Chapter 2

Conceptual Model for the Edwards–Trinity (Plateau) Aquifer System, Texas

Roberto Anaya[1]

Introduction

The passage of Senate Bill 1 in 1997 established a renewed public interest in the State's water resources not experienced since the drought of the 1950s. Senate Bill 1 of 1999 and Senate Bill 2 of 2001 provided state funding to initiate the development of groundwater availability models for all of the major and minor aquifers of Texas. The development and management of Groundwater Availability Models (GAMs) has been tasked to the Texas Water Development Board (TWDB) to provide reliable and timely information on the State's groundwater resources. TWDB staff is currently developing a GAM for the Edwards–Trinity (Plateau) aquifer. An essential task in the design of a numerical groundwater flow model is the development of a conceptual model. The conceptual model is a generalized description of the aquifer system that defines boundaries, hydrogeologic parameters, and hydrologic stress variables. The conceptual model helps to compile and organize field data and to simplify the real-world aquifer flow system into a graphical or diagrammatical representation while retaining the complexity needed to adequately reproduce the system behavior (Anderson and Woessner, 1992).

The first step in the development of a conceptual model is to delineate the study area and form an understanding of its physical landscape with regard to the physiography, climate, and geology. Another early step also involves the research and investigation of previous aquifer studies. Intermediate steps bring together all of the information for establishing the hydrogeologic setting which consists of the hydrostratigraphy, structural geometry, hydraulic properties, water levels and regional groundwater flow, recharge, interactions between surface water and groundwater, well discharge, and water quality. Assembling the information into organized descriptive text, maps, tables, and diagrams concludes the development of the conceptual model. The purpose of this chapter is to document the development of the conceptual model for the Edwards–Trinity (Plateau) aquifer system in central-west Texas.

[1] Texas Water Development Board

Geographic Setting

The Edwards–Trinity (Plateau) aquifer extends over an area of about 35,000 square miles beneath all or parts of 38 counties (Ashworth and Hopkins, 1995) in central-west Texas (Figure 2-1). Most of the counties have relatively sparse populations concentrated in small towns, usually the county seats (Figure 2-2). The study area extends to the northwest to include the Cenozoic Pecos Alluvium aquifer and to the southeast to include the Trinity aquifer because of their hydraulic connection to the Edwards–Trinity (Plateau) aquifer (Figure 2-1). The Edwards–Trinity (Plateau) aquifer is also hydraulically connected to several other major and minor aquifers of the state, which is discussed later in this chapter. The study area falls within five Regional Water Planning Areas (Far West Texas, Lower Colorado, Plateau, Region F, and South Central Texas), although the aquifer is located mostly within Region F and the Plateau region (Figure 2-3). In addition to two Priority Groundwater Management Areas, there are about 29 groundwater conservation districts in the study area (Figure 2-3).

Physiography

Physiography describes the natural features of the landscape in the context of topography, landforms, surface drainage, soils, and natural vegetation, all of which reflect upon the geologic and climatic history of the region. In the United States, natural regions have been hierarchically delineated into physiographic divisions, provinces, and sections (Fenneman, 1931; Thornberry, 1965). Under this classification, the Edwards Plateau Section occupies the southern margin of the Great Plains Province, which is located within the western portion of the Interior Plains Division. The Bureau of Economic Geology (BEG) at The University of Texas at Austin has delineated the Edwards Plateau into one of seven physiographic provinces within the state of Texas (Wermund, 1996). The BEG further subdivides the Edwards Plateau Province into the Principal Edwards Plateau, the Pecos Canyons, and the Stockton Plateau sub-provinces (Figure 2-4). The LBJ School of Public Affairs delineated eleven natural regions within the state for statewide and/or regional analysis (LBJ School of Public Affairs, 1978). Many of the eleven regions also consist of two or more sub-regions. The Edwards Plateau Region includes the Live Oak-Mesquite Savanna, Balcones Canyonlands, and Lampasas Cut Plain sub-regions. The 1957 revision of Erwin Raisz's "Landforms of the United States" remains a classic hand drawn map of natural features depicting landforms and physiographic regions of the country with remarkable detail (Raisz, 1957). The landscape image on Figure 2-4 identifies natural landforms and physiographic regions of the Edwards Plateau and adjacent landscape compiled from the various classifications.

The Edwards Plateau is defined here from the perspective of the laterally contiguous sediments of the Edwards–Trinity (Plateau) aquifer system. The Balcones Fault Zone, a system of stair-stepped faults essential to the development of the Edwards Plateau, has displaced the aquifer sediments and juxtaposed them against younger and less resistant sediments of the Gulf Coastal Plains. The resulting fault displacements have formed the Balcones Escarpment, a feature so prominent, that the effects on the landscape along the

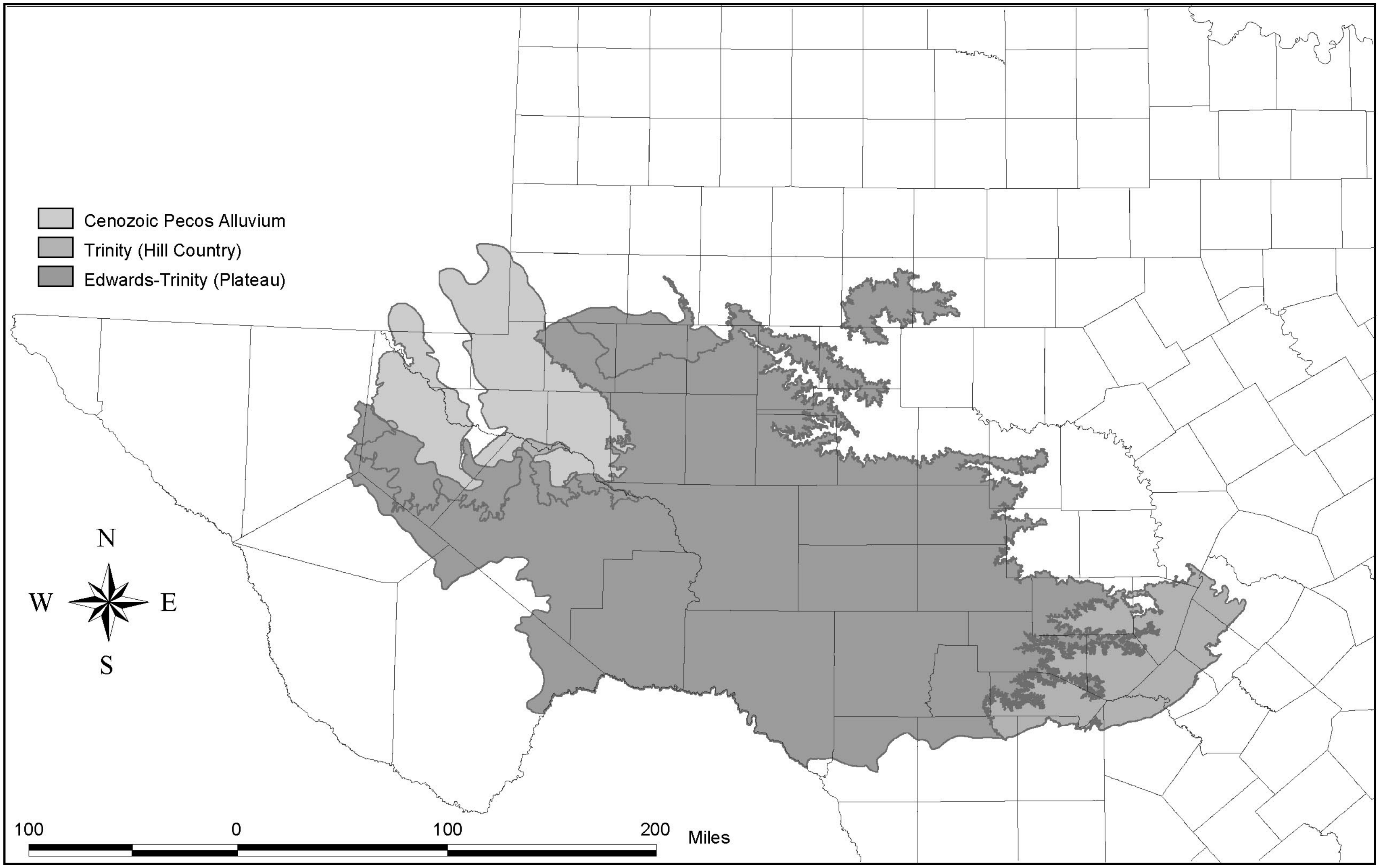


Figure 2-1: Areal extent of the Edwards–Trinity (Plateau) aquifer and the study area.

