediately outside of the study area in western Burnet County (Figure 2.2.3).
The unconfined portion of the northern segment of the Edwards (Balcones Fault Zone) Aquifer is wider in Williamson County than in Travis County, near the Colorado River (Figure 2.0.2). The narrowing of the aquifer outcrop in the south occurs due to the combined effects of intense faulting and erosion by the Colorado River and its tributaries (Figures 2.1.3 and 2.2.3; Baker and others, 1986). Fracturing also enhances the porosity of the limestone and plays a role in the development of karst features, such as caves, springs, and conduits. Normal faulting, common in the 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 6 to 8 miles wide that extends roughly from Del Rio in south-central Texas to Dallas (Figure 2.2.2). This zone of normal faulting 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). In the Balcones Fault Zone, minor faults and joints occur mainly adjacent to the major faults and flexures. These minor faults, characterized by displacement of less than 6 feet, tend to form fracture zones up to 1 mile wide. Fracture densities in these zones lie in the range of 6 to 120 joints per 100 feet. Many of these minor faults are filled partly by calcite. However, the joints that occur in this area do not have mineral fillings, and abutting relationships suggest that the minor faults formed before the joints (Collins, 1987). Fracture apertures vary with stratigraphic units in the Edwards (Balcones Fault Zone) Aquifer. Fracture apertures are generally less than 0.04 inches in Comanche Peak and Georgetown Formations and are up to several inches wide in the Edwards Limestone (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). Inner Space Caverns in Georgetown, Texas is an example of a cave formed in the Edwards Limestone.

Evaluation of fracture and lineament orientations in the northern part of the study area at different scales by Dahl (1990) shows different orientations of fractures varying in size from mapped major faults to field-observed fractures. The orientations of these fractures play a role in determining preferential flow directions in the aquifer. Preferential flow directions are generally parallel to fracture orientation. Dahl (1990) divided fractures into four groups: major mapped faults, high-altitude Landsat lineaments, field fractures, and topographic map lineaments. Major faults generally trend northeast-southwest. High-altitude Landsat lineaments are sparsely distributed and, together with the field fractures, are preferentially oriented northwest-southeast and northeast-southwest. The topographic map lineaments are generally randomly oriented, with only a slight northeast-southwest trend (Dahl, 1990). Adjacent to major faults, fractures are oriented generally northeast-
southwest, approximately parallel to major faults of the Balcones Fault Zone. Away from major faults, fractures are oriented generally northwest-southeast. This trend of northwest-southeast- and northeast-southwest-oriented fractures is also observed in the more intensely faulted parts of the aquifer farther south (Kreitler and others, 1987).

### 2.2.2 Surface Geology

Stratigraphic units underlying the study area range in age from the Paleozoic Ellenburger Group to recent alluvium (Brune and Duffin, 1983). Stratigraphic units in the study area are composed mainly of limestone and shale or clay. The oldest rock units, the Ordovician Ellenburger Group and the Pennsylvanian Bend and Strawn groups, occur at great depth and are not known to yield usable water in the study area (Brune and Duffin, 1983).

Figure 2.2.4 is a simplified geologic map of the study area. Over most of the study area, the predominant surficial deposits are Cretaceous-age rocks of the Trinity, Fredericksburg, and Washita groups, the Eagle Ford Formation, Austin Chalk, and Navarro Group. The Cretaceous stratigraphic units all dip towards the east and are eventually overlain by younger units (Figure 2.2.5). These Cretaceous units are approximately 2,000 feet thick (Trippet and Garner, 1976). Tertiary and Quaternary alluvium primarily occurs along stream channels, especially east of the footprint of the northern segment of the Edwards (Balcones Fault Zone) Aquifer.

### 2.2.3 Stratigraphy

The northern segment of the Edwards (Balcones Fault Zone) Aquifer is composed of stratigraphic units within the Fredericksburg, and Washita Groups that overlie the Cretaceous Trinity Group that makes up the Trinity Aquifer (Figure 2.2.6). These units mainly consist of the Georgetown Formation, Edwards Limestone, and Comanche Peak Limestone. The Walnut Formation acts as a semi-confining unit separating the Edwards (Balcones Fault Zone) and Trinity aquifers (see Section 4.1). The Trinity Group is divided into the Travis Peak, Glen Rose, and Paluxy Formations (Brune and Duffin, 1983). The Travis Peak Formation consists primarily of limestone, sand, and shale and is subdivided into Hosston, Sligo, Hammett Shale, Cow Creek Limestone, and Hensell Sand members. 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 and is subdivided into upper and lower members. The Paluxy Formation is composed of fine quartz sand cemented with calcium carbonate. Please note that the Paluxy Formation pinches out in northern Bell County and does not occur in the study area.

The Fredericksburg Group is divided into the Walnut Formation, Comanche Peak Limestone, and Edwards Limestone (Brune and Duffin, 1983). The Walnut and Comanche Peak Formations, which occur primarily in the subsurface in the northern part of the study area, are composed of fine-grained limestone and shale. The Edwards Limestone is
composed of massive vuggy—filled with small cavities—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 (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).

The stratigraphic nomenclature of units that compose the Edwards (Balcones Fault Zone) Aquifer differs north and south of the Colorado River. South of the river, the “Edwards” is treated as a group composed of two formations, the Kainer and Person Formations (Rose, 1972). The Kainer Formation is equivalent to the Walnut Formation, Comanche Peak Limestone, and lower parts of the Edwards Limestone. Equivalents of the Person Formation are largely absent north of the Colorado River. North of the Colorado River, the uppermost parts of the Edwards Limestone are equivalent to the basal members of the Person Formation.
Figure 2.2.1. The Edwards (Balcones Fault Zone) and Trinity aquifers. The study area includes the northern segment of the Edwards (Balcones Fault Zone) Aquifer and the southern extent of the northern part of the Trinity Aquifer.
Figure 2.2.2. Major structural features in the study area (from Senger and others, 1990).
Figure 2.2.3. Faults that cut through or lie adjacent to the study area.
Figure 2.2.4. Generalized surface geology in the study area.
Figure 2.2.5. Generalized cross-section through the northern segment of the Edwards (Balcones Fault Zone) and underlying Trinity aquifers (modified from Jones, 2003).
Figure 2.2.6. Generalized stratigraphic column for the northern segment of the Edwards (Balcones Fault Zone) Aquifer and overlying and underlying formations.

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<thead>
<tr>
<th>Series</th>
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<td>Comanche</td>
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<td>Washita</td>
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<td>Comanche Peak Limestone</td>
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<td>Walnut Formation</td>
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<td>Paluxy Formation</td>
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<td>Upper Member</td>
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<td>Lower Member</td>
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<td>Hensell Sand Member</td>
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<td>Hosston Member</td>
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3.0 PREVIOUS WORK

Many geologic and hydrogeologic reports include the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Studies of the stratigraphy and structure of the area include Tucker (1962), Rose (1972), Proctor and others (1974), Collins (1987), Land and Dorsey (1988), and Collins and others (2002). Woodruff and others (1985), and Yelderman and others (1987) are compendia that provide information on different aspects of the hydrogeology of the aquifers in the study area, such as water supply development, transmissivity distribution, and pump-test analysis. More detailed hydrogeologic studies include Klemt and others (1975), Brune and Duffin (1983), Kastning (1983), Senger and Kreitler (1984), Woodruff and others (1985), Baker and others (1986), Kreitler and others (1987), Dahl (1990), Flores (1990), Senger and others (1990), Duffin and Musick (1991),

Several regional and sub-regional models have simulated groundwater flow in the San Antonio and Barton Springs segments of the Edwards (Balcones Fault Zone) Aquifer (Campana, 1975; Knowles and Klemt, 1978; Mahin, 1978; Klemt and others, 1979; Mahin and Campana, 1983; Slade and others, 1985; Slade, 1987; Maclay and Land, 1988; Thorkildsen and McElhaney, 1992; Kuniansky, 1993; Kuniansky and Holligan, 1994; Barrett, 1996; Uliana and Sharp, 1996; Scanlon and others, 2001; Lindgren and others, 2004; Brakefield and others, 2015; Fratesi and others, 2015). There have been four regional models simulating groundwater flow through all or parts of the northern Trinity Aquifer (Morton, 1992; Dutton and others, 1996; Harden and others, 2004; Kelley and others, 2014).

This report is part of work being conducted to update a groundwater availability model of the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Jones, 2003; Figure 3.0.1). The 2003 groundwater flow model is a one-layer model run using MODFLOW-96 and assuming no interaction with the underlying Trinity Aquifer. The updated model will use up-to-date versions of MODFLOW, include interaction with the underlying Trinity Aquifer, and extend the calibration period to more recent times.
Figure 3.0.1. Approximate extents of previous model grid for models used for simulating groundwater flow through the northern segment of the Edwards (Balcones Fault Zone) Aquifer.
4.0 HYDROLOGIC SETTING

The hydrologic setting is a description of the factors that contribute to the groundwater hydrology of the northern segment of the Edwards (Balcones Fault Zone) Aquifer. These factors include the hydrostratigraphy, hydrogeologic framework, water levels and regional groundwater flow, recharge, surface-water bodies, hydraulic properties, discharge, and water quality.