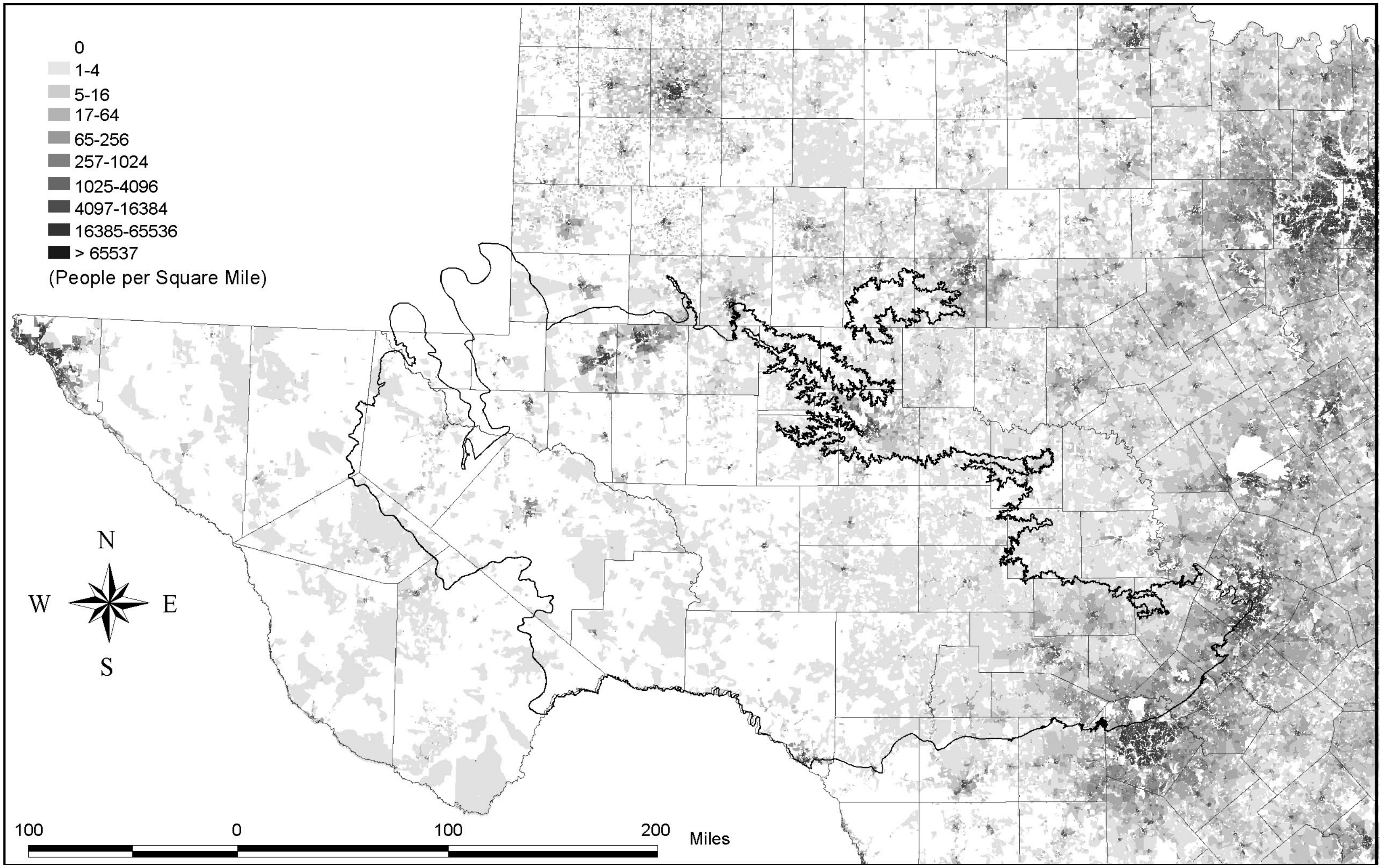


Figure 2-2: Population density from 2000 census.

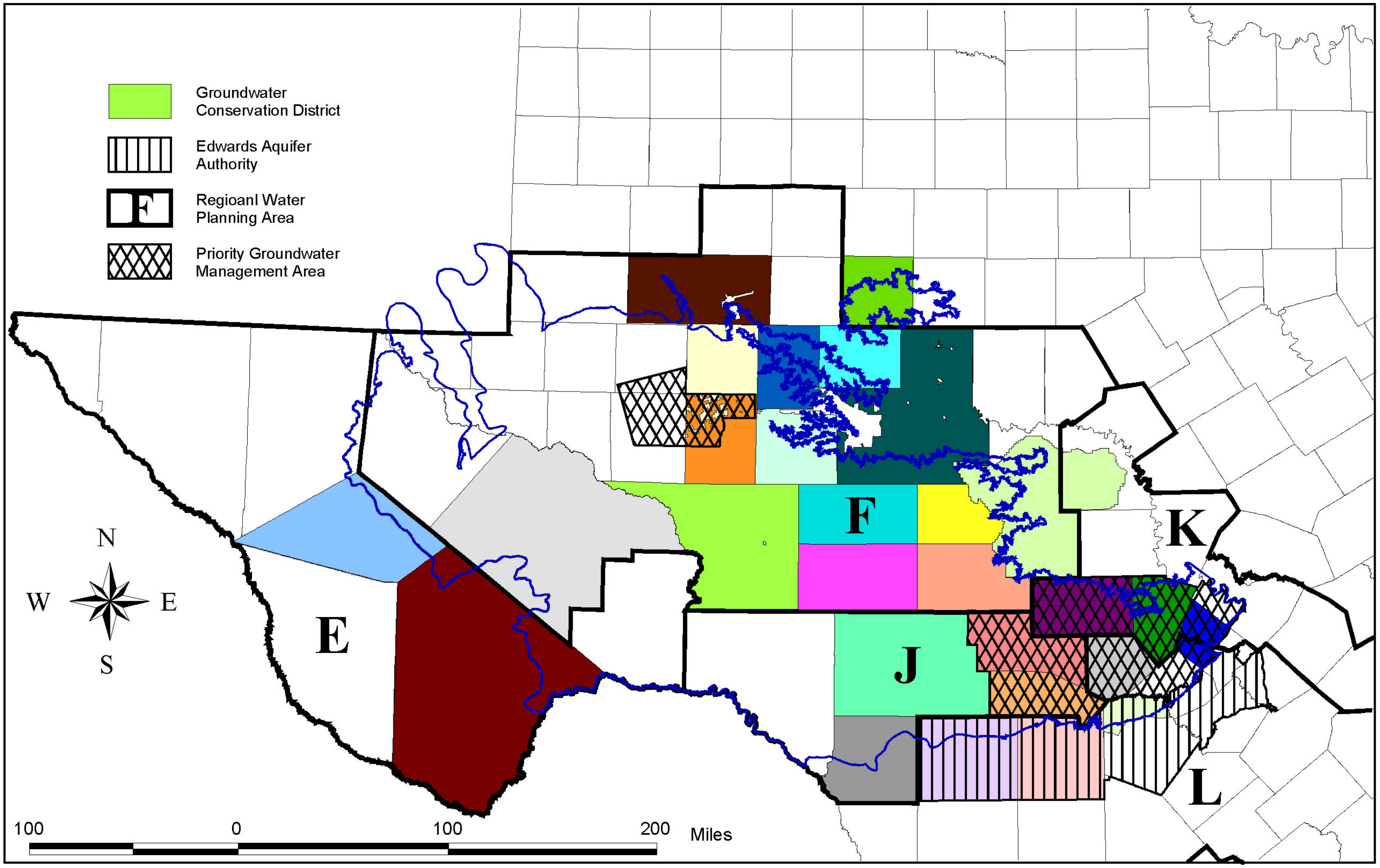


Figure 2-3: Boundaries of Regional Water Planning Areas (E = Far West Texas, F = Region F, J = Plateau, K = Lower Colorado, L = South Central Texas), Groundwater Conservation Districts, and Priority Groundwater Management Areas.

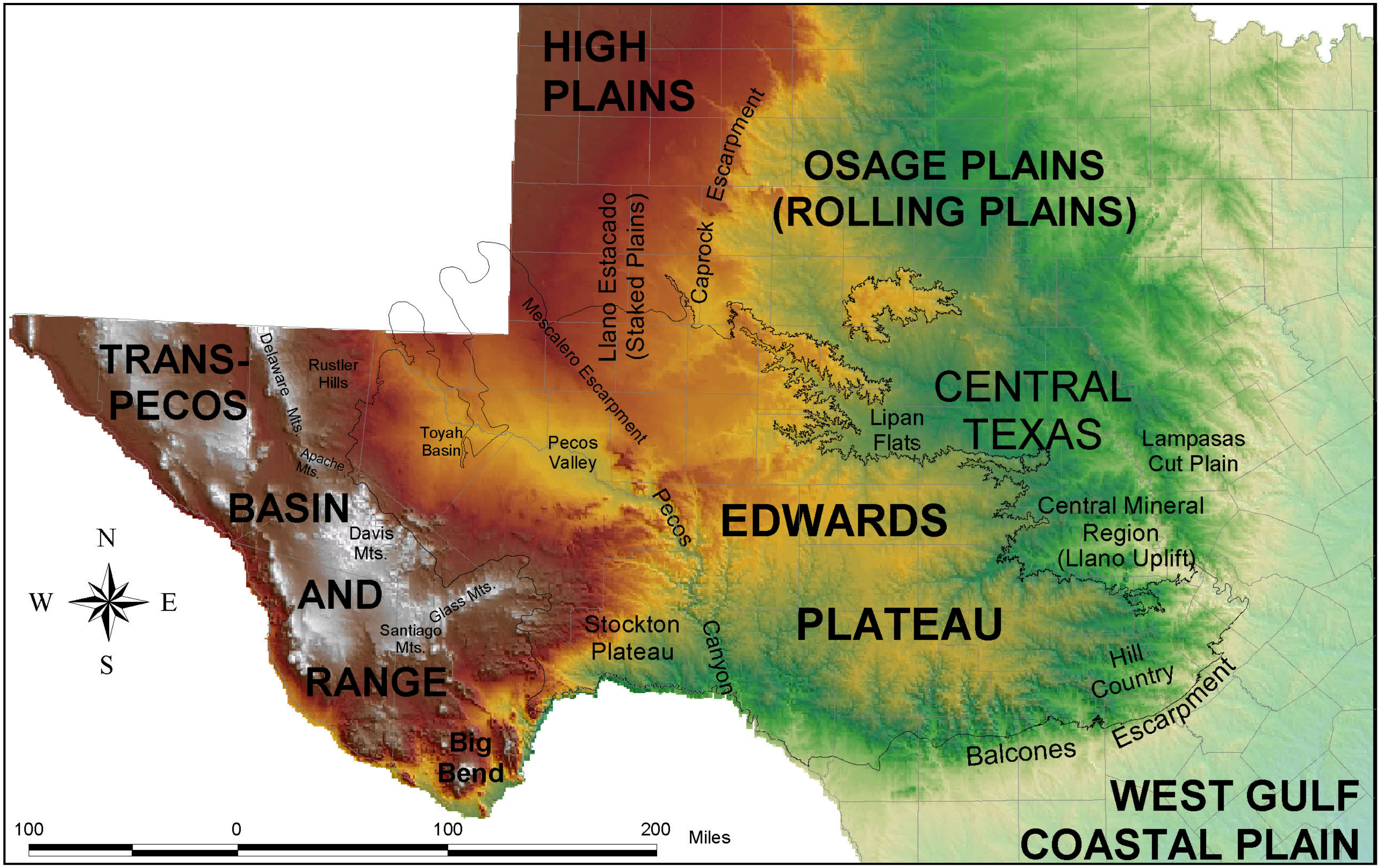


Figure 2-4: Landscape image showing natural landforms and physiographic regions.

southern and southeastern margins of the plateau are visible from space (Figure 2-5). A pronounced removal of Edwards Group or upper layer of aquifer sediments by the headward erosion of major streams transecting the Balcones Escarpment formed the Balcones Canyonlands, more traditionally known as the Hill Country. The plateau and the aquifer sediments then terminate to the east along a margin of exposed Paleozoic and Pre-Cambrian rocks in the Central Mineral Region, often referred to as the Llano Uplift. Alluvial deposits form the Lipan Flats where the Concho River has cut and filled its way onto the northern plateau. Beyond the Lipan Flats and the northern margin of the Edwards Plateau are the Osage Plains, more commonly called the Rolling Plains, which extend west to the Caprock Escarpment of the High Plains. A thin drape of remnant Quaternary sand sediments, with playa lakes characteristic of the Llano Estacado (Staked Plains) region of the High Plains, extend down to cover a small area of the northeastern Edwards Plateau. These remnant sand sediments and the underlying Edwards–Trinity aquifer sediments terminate to the southwest along the southeast trending Mescalero Escarpment. The eastern flanks of the Rustler Hills (east of the Delaware Mountains), and the Apache, Davis, Glass, and Santiago mountains of the Trans-Pecos Basin and Range form the western boundary of the Edwards Plateau. Thick alluvial deposits fill the Pecos Valley between the western plateau boundary and the Mescalero Escarpment. A local drainage area between the Davis Mountains and the Pecos River is often referred to as the Toyah Basin. The Edwards–Trinity (Plateau) aquifer sediments extend beneath the Stockton Plateau located east of the Glass and Santiago mountains and west of the Pecos River Canyon and continue south into the western Big Bend region and across the Rio Grande into the northern area of the Mexican Chihuahua Desert.

Topography and Landform

The landform of the Edwards Plateau may be described as a flat tableland gently sloping from the northwest at about 3,000 feet above sea level to the southeast at about 2,000 feet above sea level (Figure 2-6). The Edwards Plateau is also one of the largest contiguous karst regions in the United States (Kastning, 1984). The karst morphology exhibits poorly integrated solution features with a sponge-like pattern on the plateau proper, whereas the southern plateau margin has well defined corridors of connected conduits aligned with faults and fractures of the Balcones Fault Zone (Kastning, 1984). The plateau is capped with thick Edwards Group limestone sediments that protect underlying less resistant Trinity and Paleozoic sediments from erosion. The Edwards Plateau has been in a prevailing state of erosion since the formation of the Balcones Escarpment. As the protective limestone cap is breached along the plateau's margins, streams easily carve deep canyons into the softer underlying sediments along the northern, eastern, and southern edges of the plateau. Topographic relief for the entire study area ranges from about 5,000 feet in the mountains of the Trans-Pecos to about 500 feet along the Lake Austin reach of the Colorado River where it flows across the Balcones Escarpment. The greatest local surface relief occurs in the mountainous Trans-Pecos region and the western Hill Country.

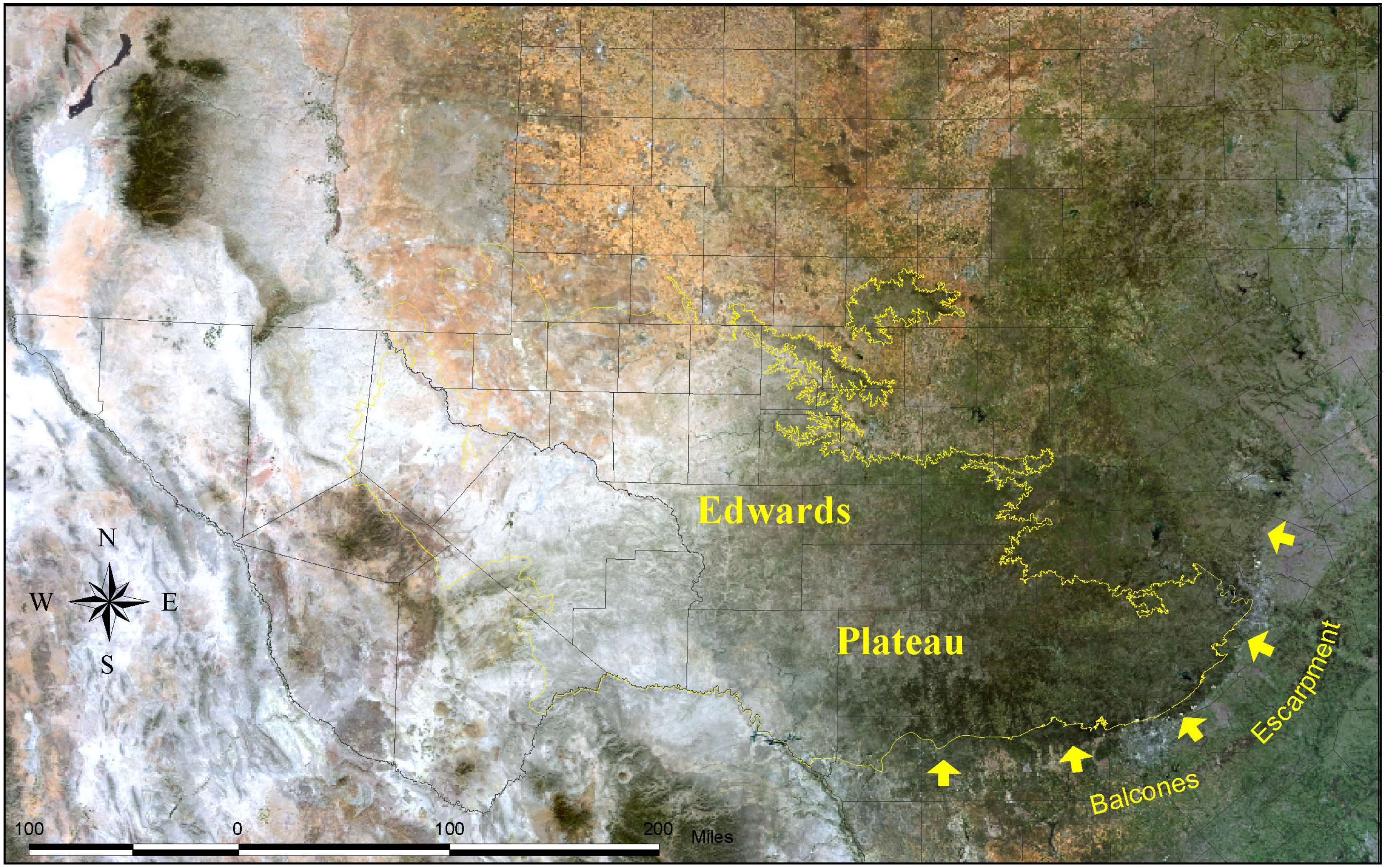


Figure 2-5: Satellite image view of central-west Texas showing the Edwards Plateau and the Balcones Escarpment (Image source from University of Texas Center for Space Research).