4.1 Hydrostratigraphy and Hydrostratigraphic Framework

The northern segment of the Edwards (Balcones Fault Zone) Aquifer (Figure 2.0.2) generally consists of the Comanche Peak Limestone, Edwards Limestone, and Georgetown Formation (Figure 4.1.1). 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 and Glen Rose formations and is overlain by younger units that consist of the Del Rio Clay, Buda Limestone, Austin Chalk, Taylor Marl, and Navarro Group. 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, although in other areas the Walnut Formation is composed of potentially permeable shell beds and may thus be included in the Edwards (Balcones Fault Zone) Aquifer.

4.1.1 Edwards (Balcones Fault Zone) Aquifer

The top of the northern segment of the Edwards (Balcones Fault Zone) Aquifer has elevations ranging from 400 feet below mean sea level to more than 1,000 feet above mean sea level (Figure 4.1.2). The subsurface top of the northern segment of the Edwards (Balcones Fault Zone) Aquifer is a combination of structural tops and erosional surfaces. Figure 4.1.3 shows the base elevations of the northern segment of the Edwards (Balcones Fault Zone) Aquifer that decrease towards the east, ranging from elevations of about 800 feet below mean sea level in the east to about 1,000 feet above mean sea level in the west. The northern segment of the Edwards (Balcones Fault Zone) Aquifer dips to the east at an average slope of 60 to 75 feet per mile (Figure 4.1.2 and 4.1.3). The slope varies generally because of faulting that produces a stair-step configuration downdip (Baker and others, 1986). The northern segment of the Edwards (Balcones Fault Zone) Aquifer thickness is highly variable, mostly ranging from 100 to 300 feet thick (Figure 4.1.4). In the study area, the northern segment of the Edwards (Balcones Fault Zone) Aquifer could be less than 100 feet thick due to erosion along some streams where the aquifer is exposed at land surface. Figures 4.1.2 and 4.1.3 indicate that the northern segment of the Edwards (Balcones Fault Zone) Aquifer dips to the east with highest elevations associated with outcrops along the western margin of the aquifer.
The Comanche Peak Limestone is composed of nodular and fossiliferous marly limestone (Figure 4.1.1). This stratigraphic unit is characterized by considerable jointing (Brune and Duffin, 1983). The Edwards Limestone is composed of up to 200 feet of highly fractured and thickly bedded to massive limestone or dolomite, with minor shale, clay, and siliceous limestone (Senger and others, 1990). The Edwards Limestone is vuggy in places because of the occurrence of solution-collapse zones (Brune and Duffin, 1983). These zones, parallel to bedding planes, are the result of dissolution of gypsum beds that formerly occurred in this stratigraphic unit. They are cavernous and iron stained, and contain brecciated limestone, chert, crystalline calcite, and residual clay. These zones occur mainly 60 to 80 feet above the base of the Edwards Limestone (Brune and Duffin, 1983; Flores, 1990). These solution-collapse zones—as much as 20 feet thick—are the main water-bearing horizons in the aquifer, with well yields greater than 300 gallons per minute (Brune and Duffin, 1983; Flores, 1990). The Georgetown Formation is a massive nodular limestone that is often hydrologically connected to the underlying Edwards Limestone (Brune and Duffin, 1983).

In addition to solution-collapse zones, groundwater in the northern segment of the Edwards (Balcones Fault Zone) Aquifer flows through a network of steeply dipping faults and joints (Brune and Duffin, 1983). Field measurements indicate that effective porosity is greatest in the Comanche Peak Limestone and decreases in the overlying Edwards Limestone and Georgetown Formation (Dahl, 1990; Flores, 1990). This trend has been attributed to limestone in the Comanche Peak Limestone and Edwards Limestone being more brittle than that in the Georgetown Formation. Additionally, the lower units of the Edwards (Balcones Fault Zone) Aquifer display greater effects of karstification (Dahl, 1990; Flores, 1990). Fracture porosity of the northern segment of the Edwards (Balcones Fault Zone) Aquifer ranges from 0.4 to 2.5 percent away from major faults, to 1.5 to 4.25 percent adjacent to faults (Dahl, 1990). These porosity values are lower than porosities (4 to 42 percent) measured in the San Antonio segment of the Edwards (Balcones Fault Zone) Aquifer (Hovorka and others, 1996).

### 4.1.2 Walnut Formation Confining Unit

The Walnut Formation occurs at the base of the Fredericksburg Group separating the Edwards (Balcones Fault Zone) and Trinity aquifers (Figure 4.1.1). It is a confining unit that yields little to no water (Brune and Duffin, 1983). The Walnut Formation is composed of alternating beds of hard and soft marly limestone with occasional shale and shell beds (Brune and Duffin, 1983). In the study area, the top of the Walnut Formation is defined by land surface in the west where it crops out or the base of the Edwards (Balcones Fault Zone) in the east where it occurs in the subsurface (Figure 4.1.5). The base of the Walnut Formation coincides with the top of the underlying Trinity Aquifer (Figure 4.1.6). The Walnut Formation is generally less than 300 feet in subcrop and less than 100 feet in outcrop due to erosion (Figure 4.1.7).
4.1.3 Trinity Aquifer

Like the overlying Edwards (Balcones Fault Zone) Aquifer, the Trinity Aquifer stratigraphic units dip towards the east and southeast, cropping out west of the Edwards (Balcones Fault Zone) Aquifer outcrop (Figures 4.1.8 and 4.1.9). The Trinity Aquifer thickness increases down-dip from as little as 40 feet along stream channels in the outcrop to more than 2,000 feet down-dip (Figure 4.1.10). The Trinity Aquifer is subdivided into three hydrostratigraphic units, the Upper, Middle, and Lower Trinity Aquifer (Figure 4.1.1).

In the study area, the members of the Travis Peak Formation—the Hosston, Sligo, Hammett Shale, Cow Creek Limestone, and Hensell Sand—make up the Lower Trinity and most of the Middle Trinity Aquifer. Total thickness of the Lower Trinity Aquifer—the combined thickness of the Hosston and Sligo members of the Travis Peak Formation—ranges up to 1,000 feet in southeastern Travis county (Brune and Duffin, 1983). The Hosston member is composed of poorly-sorted, basal, sandy conglomerate grading upward into a sand, siltstone, and shale mixture with some limestone beds. The Sligo member is composed of limestone and dolomite with some sand and shale. The Hosston and Sligo members thicken down-dip with the Sligo pinching out in western Travis County.

The Hammett Shale member of the Travis Peak Formation acts as a confining unit separating the Lower and Middle Trinity aquifers. The Hammett shale is composed of relatively uniformly thick—about 60 feet—shale with some dolomitic limestone (Brune and Duffin, 1983).

The Middle Trinity Aquifer is made up of the uppermost members of the Travis Peak Formation—the Cow Creek Limestone and Hensell Sand members—and the lower member of the Glen Rose Formation. In the study area, the thickness of the Middle Trinity Aquifer varies between 300 and 450 feet (Brune and Duffin, 1983). The Cow Creek Limestone member is made up of occasionally vuggy and fractured massive, dolomitic, fossiliferous limestone that includes some gypsum or anhydrite beds. The Hensell Sand member is made up of poorly-sorted, basal conglomerate grading upwards and downdip to sand and sandstone, then silt and sandy shale. In southeastern Travis County, the Hensell Sand member also grades into sandy limestone and dolomite. The lower member of the Glen Rose Formation consists of massive fossiliferous limestone and dolomite grading upward into thin beds of limestone, shale, marl, anhydrite and gypsum. Dissolution of the anhydrite and gypsum results in the development of dissolution cavities. The top of the lower member is marked by the “Corbula bed”, a 1-foot thick accumulation of *Corbula martinae* clam fossils.

The Upper Trinity Aquifer is composed of the upper member of the Glen Rose Formation and the Paluxy Formation. The Upper Trinity Aquifer thickness in the subsurface increases down-dip ranging from about 200 feet to 600 feet. The upper member of the Glen Rose
Formation is made up of layers of shale and marl alternating with layers of limestone and dolomite. Beds of gypsum and anhydrite also occur, but only in the subsurface. The occurrence of the Paluxy Formation, which is made up of fine-grained, compact, white quartz sand, is limited to small areas north of the study area. This formation is approximately 10 feet thick (Brune and Duffin, 1983).

![Hydrostratigraphic chart for down-dip portion of the northern segment of the Edwards (Balcones Fault Zone) Aquifer and overlying and underlying formations](modified from Brune and Duffin, 1983).

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Figure 4.1.1. Hydrostratigraphic chart for down-dip portion of the northern segment of the Edwards (Balcones Fault Zone) Aquifer and overlying and underlying formations (modified from Brune and Duffin, 1983).
Figure 4.1.2. The elevation (in feet above mean sea level) of the top of the northern segment of the Edwards (Balcones Fault Zone) Aquifer.
Figure 4.1.3. The elevation (in feet above mean sea level) of the base of the northern segment of the Edwards (Balcones Fault Zone) Aquifer (based on data from Collins and others, 2002).
Figure 4.1.4. Thickness (in feet) of the northern segment of the Edwards (Balcones Fault Zone) Aquifer.
Figure 4.1.5. The elevation (in feet above mean sea level) of the top of the Walnut Formation confining unit.
Figure 4.1.6. The elevation (in feet above mean sea level) of the base of the Walnut Formation confining unit.
Figure 4.1.7. Thickness (in feet) of the northern segment of the Walnut Formation confining unit.
Figure 4.1.8. The elevation (in feet above mean sea level) of the top of the Trinity Aquifer (based data from Kelley and others, 2014). The top of the Trinity Aquifer coincides with land surface or the base of the overlying Walnut Formation.
Figure 4.1.9. The elevation (in feet above mean sea level) of the base of the Trinity Aquifer (based on data from Kelley and others, 2014).
4.2 Water Levels and Regional Groundwater Flow

The Texas Water Development Board groundwater database contains over 18,000 water-level measurements from about 580 wells in the northern segment of the Edwards (Balcones Fault Zone) Aquifer taken between 1935 and 2016 (Figure 4.2.1; Texas Water Development Board, 2017a). Figure 4.2.2 shows the temporal distribution of water-level data in the northern segment of the Edwards (Balcones Fault Zone) Aquifer from 1980 through 2016. In the study area, the Texas Water Development Board groundwater database also contains 4,340 water-level measurements from about 430 wells in the underlying Trinity Aquifer adjacent to the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Figure 4.2.3; Texas Water Development Board, 2017a).