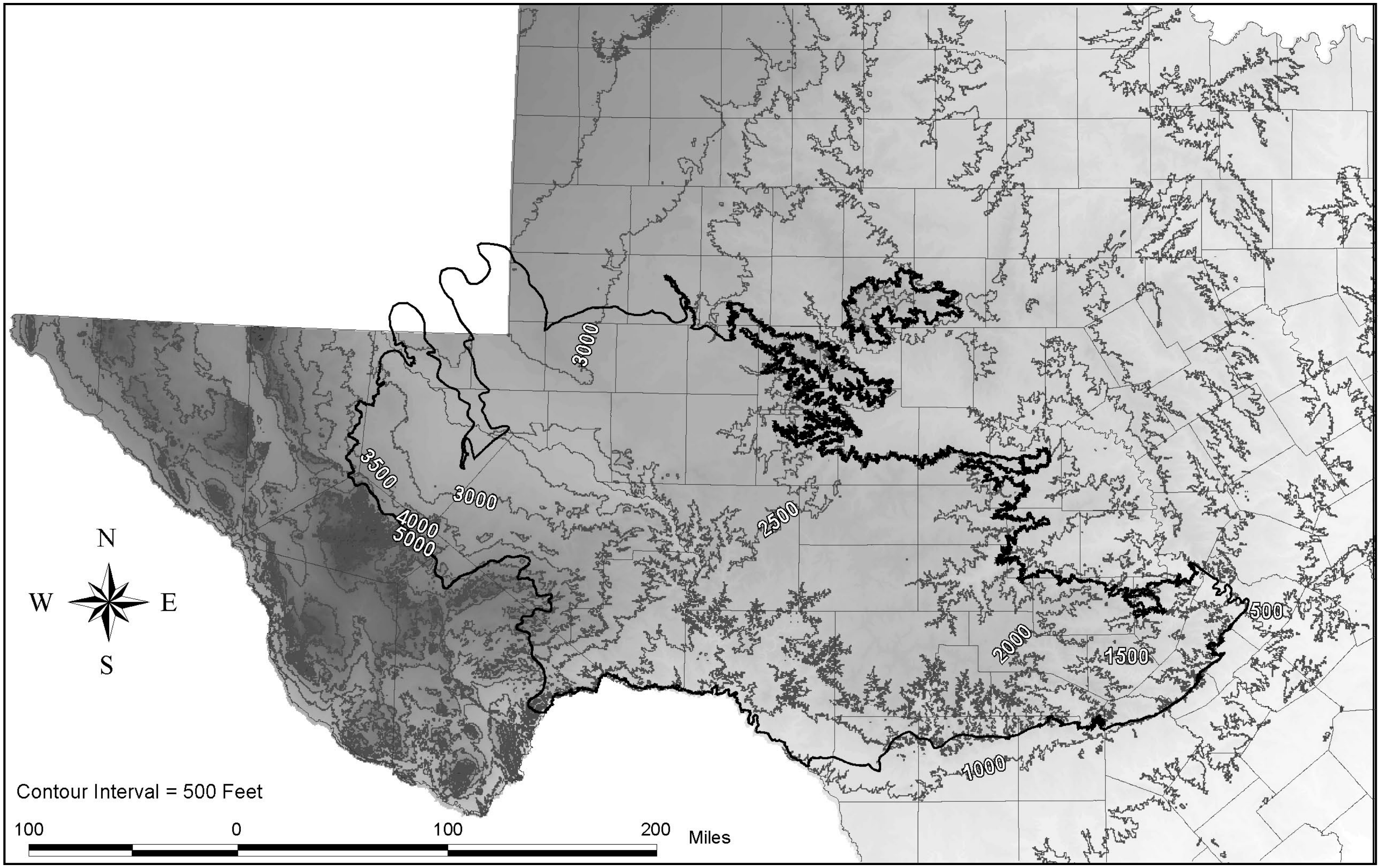


Figure 2-6: Topographic elevations of the Edwards Plateau.

Surface Drainage

Permanent surface water is sparse to non-existent on the Edwards Plateau and occurs only along the spring-fed tributaries that dissect the northern, eastern, and southern plateau margins. Streams draining the plateau have a very dendritic or branch-like pattern characteristic of drainage patterns for flat-lying geologic strata (Figure 2-7). Stream density (stream channel length per unit area) on the plateau is mostly influenced by local and regional surface-water gradients. Stream density increases with increasing surface water gradients and approaches zero as the topography becomes flat where playa lakes may be the dominant surface-drainage features. However, there is also a distinct increase in stream density towards the east that may be attributed to both the spatial distribution of eastward-increasing mean annual precipitation and the southeastward regional outflow of groundwater draining from springs of the Edwards–Trinity (Plateau) aquifer. Tributary streams of the Colorado River such as the Concho, San Saba, Llano, and Pedernales rivers drain the northeastern portion of the Edwards Plateau into the Lipan Flats and the Llano Uplift. The Blanco, Guadalupe, Medina, Sabinal, Frio, and Nueces rivers drain the southeastern and southern portion of the plateau through the Hill Country and across the Balcones Escarpment. The Pecos River and Devils River, both major tributaries to the Rio Grande, drain the entire southwestern half of the study area. Although there are some small surface-water bodies (less than one square mile) in the central region of the plateau, the only noteworthy water bodies on the plateau are Big Lake (more often a dry lakebed) in Reagan County, Orient Reservoir in Pecos County, and Balmorhea Lake in Reeves County. Other much larger water bodies along the edge of the Edwards Plateau include Amistad Reservoir in Val Verde County, Twin Buttes and San Angelo Reservoirs in Tom Green County, and E. V. Spence Reservoir in Coke County.

Soil Development

The predominant soils for most of the Edwards Plateau are classified as Ustolls, a sub-order of Mollisols that drain easily and develop under grass or savanna type vegetation in subhumid to semiarid climates (USDA, 1999). In the northwestern-most portion of the plateau, remnant soils thicken into more sandy, loamy soils characteristic of the Staked Plains. These soils are classified as Aridisols and are based on the limited availability of soil moisture to sustain plant growth (USDA, 1999). The Aridisols also extend westward across the Pecos Valley into the Trans-Pecos Basin and Range, cover the southern portion of the Stockton Plateau, and continue south into the Big Bend region. In the eastern most portion of the plateau where the Edwards Group sediments have been removed, the soils have minimal soil horizon development and form on steep slopes of young geomorphic surfaces in a humid to subhumid climate (USDA, 1999; University of Idaho, undated). These soils of the eastern Hill Country are classified as Inceptisols. Another soil order found on the plateau includes the Vertisols, which are clay-rich and have high shrink and swell potential (USDA, 1999; University of Idaho, undated). These Vertisols are located in a small central portion of the plateau along the northwest to southeast trending flat topographic divide of the Colorado River and Rio Grande and in another small area of southern Reeves and western Pecos counties (Figure 2-8). Pleistocene paleo-soils that

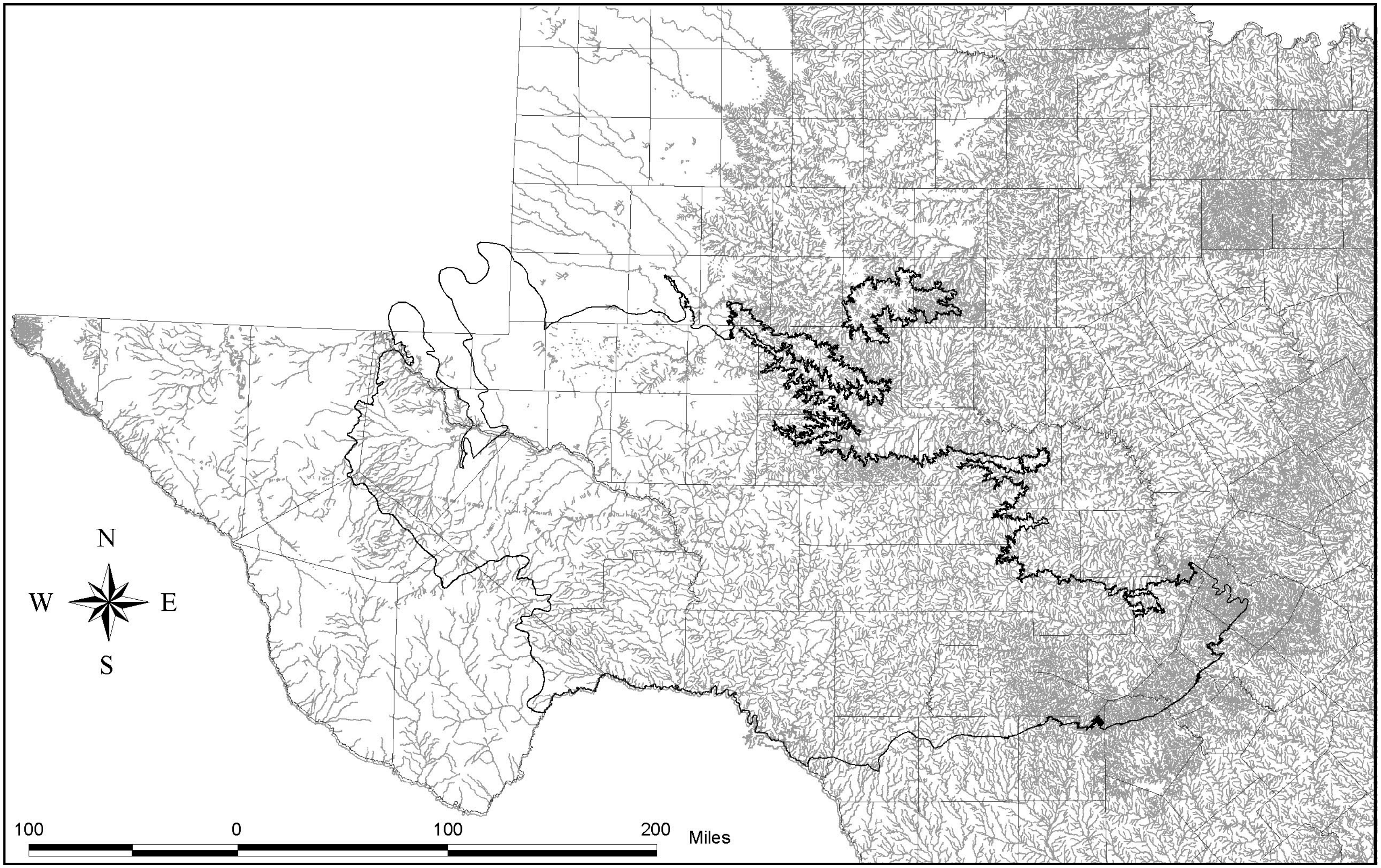


Figure 2-7: Drainage density and dendritic pattern of surface water drainage on the Edwards Plateau.

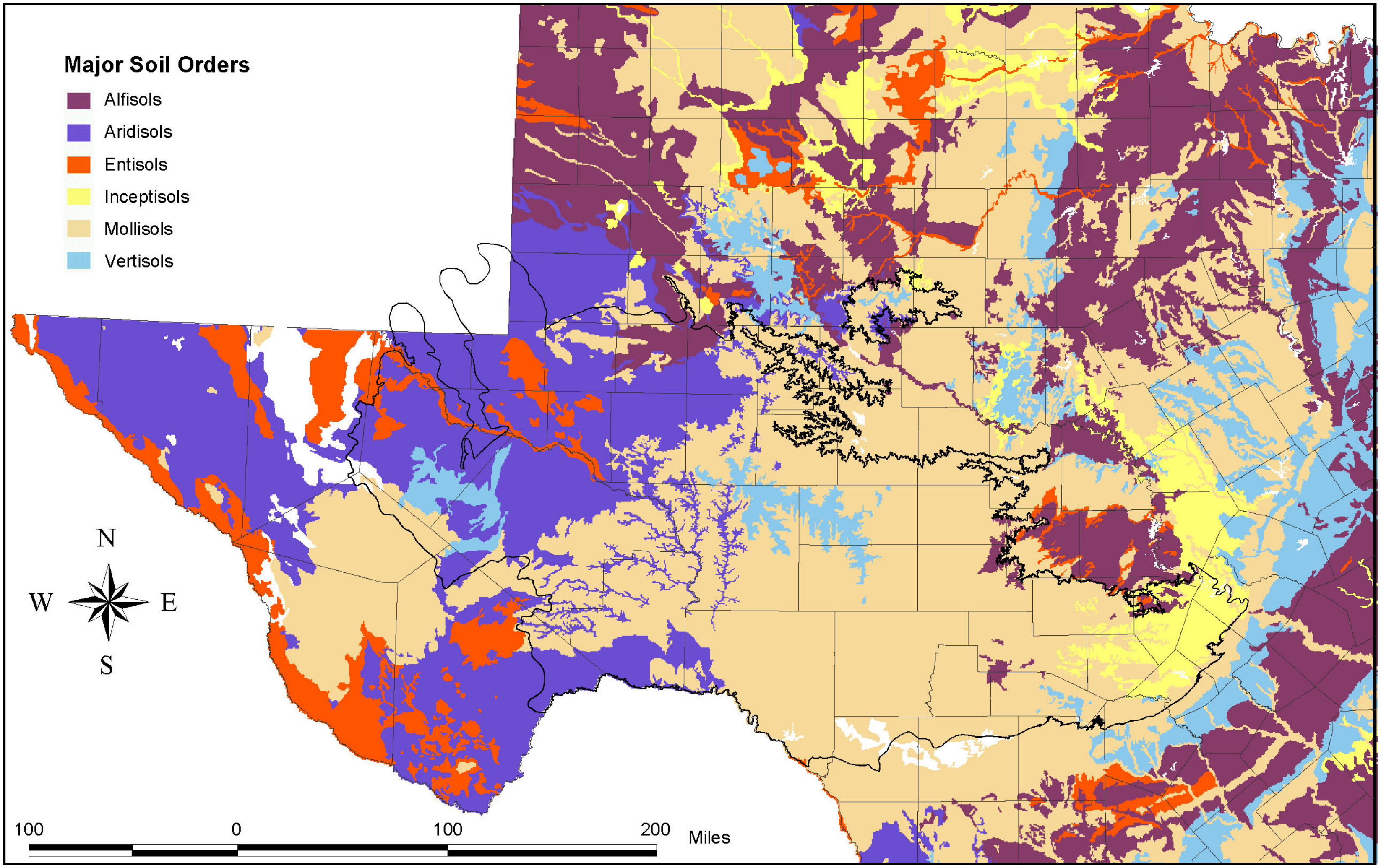


Figure 2-8: Spatial distribution of soil order types on the Edwards Plateau.

formed about 0.73 to 2.0 million years before present and often called “terra rossas” may be found scattered throughout the plateau, usually within caves and sinkholes where they have been protected from erosion (Young, 1986). Following the last glacial maximum of the Late Pleistocene, the rate of soil erosion on the plateau is thought to have increased due to an increase in aridity and increased variability of seasonal precipitation (Cooke and others, 2003). However, this climate-driven event produced a rate of soil erosion an order of magnitude less than the more recent human induced erosion of soil from the plateau (Cooke and others, 2003). Heavy grazing and the suppression of natural grass fires during the past 150 years of European settlement have augmented the erosional state of the plateau and allowed the soils to develop thin and stony characteristics (Mecke, 1996). The thin characteristic nature of soils of the Edwards Plateau is shown in Figure 2-9.

Natural Vegetation

Early Spanish explorers described the vegetation on most of the Edwards Plateau as being dominated by a diversity of mid to tall grasses with short grasses covering the more arid western regions (Mecke, 1996). The grasslands have since been transformed by unsustainable landuse into a stunted scrubby savanna of oak, juniper, and grass in the north and east and desert shrub and woody mesquite brush in the southwest. The combined landuse effects of overgrazing and inhibiting the natural rejuvenation of grasses by fire allows invasive woody species such as mesquite or *ashe juniper,* often referred to as cedar, to change the landscape. The loss of grasslands reduce the amount of effective rainfall available for groundwater recharge and increase soil erosion while the woody vegetation consume more of the effective rainfall drying up natural springs. Salt cedar has invaded some stream valleys contributing to significant amounts of evapotranspiration. On the steeper canyon slopes, oak forests and oak–juniper woodlands are common. Some recent range management and brush control projects such as the Bamberger Ranch in Blanco County have shown that restoring the native grasslands is not only possible, but also beneficial in recovering springs dehydrated by the loss of grasslands to invasive and thirsty woody vegetation. Additional discussion of brush management on the plateau is provided in a later chapter.

Landuse

Ranching of cattle, sheep, and goats along with wild game hunting leases are the primary forms of land use except for the northern portion of the plateau where irrigated croplands of cotton and grain sorghum are the more dominant land use. Oil and gas production from deep underlying Permian Basin sediments is also common in the northern and western portions of the plateau. Hay, pasture, and small grains are grown in some of the valleys along the southern and eastern margins of the plateau where surface water and rainfall is more readily available. Over a sufficient period of time, mankind is capable of changing the natural vegetation, soils, hydrologic characteristics, and consequently the natural physiographic features of a large region such as the Edwards Plateau through landuse alone.