In the northern segment of the Edwards (Balcones Fault Zone) Aquifer, the potentiometric surface slopes generally toward the east (Figure 4.2.4). An eastward sloping potentiometric surface is also observed in the underlying Trinity Aquifer (Figure 4.2.5). Hydraulic gradients in the aquifer decrease east of the main faults of the Balcones Fault Zone (Senger...
and others, 1990). Intense fracturing in the Balcones Fault Zone suggests that the aquifer is anisotropic because of preferential flow through the generally northeast-southwest-oriented fractures (Baker and others, 1986; Duffin and Musick, 1991). Groundwater flow along fractures is partially responsible for the southward flow towards the Colorado River in the southern part of the study area, where fracturing is most intense (Figures 2.2.2 and 4.2.6). 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 central and northern parts of the study area, groundwater flows west to east with tendencies to converge on the major rivers and streams—Brushy Creek, San Gabriel River and Salado Creek (Figure 4.2.6). Groundwater flow convergence on major rivers is also apparent in the Trinity Aquifer, especially towards the Salado Creek and Colorado, San Gabriel, and Lampasas rivers (Figure 4.2.7).

In the unconfined part of the northern segment of the Edwards (Balcones Fault Zone) Aquifer, the water table occurs generally less than 100 feet below land surface and approaches land surface along incised streams (Senger and others, 1990). In the confined part of the aquifer, water levels approach or in some cases exceed land surface, resulting in flowing wells. Water-level fluctuations observed in this aquifer (Figures 4.2.8 through 4.2.11) are responses to changes in recharge and discharge rates associated with rapid recharge during wet periods (Baker and others, 1986). These seasonal fluctuations are most apparent in wells with frequent water-level measurements, for example, wells 58-27-305 and 58-35-811 (Figures 4.2.10 and 4.2.11). Baker and others (1986) reports relatively small water-level fluctuations adjacent to the Colorado River because of the stabilizing effect of adjacent Lake Austin and Lady Bird Lake. Water-level declines have been observed during severe drought periods, such as the mid-1950s, 1983-84, and 1996 (Ridgeway and Petrini, 1999). A few available hydrographs indicate effects of pumping resulting in gradual long-term water-level decline, for example, Well 58-20-102 in Williamson County (Figure 4.2.11). Most hydrographs indicate a general balance between recharge and discharge in the aquifer, in other words, water levels fluctuate with no long-term water-level decline (Baker and others, 1986; Dahl, 1990; Duffin and Musick, 1991; Ridgeway and Petrini, 1999).

Locally, hydrographs in the unconfined part of the northern segment of the Edwards (Balcones Fault Zone) Aquifer show generally synchronous water-level variations at many locations and a close correlation between precipitation and water-level variation (Senger and others, 1990). Rapid water-level rises coincide with major rainfall events, especially during late spring and fall. The rate of water-level decline depends on the amount of recharge occurring during the recession period and the amount of nearby pumping (Senger
Continued rainfall tends to retard water-level declines, whereas pumping results in accelerated water-level declines. Hydrographs for wells in the confined part of the aquifer indicate a lag between major recharge events and water-level responses (Senger and others, 1990). According to Senger and others (1990), reversal of hydraulic gradients in some parts of the aquifer (Well 58-27-305; Figure 4.2.11), partly related to increased pumping, has been observed during drought periods. This reversal suggests a potential for the influx of saline groundwater from depth. However, large, persistent cones of depression that could potentially produce this influx of saline groundwater have not been identified (Senger and others, 1990).

On a longer-term scale, water-level variability over time varies across the study area. Edwards (Balcones Fault Zone) Aquifer wells with multiple years of water-level data were used to investigate water-level fluctuations over the period 1960 through 2016 (Figures 4.2.8 through 4.2.11). In Bell County, water-level fluctuations were generally minimal (Figure 4.2.9), while in the southernmost part of the study area—Travis County—water-level fluctuations of up to 200 feet can be observed in some wells (Figure 4.2.10). In most cases, groundwater hydrographs in Williamson County indicate water-level fluctuation around an average water level (Figure 4.2.11). The exception is well 58-20-102 which indicates gradual water-level decline since the mid-1970s, probably due to pumping.

Hydrographs in Trinity Aquifer wells in the study area indicate historic water-level decline that is often linear (Figure 4.2.12). Water levels in the northern segment of the Edwards (Balcones Fault Zone) Aquifer were compared to water levels in nearby wells in the underlying Trinity Aquifer. The paired Edwards (Balcones Fault Zone) and Trinity aquifer wells were located less than one mile from each other. This water-level comparison was conducted at six locations in the study area (Figure 4.2.13). Figure 4.2.14 indicates that in more down-dip portions of the Edwards (Balcones Fault Zone) Aquifer, water levels approach those in the Trinity Aquifer. While further up-dip, the differences between water levels in the Edwards (Balcones Fault Zone) and Trinity aquifers increase with higher water levels in the Edwards (Balcones Fault Zone) Aquifer.
Figure 4.2.1. Water-level measurement locations for the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Texas Water Development Board, 2017a).
Figure 4.2.2. Temporal distribution of water-level measurements for 1980 to 2016 in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Texas Water Development Board, 2017a).
Figure 4.2.3. Water-level measurement locations for the Trinity Aquifer (Texas Water Development Board, 2017a).
Figure 4.2.4. Maximum water-level elevations (in feet above mean sea level) for wells completed in the northern segment of the Edwards (Balcones Fault Zone) Aquifer. This is based on water-level measurements mostly collected over the period 1980 to 2018 (Texas Water Development Board, 2017a).
Figure 4.2.5. Maximum water-level elevations (in feet above mean sea level) for wells completed in the Trinity Aquifer. This is based on water-level measurements mostly collected over the period 1980 to 2018 (Texas Water Development Board, 2017a).
Figure 4.2.6. Simulated water levels for 1980 in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (from Jones, 2003). Groundwater generally flows from west to east, converging on the Salado Creek in the north, San Gabriel River in the center and Colorado River in the south.
Figure 4.2.7. Maximum water levels for the Trinity Aquifer. This is based on water-level measurements mostly collected over the period 1980 to 2018 (Texas Water Development Board, 2017a). Groundwater generally flows from west to east, converging on the Salado Creek in the north and Colorado River in the south.
Figure 4.2.8. Locations of selected northern segment of the Edwards (Balcones Fault Zone) and Trinity aquifers wells with transient water-level data (Texas Water Development Board, 2017a; United States Geological Survey, 2017a).
Figure 4.2.9. Hydrographs of transient water-level data (in feet above mean sea level) for the selected northern segment of the Edwards (Balcones Fault Zone) Aquifer wells in Bell County (Texas Water Development Board, 2017a). See Figure 4.2.10 for locations.
Figure 4.2.9. (continued)
Figure 4.2.10. Hydrographs of transient water-level data (in feet above mean sea level) for the selected northern segment of the Edwards (Balcones Fault Zone) Aquifer wells in Travis County (Texas Water Development Board, 2017a). See Figure 4.2.10 for locations.
Figure 4.2.10. (continued)
Figure 4.2.11. Hydrographs of transient water-level data (in feet above mean sea level) for the selected northern segment of the Edwards (Balcones Fault Zone) Aquifer wells in Williamson County (Texas Water Development Board, 2017a). See Figure 4.2.10 for locations.
Figure 4.2.11. (continued)
Figure 4.2.11. (continued)
Figure 4.2.12. Hydrographs of transient water-level data (in feet above mean sea level) for selected Trinity Aquifer wells in Bell, Travis, and Williamson counties (Texas Water Development Board, 2017a). See Figure 4.2.10 for locations.
Figure 4.2.12. (continued)
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Figure 4.2.12. (continued)
Figure 4.2.13. Locations of wells used for comparing water-level elevations between the northern segment of the Edwards (Balcones Fault Zone) and Trinity aquifers (Texas Water Development Board, 2017a).
Figure 4.2.14. Comparison of water-level elevations (in feet above mean sea level) in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (blue) and Trinity Aquifer (green) (Texas Water Development Board, 2017a).
Figure 4.2.14. (continued)
Figure 4.2.14. (continued)
4.3 Recharge

Recharge is defined as the processes involved in the addition of water to the water table (Jackson, 1997). Potential sources for recharge include infiltration of precipitation and stream water, and irrigation return-flow.