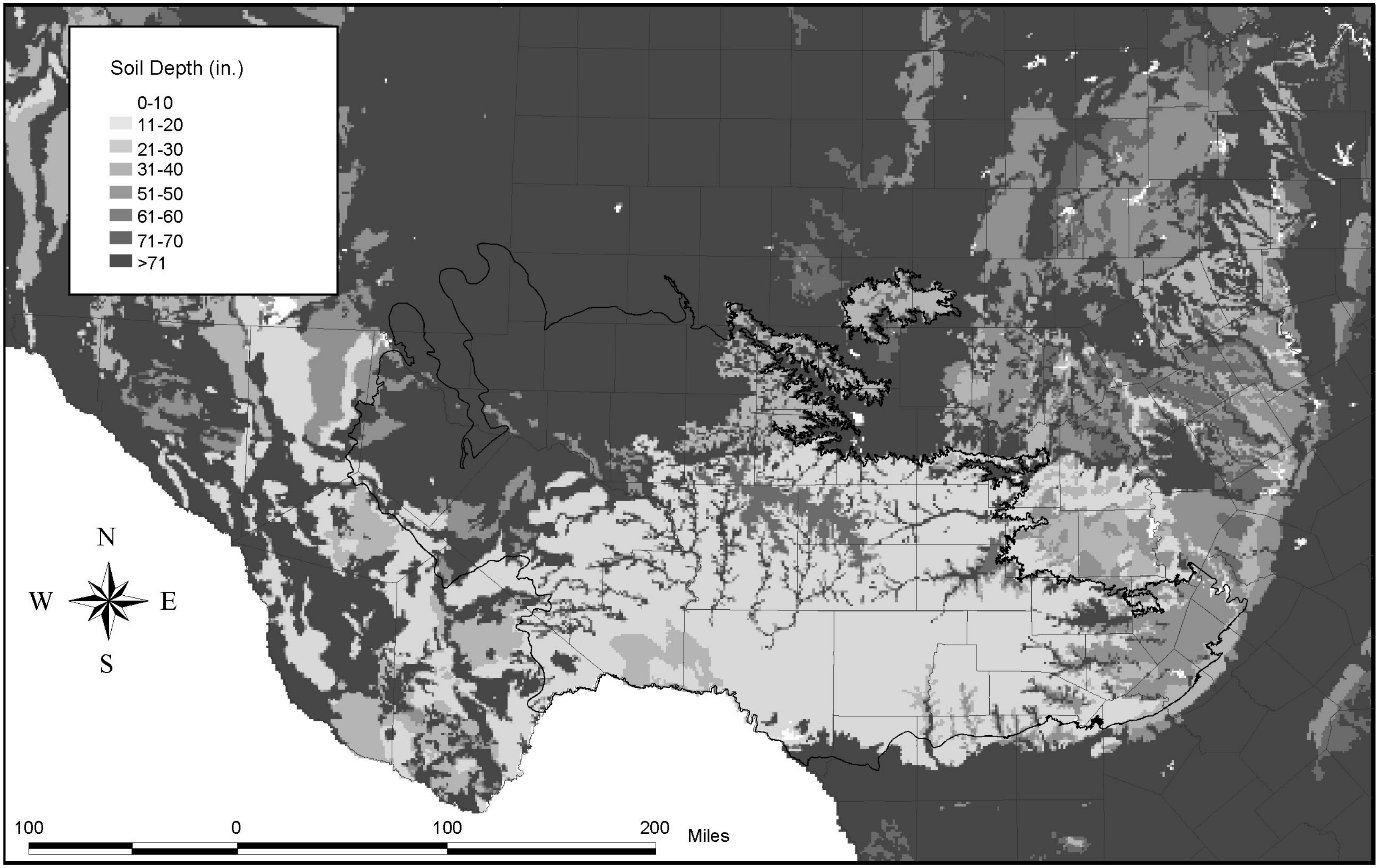


Figure 2-9: Spatial distribution of soil thickness on the Edwards Plateau. Note the thinner soils of the plateau.

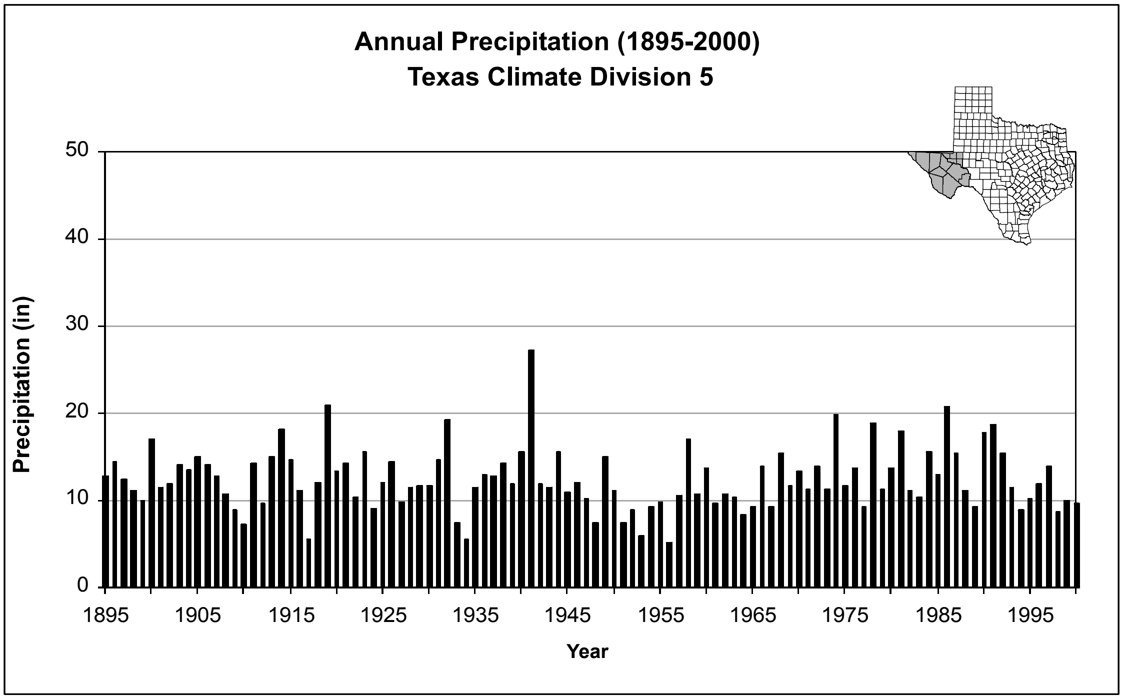
Climatic History

The climate of the Edwards Plateau was twice as wet during the Pleistocene as it is today according to studies of the "terra rossas" found in central Texas (Young, 1986). At some point after the last major ice age, the climate became more arid and variable (Cooke and others, 2003). The more recent climate of the Edwards Plateau ranges from subhumid in the eastern to semiarid in the western plateau (Walker, 1979). The long-term mean annual precipitation for the study area ranges from about 34 inches in the east to about 12 inches in the west (Figure 2-10, for years 1895 through 2000). On the eastern two thirds of the Edwards Plateau, precipitation occurs mostly during late spring and early fall as cool northern frontal air masses collide with warm moist Gulf air masses from the south. On the western third of the plateau, most of the precipitation occurs during July, August, and September. Figure 2-11 shows the significance of orographic precipitation along the Balcones Escarpment that is evident by the westward distortion of the thirty-year mean annual rainfall contours for 1961 to 1990 (Carr, 1967).

Tropical disturbances occasionally find their way onto the plateau from the warm late summer waters of the Gulf of Mexico and contribute to variability in annual precipitation totals. The variability of rainfall generally increases towards the arid west (Bomar, 1983) and the variation of total monthly precipitation is greatest for the month of September throughout the plateau. Other variations in the mean annual precipitation of the plateau may also be attributed to the cyclic interaction between the Pacific Ocean and the atmosphere, known as the El Nino-Southern Oscillation. Precipitation usually increases during the El Nino phase and decreases during the La Nina phase with the greatest variations in rainfall occurring during the fall and winter periods (Slade, 2001). Moreover, the statistical data analysis of stream-flow and precipitation records suggest a slight apparent increasing trend in the general variability of precipitation events over time (Slade, 2001). Rates of evaporation are high throughout the plateau and range between 43 inches in the east (Walker, 1979) to 80 inches in the west (Rees and Buckner, 1980). Droughts are common on the Edwards Plateau with about 10 moderate to severe droughts during the last 100 years. The drought of record occurred during the 1950s, consistent with the rest of the state. Drought on the plateau is discussed in more detail in a later chapter.

Geologic History

The Edwards–Trinity (Plateau) aquifer is composed of Early Cretaceous age sediments of the Trinity, Fredericksburg, and Lower Washita groups (Figure 2-12). The Trinity Group sediments form the underlying Trinity portion of the aquifer while the Fredericksburg and Lower Washita Group sediments form the overlying Edwards portion of the aquifer. The Edwards–Trinity aquifer sediments rest unconformable on top of an uneven erosional surface of Pre-Cretaceous age sediments, mostly folded and faulted Paleozoic age sediments. The following subsections a brief historical account of the evolutionary development of the Edwards–Trinity (Plateau) aquifer system (Figures 2-13 and 2-14).



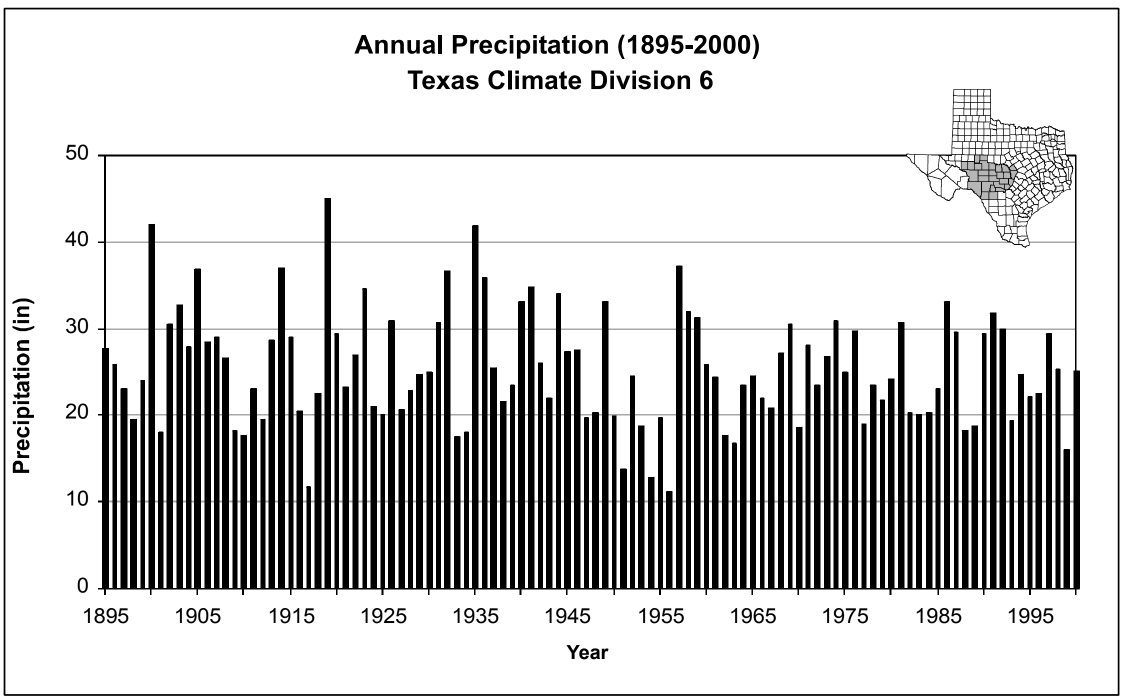


Figure 2-10: Long-term mean annual precipitation for 1895 to 2000.

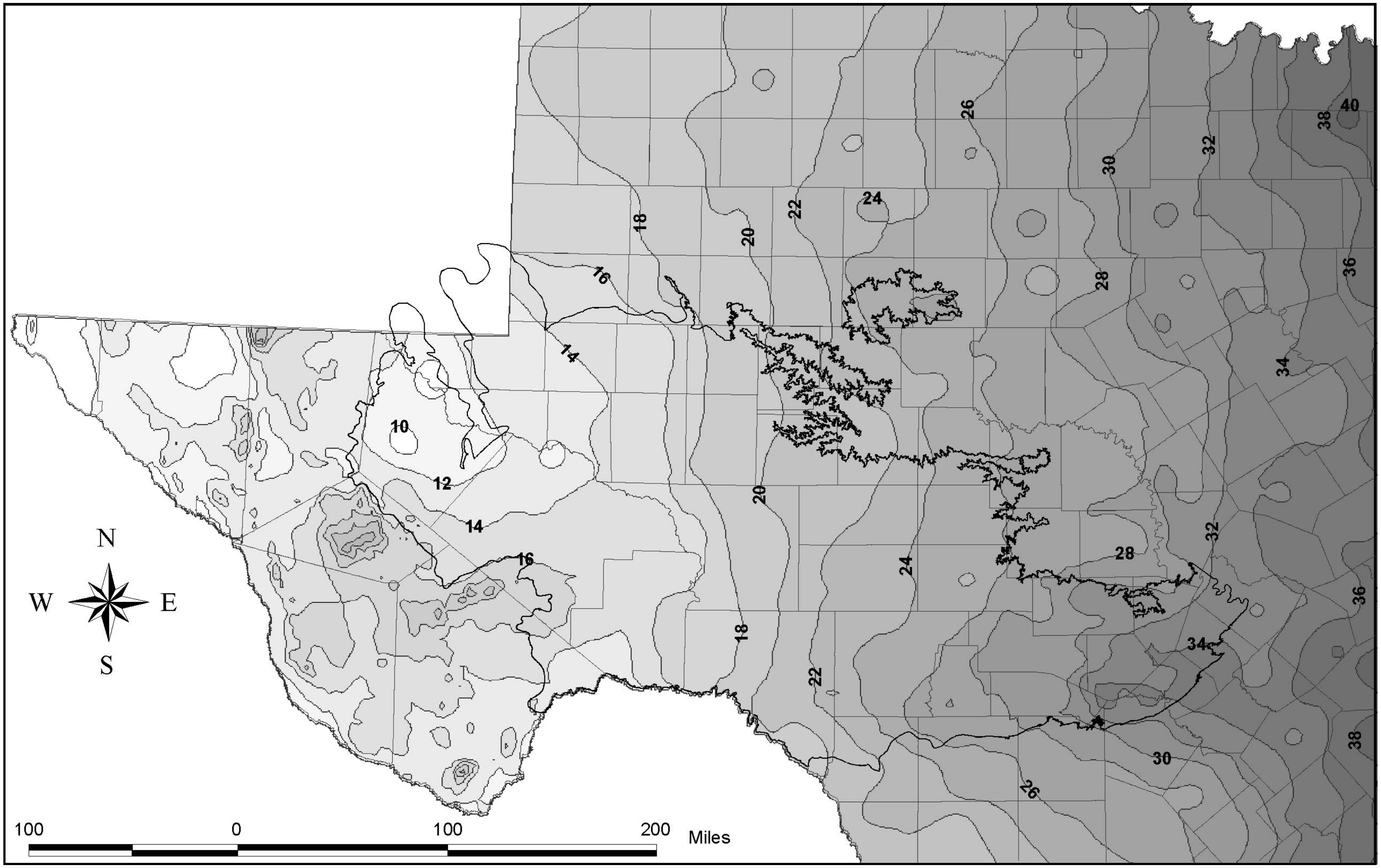


Figure 2-11: Mean annual precipitation for 1961 to 1990 in Texas (in inches).

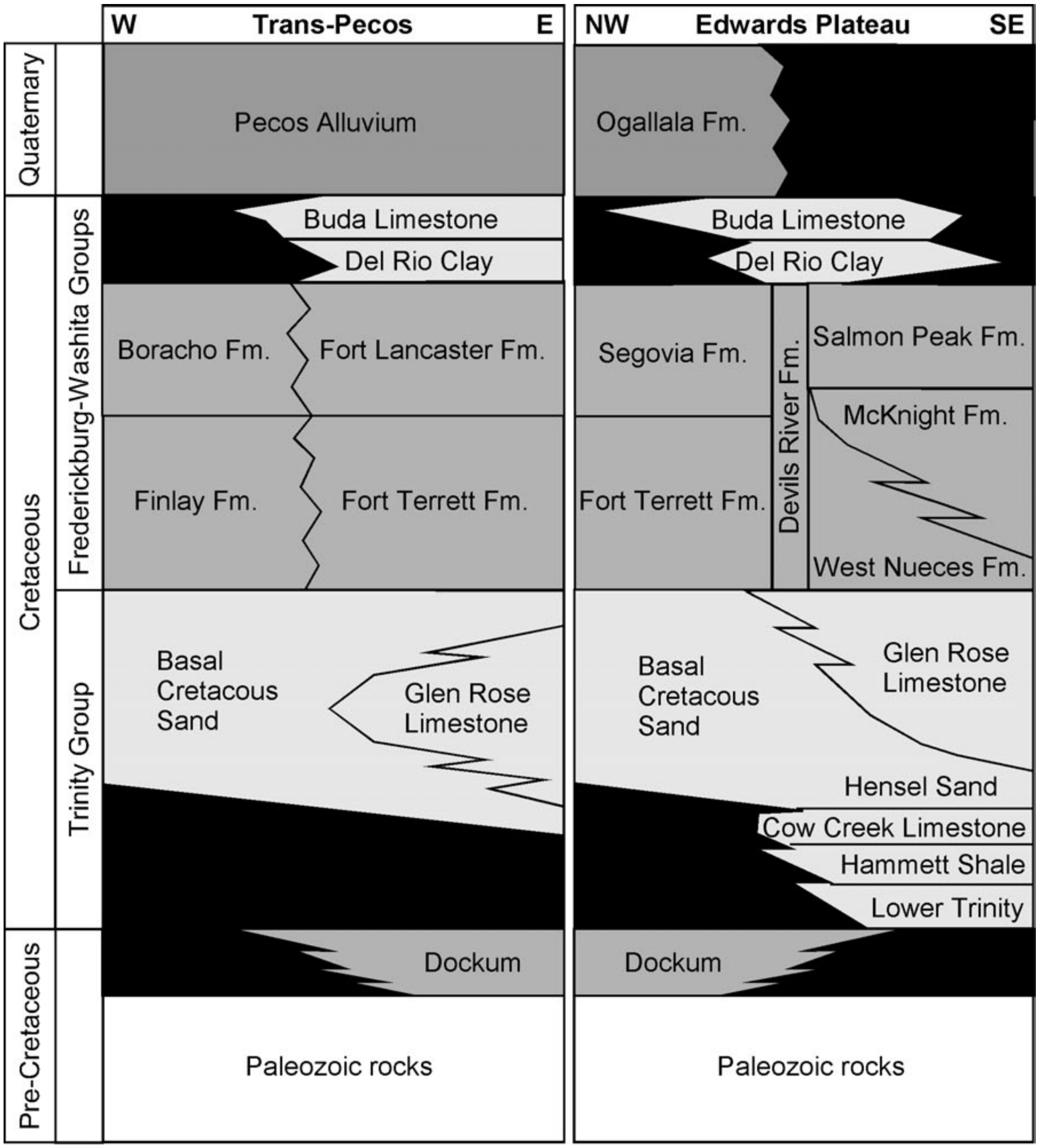


Figure 2-12: Stratigraphic chart of the Edwards–Trinity aquifer sediments (after Barker and Ardis, 1996).