During a rainfall event, some of the precipitation: (1) runs off through streams, (2) is taken up through evapotranspiration, and (3) the remainder—if any—infiltrates into the soil and rock and recharges the underlying aquifer. The potential for the occurrence of recharge to the northern segment of the Edwards (Balcones Fault Zone) Aquifer is greater where it is exposed at land surface (see Figure 2.0.2) compared to areas where infiltrating water must pass through overlying units. Faults and karst dissolution features potentially facilitate recharge by acting as pathways for rapid infiltration of water both where the northern segment of the Edwards (Balcones Fault Zone) Aquifer crops out and where it is confined by overlying aquifers or aquitards—rocks that do not transmit useable amounts of water and thus do not meet the criteria to be aquifers. Recharge to the northern segment of the Edwards (Balcones Fault Zone) Aquifer is potentially topographically controlled, with higher recharge in the areas of higher elevation.

Recharge to the northern segment of the Edwards (Balcones Fault Zone) Aquifer takes the form of infiltration of precipitation that falls on the aquifer outcrop or infiltration of runoff derived from watershed areas upstream from the aquifer outcrop. The recharge zone in the study area consists mainly of gently rolling terrain of the Lampasas Cutplains in the north, and is characterized by steeper, more highly dissected terrain of the Jollyville Plateau in the south (Figure 2.1.1; Duffin and Musick, 1991). The aquifer outcrop is characterized by the occurrence of numerous scattered karst features, such as dissolution-enhanced fractures, sinkholes, and caves, which are potential recharge sites.

Sinkholes that occur in the Jollyville Plateau can transmit large amounts of water to the aquifer following heavy rainfall events (Figure 2.1.1; Kreitler and others, 1987). Recharge also takes the form of infiltration along faults and joints that intersect losing segments of perennial and intermittent streams that cross the study area. These fractures are often enlarged by karstification (Brune and Duffin, 1983). Infiltrating water tends to perch within the Georgetown Formation because of the occurrence of low-permeability shale members. Resultant lateral flow often discharges from small seeps and springs. Rapid recharge occurs when underlying Edwards and Comanche Peak limestones are encountered (Dahl, 1990).

Recharge processes are more complex in the north, where whether stream segments are gaining or losing depends on relative elevations of the water table and streambeds and thus may vary seasonally (Duffin and Musick, 1991). Streamflow studies by the United States Geological Survey (USGS) in 1978 and 1979 indicate that, in the north, streams
generally act as points of groundwater discharge rather than recharge (Figure 4.3.1; Senger and others, 1990; Duffin and Musick, 1991; Slade and others, 2002). Recharge in the north occurs primarily by infiltration along intermittent streams and by infiltration of precipitation on the aquifer outcrop. Recharge also occurs in losing segments of the major rivers that occur along the western margin of the aquifer (Dahl, 1990; Slade and others, 2002). This recharge results in the formation of groundwater mounds along the western margin of the aquifer (Figure 4.2.6). Potential for groundwater inflow by cross-formational flow also exists from the underlying Trinity Aquifer (Duffin and Musick, 1991). However, the water-level differences more than 100 feet in the up-dip portions of the Edwards (Balcones Fault Zone) Aquifer suggest groundwater perching in the Edwards (Balcones Fault Zone) Aquifer due to isolation from the Trinity Aquifer by aquitards—parts of the Walnut and Glen Rose formations—separating the two aquifers (Figures 4.2.13 and 4.2.14).

Recharge estimates in the Salado Creek basin by Dahl (1990) indicate recharge of 15 percent of precipitation over the Edwards (Balcones Fault Zone) Aquifer outcrop and 60 percent of storm runoff originating from upstream of the aquifer outcrop. These estimates of precipitation recharge were based on groundwater-level responses and an assumption of 2 percent porosity. The storm-runoff recharge was estimated based on stream discharge measurements above and below losing stream segments. Dahl (1990) indicated that recharge of precipitation in the Salado Creek basin contributes much larger volumes of water to the aquifer (about 29,000 acre-feet in 1985) than storm runoff (about 2,700 acre-feet).

Isotopes in groundwater, such as carbon-13, carbon-14, tritium, and stable hydrogen and oxygen can be used to determine the spatial and seasonal distribution of recharge to an aquifer (See Section 4.7). The tritium, carbon-13, and carbon-14 isotopic compositions of northern segment of the Edwards (Balcones Fault Zone) Aquifer groundwater indicate recharge zones where the aquifer crops out and suggests little groundwater circulation in the confined parts of the aquifer. The stable oxygen and hydrogen isotopes indicate that most recharge to the northern segment of the Edwards (Balcones Fault Zone) Aquifer occurs during fall and winter months (Jones, 2006).
Interaction between groundwater and surface water occurs primarily where surface water bodies—rivers and streams, springs, and lakes—intersect with aquifer outcrops. These interactions result in flow between the aquifer and surface-water bodies. The direction of flow depends on the relative groundwater and surface-water levels with water flowing from relatively high to relatively low water levels.

4.4.1 Rivers and Streams
The northern segment of the Edwards (Balcones Fault Zone) Aquifer is bisected by the hydrologic divide between the Colorado and Brazos River basins (Figure 2.0.11). This hydrologic divide coincides approximately with the boundary between Travis and Williamson counties. Consequently, surface water flows to the north and east toward the Brazos River in Bell and Williamson counties and toward the south to the Colorado River in Travis County. The Lampasas and Colorado rivers that form the northern and southern boundaries of the study area are the largest rivers in the area (Figure 2.0.4). Smaller rivers
and creeks, such as Brushy Creek, Berry Creek, Salado Creek, and San Gabriel River, cross the outcrop of the aquifer and are likely recipients of groundwater discharge, indicated by their perennial flow (Figure 4.3.1). Smaller tributaries of these rivers and creeks often flow intermittently because of storm-related runoff. Groundwater and surface-water systems are closely related in recharge and discharge zones, where interchange occurs as a result of recharge and discharge processes, respectively (Baker and others, 1986). Groundwater-surface-water interaction along gaining and losing stream segments of major rivers and creeks varies by location and hydrologic conditions because of significant hydrologic connections between streams and the underlying aquifer (Land and Dorsey, 1988).

Interaction between groundwater and rivers and streams depends on the relative elevations of the aquifer water table and the stream stage. In losing streams, the water table is below the elevation of the stream stage, and the gradient causes water to flow from the stream into the aquifer. In gaining streams, the water table is above the elevation of the stream stage and consequently water flows from the aquifer into the stream. The results of several streamflow gain/loss studies in the northern segment of the Edwards (Balcones Fault Zone) Aquifer study area are documented by Slade and others (2002) (Figure 4.3.1).

In the study area, there is variation of the relative impacts on streamflow of (1) storm-related runoff and (2) groundwater discharge in the form of baseflow. Streams in which streamflow is dominated by baseflow are characterized by relatively small flow-rate fluctuations (Figures 4.4.1 and 4.4.2). Salado Creek, which is dominated by discharge from numerous springs, notably from Salado Springs, is an example of this type of stream. Streams dominated by storm runoff, such as Shoal Creek, are characterized by rapid recession after storms and low baseflow. Streamflow in Berry Creek is more representative of the streams in the study area, and streamflow fluctuations indicate inputs from both baseflow and storm-related runoff. Comparison of streamflow at pairs of stream gages can be used to indicate whether the stream is losing flow owing to recharge or receiving groundwater discharge (Figure 4.4.2). Decreased downstream flow commonly indicates a losing stream because of recharge to the underlying aquifer, whereas consistent increases in flow are quite often the result of groundwater discharge entering the stream. In the study area, decreased streamflow in downstream parts of Shoal Creek is consistent with recharge to the aquifer, whereas increased downstream flow in Berry Creek and the San Gabriel River can be attributed to groundwater discharge through numerous springs and seeps that occur in the area (Figure 4.4.2).

4.4.2 Springs
Springs are locations where the water table intersects the ground surface (Figure 4.4.3). Spring data for the northern segment of the Edwards (Balcones Fault Zone) Aquifer were found in the Texas Water Development Board groundwater database (Texas Water Development Board, 2017a), a database of Texas springs compiled by the United States
Spring 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 (Kreitler and others, 1987). The identified springs mostly occur in the Salado Creek, Brushy Creek and San Gabriel River watersheds and along the southern boundary of the Edwards (Balcones Fault Zone) Aquifer outcrop where contact between the Edwards (Balcones Fault Zone) Aquifer and underlying confining unit is exposed by downward erosion by streams such as Bull Creek. The major springs—springs with the highest discharge rates—are associated with major faults, generally occurring some distance east of these faults (Figure 4.4.4). These springs occur primarily in the Salado Creek and San Gabriel River watersheds (Figure 4.4.5).

4.4.3 Lakes and Reservoirs
Typically, interaction between an aquifer and a lake or reservoir is restricted to the outcrop area of an aquifer where the lake or reservoir lies directly on the aquifer. There are no natural lakes on the outcrop of the northern segment of the Edwards (Balcones Fault Zone) Aquifer. However, there is thought to be interaction between the Edwards (Balcones Fault Zone) Aquifer and Lake Georgetown, which is located on the San Gabriel River overlying the Edwards (Balcones Fault Zone) Aquifer. Slade and others (2002) indicate that Lake Georgetown receives baseflow from the Edwards (Balcones Fault Zone) Aquifer (Figure 4.3.1).
Figure 4.4.1. Locations of hydrographs from stream gauges in the northern segment of the Edwards (Balcones Fault Zone) Aquifer.
Figure 4.4.2. Streamflow hydrographs for selected stream gages in the study area (United States Geological Survey, 2017b). See Figure 4.4.1 for locations.
Figure 4.4.2. (continued).
Figure 4.4.2. (continued).
Figure 4.4.2. (continued).
Figure 4.4.3. Locations of springs in the northern segment of the Edwards (Balcones Fault Zone) Aquifer study area.
Figure 4.4.4. Locations of the major springs in the northern segment of the Edwards (Balcones Fault Zone) Aquifer study area.
4.5 Hydraulic Properties

There is a paucity of hydraulic property data for the northern segment of the Edwards (Balcones Fault Zone) Aquifer. The ability of the aquifer to transmit groundwater to a well varies greatly. Factors impacting the ability of the aquifer to transmit groundwater include: aquifer lithology, karstification, structural deformation, and fracturing. This section reviews the sources of available data describing the northern segment of the Edwards (Balcones Fault Zone) Aquifer hydraulic properties. Several hydraulic properties are used to describe groundwater flow in aquifers. The properties discussed here are hydraulic conductivity, transmissivity, coefficient of storage or storativity, and specific capacity. Each of these terms is briefly described below.

Hydraulic conductivity is a measure of the ease with which groundwater can flow through an aquifer. Higher hydraulic conductivity indicates that an aquifer will allow more groundwater flow under the same hydraulic gradient. In this study, units for hydraulic conductivity are feet per day.

Figure 4.4.5. Spring discharge measurements from springs in the northern segment of the Edwards (Balcones Fault Zone) Aquifer study area.
Transmissivity is a term closely related to hydraulic conductivity but is a function of the saturated thickness of an aquifer. Transmissivity describes the ability of groundwater to flow through the entire saturated thickness of an aquifer. As the saturated thickness increases, the transmissivity increases for a given hydraulic conductivity. In this study, units for transmissivity are square feet per day.

Storativity—also referred to as the coefficient of storage—is the volume of water that a confined aquifer releases per square foot of surface area per foot decline of water level. Storativity is a dimensionless parameter.

Specific capacity is a measure of well productivity represented by the ratio between the well pumping rate and the corresponding drawdown decline in water level. In this study, specific capacity is expressed in gallons per minute per foot of drawdown in a well.

4.5.1 Data Sources
Development of hydraulic properties for the northern segment of the Edwards (Balcones Fault Zone) Aquifer in the study area used multiple sources including submitted drillers’ reports and the groundwater database the Texas Water Development Board website (Texas Department of Licensing and Regulation, 2017; Texas Water Development Board, 2017a).

The hydraulic property data for the northern segment of the Edwards (Balcones Fault Zone) Aquifer are shown in Figures 4.5.1 through 4.5.3 and Table 4.5.1. Using all sources available, 83 estimates of specific capacity were found for the northern segment of the Edwards (Balcones Fault Zone) Aquifer.

4.5.2 Calculation of Hydraulic Conductivity from Specific Capacity
Specific capacity values are calculated from the pumping rate and corresponding drawdown, which are commonly reported in well records. However, hydraulic conductivity or transmissivity are more useful parameters than specific capacity for regional groundwater flow modeling. The following methodology was used to estimate transmissivity from specific capacity data.

Point estimates of aquifer transmissivity can be made based on measurements of specific capacity. In the absence of pump test data, transmissivity can still be estimated using the Cooper-Jacob solution for drawdown in a pumping well (Cooper and Jacob, 1946):
\[ s = \frac{Q}{4\pi T} \ln \left( \frac{2.25TL}{r^2S} \right) \]  

(4.5.1)

where:

- \( s \) = drawdown in the well [L],
- \( Q \) = pumping rate [L³/T],
- \( T \) = transmissivity [L²/T],
- \( t \) = time [T],
- \( r \) = radius of the well [L], and
- \( S \) = storativity [-].

Equation (4.5.1) can be rearranged to solve for specific capacity as:

\[ \frac{Q}{s} = \frac{4\pi T}{\ln \left( \frac{2.25TL}{r^2S} \right)} \]  

(4.5.2)

For a given specific capacity, transmissivity can be solved iteratively. Table 4.5.1 provides specific capacity and calculated transmissivity and hydraulic conductivity data for Edwards (Balcones Fault Zone) Aquifer wells. Transmissivity was calculated using the iterative method outlined by Equation 4.5.2 and assuming a storativity value of 0.0001. Hydraulic conductivity was calculated by dividing the transmissivity by the well screen length or, in the absence of screen information, by the thickness of the Edwards (Balcones Fault Zone) Aquifer indicated in Figure 4.1.4.

As one would expect in a karst system, the hydraulic properties of the northern segment Edwards (Balcones Fault Zone) Aquifer are highly variable. This variability can be attributed to many factors, such as (1) limestone primary porosity due to facies changes within or between individual stratigraphic units, (2) fracture densities, and (3) development of karst features. Hovorka and others (1996) showed that limestones deposited in subtidal environments exhibit lower porosities than carbonate sandstones or dolomite. Based on outcrop descriptions, Hovorka and others (1998) showed that fractures and karst features make up 1 to 3 percent of the outcrop area, and karst features develop preferentially adjacent to faults and in dolomitized limestone. Matrix permeability accounts for only about 1 percent of the flow through the aquifer, and the remainder is contributed by fractures and karst features.

Transmissivity estimates for the Edwards and associated limestones in the northern segment of the Edwards (Balcones Fault Zone) Aquifer vary widely, lying in the range of 0.5
to $4 \times 10^6$ square feet per day, seven orders of magnitude (Figure 4.5.1). These transmissivity estimates are calculated from specific-capacity data from the Texas Water Development Board (TWDB) well database using methods outlined in Mace (2001). The highest transmissivities can be attributed to cave systems, whereas solution-enhanced fracture porosity and intergranular porosity produce intermediate and low transmissivities, respectively (Hovorka and others, 1998). In the aquifer, transmissivity in the central part of the study area—along the eastern boundary of the outcrop—is generally higher than along the eastern or western boundaries (Slade, 1987). This phenomenon is attributed to fracture densities that are associated with the major faults of the Balcones Fault Zone.

There is little hydraulic conductivity data that are based on pumping tests for the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Transmissivity data from the available specific capacity test data were converted to hydraulic conductivity based on aquifer thickness (Figure 4.5.2). Resultant hydraulic conductivity values range between 0.005 and more than 30,000 feet per day, and median and geometric mean values are 9 feet per day (Figure 4.5.3). These values overlap with hydraulic conductivity data—$2.7 \times 10^{-5}$ to 13 feet per day—for the San Antonio segment of the Edwards (Balcones Fault Zone) Aquifer (Hovorka and others, 1996). There is very little hydraulic conductivity data on the unconfined part of the aquifer. Spatial distribution of the data suggests no apparent trends, with the highest hydraulic conductivity occurring within a few hundred feet of very low hydraulic conductivity values. The Jollyville Plateau zone (Figure 2.1.1) coincides with the outcrop of relatively low permeability stratigraphic units, such as the Keys Valley Marl member and Cedar Park limestone member of the Walnut Formation, and the Comanche Peak Limestone. The remainder of the aquifer outcrop is composed of the Edwards Limestone and Georgetown Formation, which have generally higher permeability than the Jollyville Plateau.

The estimated hydraulic conductivity values for the Edwards (Balcones Fault Zone) Aquifer range from 0.005 to 31,178 feet per day, with a median of 10 feet per day (Figures 4.5.2 and 4.5.3). Highest hydraulic conductivity in the northern segment of the Edwards (Balcones Fault Zone) Aquifer is associated with karstification of the limestone (Senger and others, 1990). Underlying estimates of Trinity hydraulic conductivity of 0.01 to 4 feet per day are much lower than hydraulic conductivities in the overlying Edwards (Balcones Fault Zone) Aquifer (Table 4.5.1; Figure 4.5.4).

**4.5.3 Storativity**

The specific storage of a confined aquifer is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head (Freeze and Cherry, 1979). The storativity is equal to the product of specific storage and aquifer thickness and is dimensionless. For unconfined conditions, the storage is referred to as the
specific yield and is defined as the volume of water an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in water table (Freeze and Cherry, 1979). Aquifer storage properties are directly related to aquifer porosity in the unconfined portions of an aquifer and aquifer porosity and matrix compressibility in the confined portions of the aquifer.

No published storativity data exist for the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Consequently, specific yield and specific storage values from the groundwater availability model for the adjacent Barton Spring segment of the Edwards (Balcones Fault Zone) Aquifer were used to represent storage in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Scanlon and others, 2001). This is appropriate considering the close proximity, relatively small size, and stratigraphic similarities of the two aquifer segments.
Table 4.5.1. Hydraulic property data from wells shown in Figure 4.5.1, located within the northern segment of the Edwards (Balcones Fault Zone) Aquifer. $Q =$ well discharge (gallons per minute), $s =$ drawdown (feet), $SC =$ specific capacity (gallons per minute per foot), $t =$ time (hours), $r =$ casing diameter (inches), $T =$ transmissivity (square feet per day), $K =$ hydraulic conductivity (feet per day).

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* - Trinity Aquifer wells
Figure 4.5.1. Transmissivity estimates based on specific capacity data for the northern segment of the Edwards (Balcones Fault Zone) Aquifer (see Table 4.5.1 for the specific capacity data used to calculated transmissivity).
Figure 4.5.2. Hydraulic conductivity data for the northern segment of the Edwards (Balcones Fault Zone) Aquifer (see Table 4.5.1 for the specific capacity data used to calculated hydraulic conductivity).
Figure 4.5.3. Histogram of hydraulic conductivity data in feet per day for the northern segment of the Edwards (Balcones Fault Zone) Aquifer based on data from the hydraulic data indicated in Table 4.5.1.
4.6 Discharge

The term, discharge, refers to processes by which water leaves an aquifer. These processes include both natural and anthropogenic processes. Groundwater discharges from aquifers naturally to streams or springs, evapotranspiration, and cross-formational flow. Pumping wells are an anthropogenic form of discharge from aquifers.

4.6.1 Natural Aquifer Discharge

In a typical topographically-driven flow system, percolation of precipitation results in recharge at the water table, which flows from topographic highs and discharges at topographic lows through streams and springs and groundwater evapotranspiration. Water that moves down-dip eventually discharges upward through cross-formational flow. In the northern segment of the Edwards (Balcones Fault Zone) Aquifer, the most likely forms of discharge are stream and spring discharge and cross-formational flow in the subsurface. Groundwater isotopes indicate that in the northern segment of the Edwards (Balcones Fault Zone) Aquifer, most groundwater flow is limited to the unconfined portion.
of the aquifer (see Section 4.7) and consequently most discharge is likely to take the form of discharge to the perennial rivers and streams in the study area.

Groundwater discharge to surface water bodies is discussed in Sections 4.4.1 through 4.4.3. This discharge primarily occurs in the outcrop of the northern segment of the Edwards (Balcones Fault Zone) Aquifer or adjacent to the boundary between the unconfined and confined parts of the aquifer (Figure 4.4.4).

Discharge via cross-formational flow is likely to occur in the confined part of the northern segment of the Edwards (Balcones Fault Zone) Aquifer by upward discharge through overlying stratigraphic units such as the Del Rio Clay and Austin Chalk. It is unlikely that cross-formation discharge is a major factor in groundwater discharge from the northern segment of the Edwards (Balcones Fault Zone) Aquifer because (1) groundwater isotopes suggest little groundwater circulation in the confined portion of the aquifer (Jones, 2006), and (2) the non-aquifer rocks, such as the Del Rio Clay, Buda Limestone and Austin Chalk that overlie the Edwards (Balcones Fault Zone) Aquifer have low hydraulic conductivities.

### 4.6.2 Aquifer Discharge through Pumping

Estimates of groundwater pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer for the years 1980 through 2015 were obtained from the Texas Water Development Board historical water use estimates. The six water-use categories defined in the Texas Water Development Board database are municipal, manufacturing, steam electric generation, irrigation, mining, and livestock. Rural domestic pumping is likely to be more important in less urbanized parts of the study area.

Potential areas for irrigation pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer are in the eastern and northern parts of the study area (Figure 4.6.1). This spatial distribution assumes that irrigation pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer is directly associated with crops—such as orchards, hay, row crops, and small grains—as determined by National Land Cover Database land classification (Vogelmann and others, 1998a; 1998b). This spatial distribution is supported by the spatial distribution of irrigation wells drilled during the period 2001 through 2017 (Texas Department of Licensing and Regulation, 2017). Texas Water Development Board pumping data for the northern segment of the Edwards (Balcones Fault Zone) Aquifer indicate irrigation pumping up to 130 acre-feet per year—mostly in Bell County (Figure 4.6.2; Table 4.6.1).

Livestock pumping was distributed using land cover data obtained from the National Land Cover Dataset (Vogelman and others, 1998a; 1998b). We assume that livestock pumping is associated with grassland and scrubland land cover (Figure 4.6.3). These types of land cover are distributed over most of the land cover over the northern segment of the Edwards (Balcones Fault Zone) Aquifer; however, recent livestock well drilling suggests
that livestock pumping is most likely to be restricted to the more rural eastern and northern parts of the study area. Estimates of livestock pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer peak at about 600 acre-feet per year (Figure 4.6.2; Table 4.6.2).

Manufacturing, mining and municipal pumping are spatially distributed based on known well locations (Figure 4.6.4). These wells are primarily located in or adjacent to the confined part of the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Pumping estimates are taken from Texas Water Development Board water use surveys (TWDB, 2017b). Texas Water Development Board pumping data indicates manufacturing pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer is mostly in Travis and Williamson counties, totaling up to 1,400 acre-feet per year (Figure 4.6.5; Table 4.6.3). These data show a decline of manufacturing in the mid-2000s to about 800 acre-feet per year. The water use survey pumping estimates suggest that mining pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer occurs in Williamson County, associated with the limestone quarries located there. Mining pumping estimates are as high as 1,800 acre-feet per year (Figure 4.6.5; Table 4.6.4). Municipal pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer are as high as 26,000 acre-feet per year (Figure 4.6.6; Table 4.6.5).

Rural domestic pumping—which consists primarily of unreported domestic water use—is assumed to: (1) be related to the lower population densities in non-urban areas (Figure 4.6.7). the Submitted Drillers' Reports database suggests that rural domestic pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer is expected to occur in the rural eastern and northern parts of the study area (Figure 4.6.7). Rural domestic pumping estimates are based partially on per capita water usage rate estimates of 137 gallons per day, 131 gallons per day, and 132 gallons per day in Bell, Travis, and Williamson counties, respectively. These estimates suggest relatively constant pumping rates of about 3,000 to 5,000 acre-feet per year prior to 2000, increasing rapidly with population to over 30,000 acre-feet per year (Figure 4.6.6; Table 4.6.6).

Total pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer over the period 1980 through 2015 has risen from about 16,000 acre-feet per year to about 50,000 acre-feet per year (Table 4.6.7; Figure 4.6.8). This variation of pumping largely reflects variation of municipal and domestic pumpage over that time period. Overall, municipal and domestic pumpage accounts for 90 percent of all pumpage from the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Figure 4.6.9). Locally, irrigation, mining and manufacturing pumpage are significant.

Pumping from the Trinity Aquifer in the study area is lower than in the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Unlike pumping from the northern segment
of the Edwards (Balcones Fault Zone) Aquifer, annual pumping from the adjacent Trinity Aquifer has been relatively constant, ranging from a low of about 7,000 acre-feet to a high in excess of 15,000 acre-feet and averaging about 10,000 acre-feet (Figure 4.6.10; Table 4.6.8).

Table 4.6.1. Estimates of northern segment of the Edwards (Balcones Fault Zone) Aquifer irrigation pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2017b).

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Table 4.6.5. Estimates of northern segment of the Edwards (Balcones Fault Zone) Aquifer municipal pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2017b).

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Table 4.6.6. Estimates of northern segment of the Edwards (Balcones Fault Zone) Aquifer domestic pumping expressed in acre-feet per year (AFY).

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Table 4.6.7. Estimates of northern segment of the Edwards (Balcones Fault Zone) Aquifer total pumping expressed in acre-feet per year (AFY).

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Table 4.6.8. Estimates of Trinity Aquifer pumping in the study area expressed in acre-feet per year (AFY).

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Figure 4.6.1. Spatial distribution of potentially groundwater-irrigated farmland overlying the northern segment of the Edwards (Balcones Fault Zone) Aquifer (left) and irrigation wells drilled over the period 2001 through 2017 (right). Data from Vogelmann and others (1998a and 1998b) and the Submitted Drillers' Reports database (TDLR, 2017).
Figure 4.6.2. Estimated irrigation and livestock pumpage from the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Data from Texas Water Development Board (2017b).
Figure 4.6.3. The spatial distribution of livestock pumping (left) from the northern segment of the Edwards (Balcones Fault Zone) Aquifer based grassland and scrubland land cover from the National Land Cover Dataset throughout the study area (Vogelman and others, 1998a; 1998b) and (right) livestock wells drilled over the period 2001 through 2017 from the Submitted Drillers’ Reports database (TDLR, 2017).
Figure 4.6.4. The spatial distribution of manufacturing (industrial), mining and municipal (public supply) pumping. Manufacturing, mining and public supply pumping will be distributed in model cells that coincide with the well locations. Data from Water Use Survey and the Submitted Drillers’ Reports database (TDLR, 2017).
Figure 4.6.5. Estimated manufacturing and mining pumpage from the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Data from Texas Water Development Board (2017b).
Figure 4.6.6. Estimated municipal and rural domestic pumpage from the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Data from Texas Water Development Board (2017b).
Figure 4.6.7. Population density in the northern segment of the Edwards (Balcones Fault Zone) Aquifer study area (left). Spatial distribution of domestic wells drilled over the period 2001 through 2017 (right). Data from U.S. Department of Commerce (2013) and Submitted Drillers’ Reports database (TDLR, 2017).
Figure 4.6.8. Total estimated pumpage from the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Data from Texas Water Development Board (2017b).
Figure 4.6.9. Pie charts showing relative amounts of each category of pumping—rural domestic, irrigation, livestock, manufacturing, and municipal—in each of the three counties that overlie the northern segment of the Edwards (Balcones Fault Zone) Aquifer and for the entire aquifer segment.
4.7 Water Quality

The northern segment of the Edwards (Balcones Fault Zone) Aquifer generally has fresh groundwater and is generally less saline than the underlying Trinity Aquifer. This section is a discussion of the major element and isotopic compositions of groundwater in the northern segment of the Edwards (Balcones Fault Zone) Aquifer and adjacent Trinity Aquifer with implications for determination of groundwater flow through and recharge to the respective aquifers.

4.7.1 Major Elements

In some parts of the northern segment of the Edwards (Balcones Fault Zone) Aquifer, concentrations of total dissolved solids, chloride, nitrate and sulfate exceed applicable water quality standards. Except for nitrate, high concentrations of these constituents occur in down-dip portions of the aquifer (Baker and others, 1986). Excessively high concentrations of nitrate have been identified in a few wells, mostly located in urbanized
parts of the northern segment of the Edwards (Balcones Fault Zone) Aquifer in Travis and Williamson counties, and seem to be associated with major faults. This suggests that faults are acting as preferential pathways for recharge and therefore the potential transmission of contaminants to the aquifer.

Figure 4.7.1 shows total dissolved solids concentrations in northern segment of the Edwards (Balcones Fault Zone) Aquifer groundwater. Fresh groundwater—total dissolved solids less than 1,000 milligrams per liter—occurs throughout the aquifer. Slightly to very saline groundwater—total dissolved solids of 1,000 milligrams per liter to greater than 10,000 milligrams per liter—occur mostly in the deeper parts of the aquifer. These more saline groundwaters occur beyond the official down-dip boundary of the Edwards (Balcones Fault Zone) Aquifer which is defined by the occurrence of groundwater with total dissolved solids less than 1,000 milligrams per liter. The most saline groundwater occurs in the southernmost, narrowest parts of the Edwards (Balcones Fault Zone) Aquifer. This moderate to very saline groundwater is also the shallowest consistent occurrence of saline groundwater in the study area. This has been attributed to the effects of intense faulting that acts as a barrier to down-dip flow of fresh groundwater and facilitates upward influxes of very saline groundwater (Baker and others, 1986; Senger and others, 1990; Ridgeway and Petrini, 1999).

In the Trinity Aquifer, groundwater is fresh to moderately saline (Figure 4.7.2). There is a tendency for Trinity Aquifer groundwater to be more saline in lower formations that make up the aquifer. In the study area, this is most evident by the more frequent occurrence of moderately saline groundwater in the southern part of the study area where Trinity Aquifer groundwater is discharging in the Colorado River Valley (Figures 4.2.7 and 4.7.2).

Groundwater in the northern segment of the Edwards (Balcones Fault Zone) Aquifer displays a wide range of geochemical compositions (Figure 4.7.3). Groundwater compositions range from calcium-magnesium to sodium compositions and bicarbonate to sulfate and chloride compositions. These compositional ranges are determined by geochemical processes that take place as the groundwater flows through the aquifer interacting with aquifer rock and mixing with groundwater inflows from surrounding stratigraphic units (Figure 4.7.4). These compositions indicate groundwater interaction with calcite, dolomite, and gypsum, minerals that occur within the Edwards (Balcones Fault Zone) Aquifer and adjacent stratigraphic units. Groundwater interaction with dolomite and calcite would produce calcium-magnesium-bicarbonate compositions, gypsum would produce calcium-sulfate compositions, and sodium-chloride groundwater compositions are most likely the result of upward migration of groundwater from deep evaporite units. In the northern segment of the Edwards (Balcones Fault Zone) Aquifer, groundwater compositions change from calcium and bicarbonate compositions in up-dip parts of the
aquifer to become increasingly sodium-rich with depth. These changes in groundwater compositions are also accompanied by increasing total dissolved solids concentrations.

4.7.2 Isotopes

Groundwater isotopic compositions can provide information about groundwater hydrology. Concentrations of different isotopes often change in response to processes such as evaporation, water-rock interaction, recharge processes, and the elapsed time since recharge.

Groundwater carbon-13 isotopic compositions ($\delta^{13}C$) represent the ratios of stable carbon isotopes—$^{12}C$ and $^{13}C$—in groundwater relative to the composition of a standard—PDB calcite (Clark and Fritz, 1997). These isotope ratios are expressed as the relative difference in parts per thousand—per mil. Groundwater carbon-13 isotopic compositions often reflect relative carbon inputs from interaction with soil and aquifer rock. Groundwater near recharge zones tend to have more negative carbon-13 compositions reflecting recent contact with the soil. As the groundwater flows through the aquifer—away from the recharge zone—water-rock interaction results in the groundwater taking on more positive carbon-13 isotopic compositions reflecting those of the aquifer rock. This trend is most apparent in the northern segment of the Edwards (Balcones Fault Zone) Aquifer when comparing carbon-13 compositions of groundwater in the unconfined and confined parts of the aquifer (Figure 4.7.5). In the unconfined parts of the Edwards (Balcones Fault Zone) Aquifer, groundwater is characterized by more negative groundwater carbon-13 compositions—about -15 to -9 per mil—indicating recent recharge. On the other hand, in the confined parts of the northern segment of the Edwards (Balcones Fault Zone) Aquifer, groundwater carbon-13 compositions range from about -12 to -4 per mil with the more negative compositions—about -12 per mil—occurring immediately adjacent to the boundary between the unconfined and confined parts of the aquifer. In the down-dip parts of the aquifer, groundwater carbon-13 compositions are less negative with compositions of about -4 to -5 per mil indicative of more rock and less soil influences on groundwater compositions.

Carbon-14 decays over time and, consequently, without a continuous influx of carbon-14 with recharging groundwater, the carbon-14 activity in groundwater will decrease over time. The result typically is that groundwater carbon-14 activity is higher in shallower parts of an aquifer where recharge is occurring. In the northern segment of the Edwards (Balcones Fault Zone) Aquifer, carbon-14 activity is generally highest—up to 100 percent modern carbon—within and immediately adjacent to the unconfined parts of the aquifer where the aquifer crops out and recharge occurs, and lowest—less than 10 percent modern carbon—in the subcrop where there is no recharge and almost all of the groundwater carbon-14 has decayed (Figure 4.7.6).
Groundwater tritium behaves like carbon-14. The difference is that tritium has a faster decay rate with a half-life of 12.3 years compared to 5,730 years for carbon-14 (Clark and Fritz, 1997). High tritium activity indicates the most recent recharge. In the northern segment of the Edwards (Balcones Fault Zone) Aquifer, the groundwater tritium activity ranges between 0 and 3 Tritium Units (Figure 4.7.7). In or immediately adjacent to the unconfined parts of the aquifer tritium activity lies in the range of about 1.5 to 3 Tritium Units. In the confined part of the aquifer, tritium activity is below detection indicating groundwater that is much older than the groundwater in the unconfined part of the aquifer.

Groundwater stable hydrogen ($\delta^2$H) and oxygen ($\delta^{18}$O) isotopic compositions represent the ratios of stable hydrogen isotopes—H and $^2$H—and stable oxygen isotopes—$^{16}$O and $^{18}$O—in groundwater relative to the composition of standard mean ocean water (Clark and Fritz, 1997). These isotope ratios are expressed as the relative difference in parts per thousand—per mil. Groundwater stable hydrogen ($\delta^2$H) and oxygen ($\delta^{18}$O) isotopic compositions reflect the composition of the precipitation that recharged the aquifer which may vary spatially or temporally in response to factors such as elevation, temperature, amount of precipitation (Dansgaard, 1964; Fontes and Olivry, 1977; Fontes, 1980; Gonfiantini, 1985; Scholl and others, 1996). Consequently, the hydrogen and oxygen isotopic compositions of groundwater can be used as an indicator of the conditions under which recharge to the aquifer occurred. Figures 4.7.8 and 4.7.9 show groundwater hydrogen and oxygen isotopic compositions in the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Groundwater stable hydrogen and oxygen isotopic compositions in the northern segment of the Edwards (Balcones Fault Zone) Aquifer lie in the ranges -31 to -13 per mil and -6 to -2 per mil, respectively. Stable hydrogen and oxygen isotope compositions generally lie along the Global Meteoric Water Line—the average relationship between stable hydrogen and oxygen isotopic compositions in precipitation around the world (Craig, 1961). Figure 4.7.9 shows northern segment of the Edwards (Balcones Fault Zone) Aquifer groundwater stable hydrogen and oxygen isotopic compositions relative to the Global Meteoric Water Line. Hydrogen and oxygen isotopic compositions in the underlying Trinity Aquifer are similar to those in the overlying Edwards (Balcones Fault Zone) Aquifer (Figure 4.7.9).

4.7.3 Implications for Recharge Based on Groundwater Major Element and Isotopic Compositions

Figure 4.7.10 shows a comparison of hydrogen and oxygen isotopic compositions in the northern segment of the Edwards (Balcones Fault Zone) Aquifer groundwater in the San Gabriel River and Salado Creek watersheds with precipitation compositions. The figure shows that groundwater has a much narrower range of compositions than precipitation. This occurs because groundwater compositions reflect that fraction of precipitation that recharges the aquifer—most precipitation is taken up by runoff, evaporation or transpiration (Jones, 2002).
The range of stable hydrogen and oxygen isotopic compositions in precipitation can be influenced by the effects of temperature, altitude, and amount of precipitation (Dansgaard, 1964; Fontes and Olivry, 1977; Fontes, 1980; Gonfiantini, 1985; Scholl and others, 1996). The most likely effects influencing the range of precipitation stable hydrogen and oxygen isotopic compositions in the northern segment of the Edwards (Balcones Fault Zone) Aquifer are the temperature and amount effects. Together, the temperature and amount effects would result in seasonal fluctuations of stable hydrogen and oxygen isotopic compositions. Higher precipitation amounts, and/or lower temperatures produce more negative isotopic compositions in the precipitation and resultant groundwater. Figure 4.7.11 variation of average monthly precipitation oxygen isotopic compositions together with the range of northern segment of the Edwards (Balcones Fault Zone) Aquifer groundwater compositions. If groundwater compositions are the average composition of precipitation water that recharges the aquifer, then most recharge to the northern segment of the Edwards (Balcones Fault Zone) Aquifer is likely to occur in the winter and fall months where median precipitation compositions approach that of groundwater (Figure 4.7.11).

The groundwater flow characteristics in the northern segment of the Edwards (Balcones Fault Zone) Aquifer were investigated by Jones (2006). This study investigated changes in groundwater major element and isotopic compositions along two flow paths in the San Gabriel River and Salado Creek watersheds. Please note: groundwater flow is approximately parallel to these rivers. Figures 4.7.12 shows variation of total dissolved solids, and carbon-13 and tritium isotopic compositions. The variation of total dissolved solids along the respective flow paths shows relatively uniform concentrations along the Salado Creek flow path which is entirely located in the unconfined portion of the aquifer, and a rise in total dissolved solids in the confined part of the aquifer along the San Gabriel River flow path—the two most down-gradient wells. We see similar trends in carbon-13 and tritium isotopes where isotope activity is much lower in the confined part of the aquifer than in the unconfined part of the aquifer. These trends indicate: (1) groundwater in the confined parts of the northern segment of the Edwards (Balcones Fault Zone) Aquifer is much older than in the unconfined part of the aquifer, (2) the higher groundwater salinity in the confined part of the aquifer can be attributed to the lack of freshwater influxes from the unconfined part of the aquifer. These trends indicate that there is very little groundwater flow in the confined part of the aquifer and that most hydrologic activity—recharge, groundwater flow and discharge—is occurring in the unconfined part of the aquifer. The decrease in hydraulic gradient noted in Section 4.2 is additional evidence of relatively less groundwater flow in the confined parts of the aquifer (Figure 4.2.6).
Figures 4.7.13 and 4.7.14 show a comparison of groundwater isotopic composition in the northern segment of the Edwards (Balcones Fault Zone) Aquifer and underlying Trinity Aquifer. This comparison indicates that in most cases, Trinity Aquifer groundwater is isotopically similar to Edwards (Balcones Fault Zone) Aquifer groundwater in the confined part of the aquifer. In other words, old groundwater with little tritium and carbon-14 indicating little to no recent recharge.

Figure 4.7.1. Total dissolved solids concentration (in milligrams per liter) in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Data from Texas Water Development Board, 2017a).
Figure 4.7.2. Total dissolved solids concentration (in milligrams per liter) in the Trinity Aquifer (Data from Texas Water Development Board, 2017a).
Figure 4.7.3. A Piper diagram showing the range of groundwater compositions in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (blue dots) and the underlying Trinity Aquifer (green dots). The arrows indicate compositional changes along flow paths (Data from Texas Water Development Board, 2017a).
Figure 4.7.4. Groundwater types in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Data from Texas Water Development Board, 2017a).
Figure 4.7.5. Groundwater Carbon-13 isotopes (in per mil) in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Data from Texas Water Development Board, 2017a).
Figure 4.7.6. Groundwater Carbon-14 (in percent modern carbon) in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Data from Texas Water Development Board, 2017a).
Figure 4.7.7. Groundwater tritium (in Tritium Units) in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Data from Texas Water Development Board, 2017a).
Figure 4.7.8. Groundwater stable oxygen isotopes (δ¹⁸O, in per mil) in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Data from Texas Water Development Board, 2017a).
Figure 4.7.9. Groundwater stable oxygen isotopes ($\delta^{18}O$, in per mil) and stable hydrogen isotopes ($\delta^2H$, in per mil) in the northern segment of the Edwards (Balcones Fault Zone) and underlying Trinity aquifers (Data from Texas Water Development Board, 2017a).
Figure 4.7.10. Northern segment of the Edwards (Balcones Fault Zone) Aquifer and Trinity Aquifer groundwater and Waco precipitation stable hydrogen and oxygen isotopes (in per mil) relative to the Global Meteoric Water Line (Data from IAEA/WMO, 2004; Texas Water Development Board, 2017a).
Figure 4.7.11. Plot of precipitation oxygen isotopes versus time showing variation in isotopic composition during different months of the year (Data from IAEA/WMO, 2004; Texas Water Development Board, 2017a).
Figure 4.7.12. Bar diagrams showing changes in groundwater total dissolved solids, stable carbon and tritium isotope compositions along flow paths (Data from Texas Water Development Board, 2017a).
Figure 4.7.13. Groundwater tritium and carbon-14 isotopes in the northern segment of the Edwards (Balcones Fault Zone) and underlying Trinity aquifers. The arrow indicates down-dip groundwater compositions (Data from Texas Water Development Board, 2017a).
5.0 CONCEPTUAL MODEL OF GROUNDWATER FLOW IN THE NORTHERN SEGMENT OF THE EDWARDS (BALCONES FAULT ZONE) AND ASSOCIATED TRINITY AQUIFERS

The conceptual model of groundwater flow in the northern segment of the Edwards (Balcones Fault Zone) Aquifer is based on the hydrogeologic setting, described in Section 4.0. The conceptual model is a simplified representation of the hydrogeological features that govern groundwater flow in the aquifer. It includes the hydrostratigraphy, hydrogeologic framework, hydraulic properties, hydrologic boundaries, recharge, and discharge.

The northern segment of the Edwards (Balcones Fault Zone) Aquifer is the northern extent of the larger Edwards (Balcones Fault Zone) Aquifer that extends north of the Colorado River. The Edwards (Balcones Fault Zone) Aquifer is composed of the Georgetown
Formation, Edwards Limestone, and Comanche Peak Limestone (Figure 2.2.6). The northern segment of the Edwards (Balcones Fault Zone) Aquifer is also bounded by the Del Rio Clay and Walnut Formation that act as confining units. In the study area, the Trinity Aquifer is composed of the Glen Rose and Travis formations.

Work by Jones (2003; 2006) indicates groundwater flow through the northern segment of the Edwards (Balcones Fault Zone) Aquifer is generally west to east (Figure 4.2.4). Groundwater flow apparently converges on the major rivers and streams in or near the unconfined part of the aquifer—Brushy Creek, Colorado River, Salado Creek, San Gabriel River, and Lampasas River—the most likely discharge zones. The northern segment of the Edwards (Balcones Fault Zone) Aquifer likely recharges by infiltration of precipitation where the aquifer crops out as noted in Section 4.3. Groundwater inflow to and outflow from the northern segment of the Edwards (Balcones Fault Zone) Aquifer in the form of cross-formational flow is believed to be relatively minor, indicated by: (1) the lower hydraulic gradients in the confined part of the aquifer are probably indicative of an inactive aquifer characterized by little groundwater flow (Figure 4.2.4), (2) low hydraulic conductivity of bounding stratigraphic units such as the Del Rio Clay and the Walnut Formation and Glen Rose Formation, and (3) the low vertical hydraulic gradients between the Edwards (Balcones Fault Zone) Aquifer and underlying Trinity Aquifer (Figure 4.2.6). Cross-formation flow is also likely to be minor in up-gradient parts of the northern segment of the Edwards (Balcones Fault Zone) Aquifer as suggested by large differences in water levels between the Edwards (Balcones Fault Zone) Aquifer and underlying Trinity Aquifer indicating perch groundwater in the Edwards (Balcones Fault Zone) Aquifer (Figure 4.2.6).

The schematic diagram in Figure 5.0.1(A) is a conceptual block diagram illustrating aquifer contact relationships and sources and sinks of groundwater in the northern segment of the Edwards (Balcones Fault Zone) Aquifer used by Jones (2003). The original groundwater availability model for the northern segment of the Edwards (Balcones Fault Zone) Aquifer was a one-layer model that assumed no interaction with the underlying Trinity Aquifer and simulates cross-formation discharge to overlying units using a general-head boundary. Figure 5.0.1(B) shows the proposed conceptual model for the updated groundwater availability model for the northern segment of the Edwards (Balcones Fault Zone) Aquifer. The updated model would be made up of at least three layers simulating the northern segment of the Edwards (Balcones Fault Zone) Aquifer and underlying parts of the Walnut Formation and Trinity Aquifer. Cross-formational flow between the Edwards (Balcones Fault Zone) Aquifer and overlying stratigraphic units would be simulated either using a general-head boundary or and additional model layer.
Figure 5.0.1. Schematic cross section and conceptual groundwater flow model for the northern segment of the Edwards (Balcones Fault Zone) Aquifer Groundwater Availability Model. (A) conceptual model used in Jones (2003) and (B) proposed conceptual model.
Figure 5.0.1. (continued).
6.0 ACKNOWLEDGEMENTS

I would like to acknowledge the interest in this project shown by the stakeholders who attended the initial and conceptual model stakeholder advisory forums. I would also like to thank the Clearwater Underground Water Conservation District and Mike Keester for their help that made completion of this project possible. I would also like to acknowledge staff who reviewed and otherwise contributed to this conceptual model report, Cindy Ridgeway, Larry French, and Alisa Richey.

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APPENDIX A. CONCEPTUAL MODEL REPORT COMMENTS AND RESPONSES

General Comments

1.