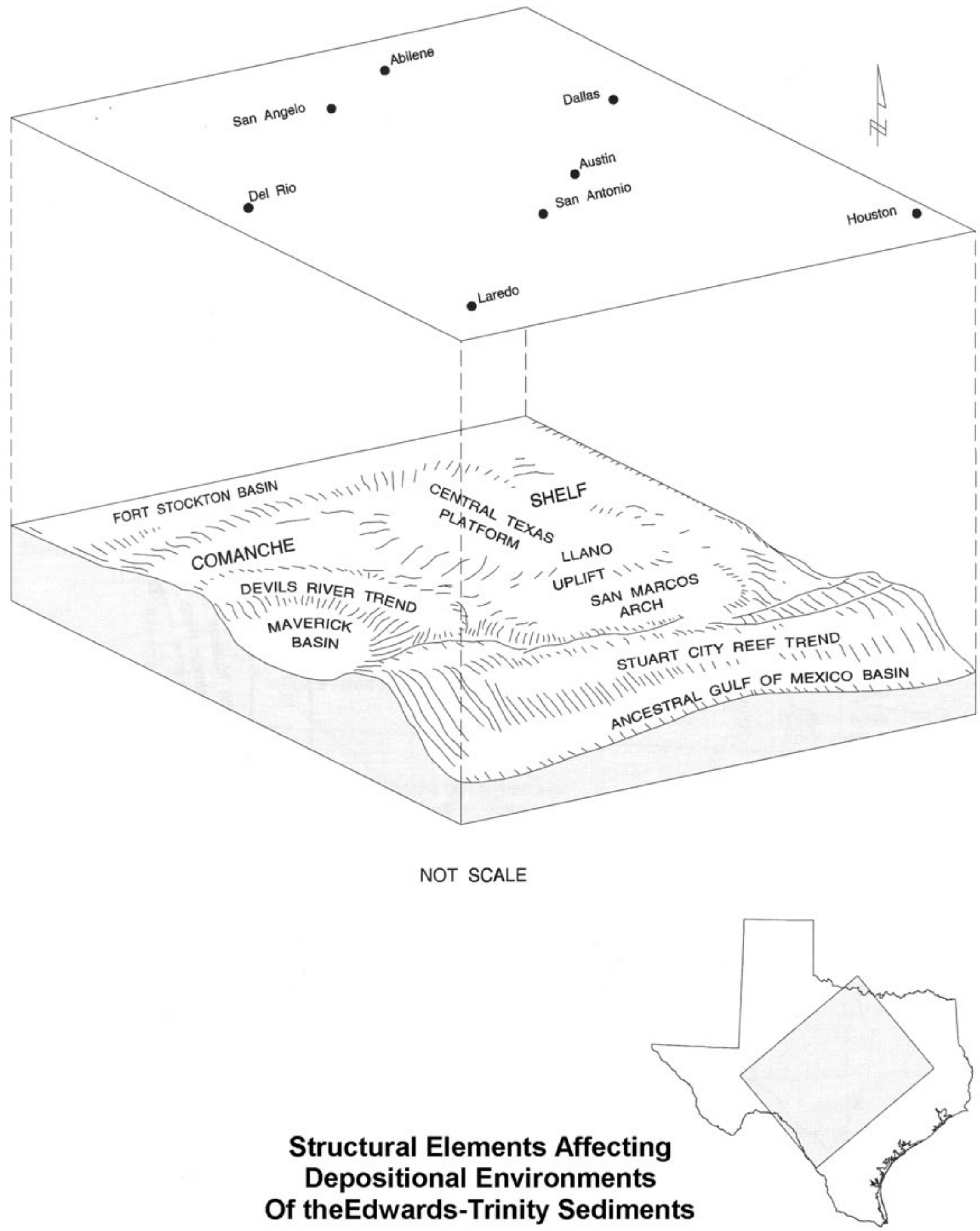


Figure 2-13: Structural elements affecting the depositional environments of the Edwards–Trinity sediments (from Barker and Ardis, 1996).

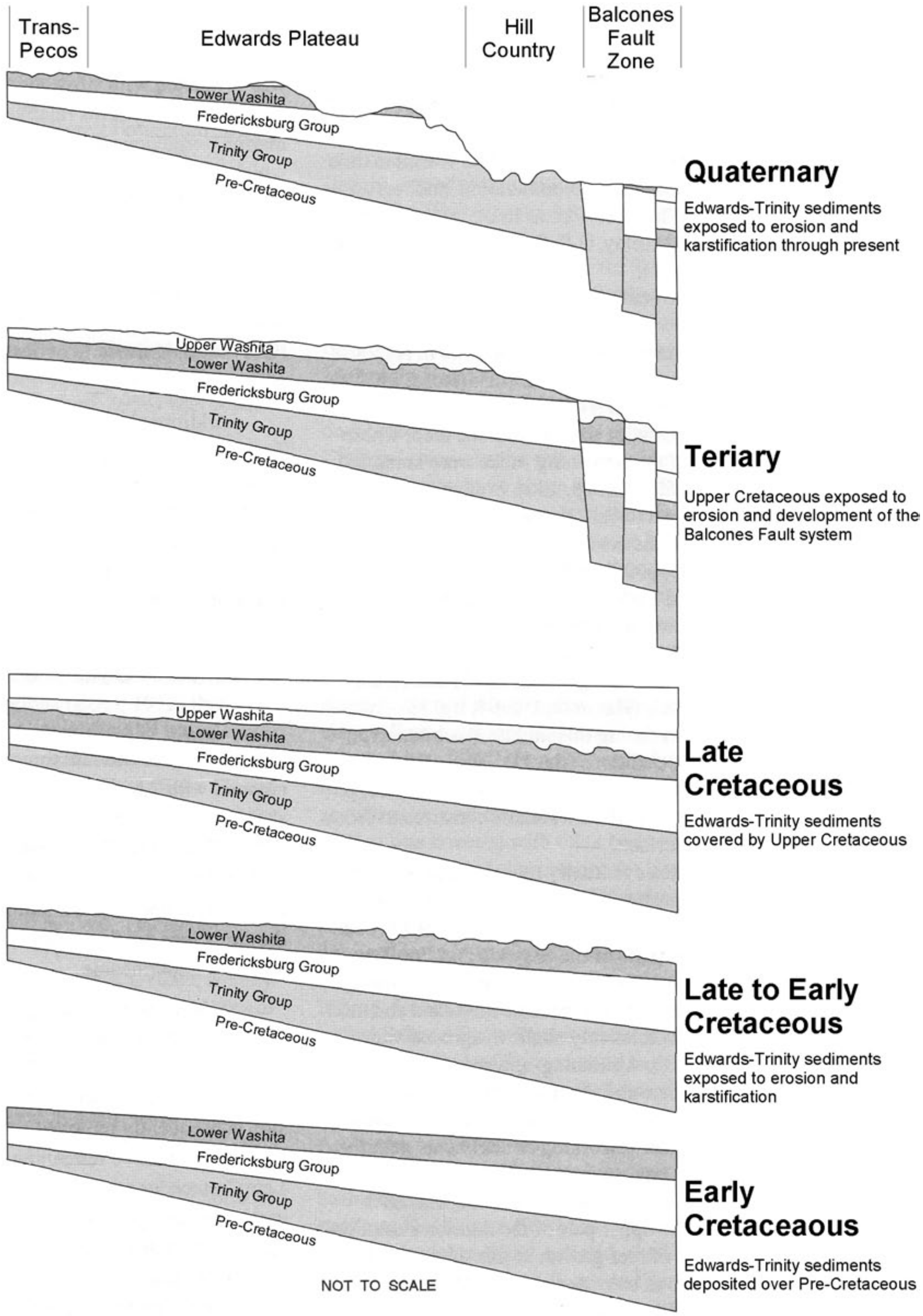


Figure 2-14: Evolutionary development of the Edwards–Trinity aquifer system (after Barker and others, 1994).

Paleozoic

The Paleozoic Era ended with a tectonic event known as the Quachita orogeny. This orogenic event resulted in the formation of a structural fold belt of sediments deposited during the Ordovician, Silurian, Devonian, and Mississippian periods. The sediments were uplifted, faulted, and folded into a late Paleozoic mountain range that extended from northern Mexico along the present day Balcones Escarpment up into the Quachita Mountains of Oklahoma and Arkansas (Barker and Ardis, 1996). Before a final uplift during the Paleozoic Era, an arid and restricted shallow marine sea deposited Upper Permian sediments and evaporites into the Permian Basin of West Texas.

Triassic

During the Triassic Period, terrigenous clastic red beds were deposited over the Paleozoic rocks as the Dockum Group sediments. The area of the Edwards Plateau was then exposed to erosion during the Jurassic Period to form a rolling peneplain known as the Wichita Paleoplain (Barker and Ardis, 1996). By the end of the Jurassic Period, the Gulf of Mexico had begun to open and tilting of the peneplain towards the southeast provided a structural base for the deposition of the Cretaceous age Edwards–Trinity sediments.

Cretaceous

As the Gulf of Mexico continued to open and the Cretaceous seas advanced from the southeast, a broad continental shelf known as the Comanche Shelf began to form. The Llano Uplift, a tectonically active structural feature since the Pre-Cambrian, became a prominent structural shelf element for the deposition of the Trinity Group sediments (Barker and Ardis, 1996). The Early Cretaceous seas advanced across the Pre-Cretaceous structural base in three cycles of transgressive-regressive stages to deposit the Trinity Group sediments (Barker and others, 1994). The Stuart City Reef Trend began to form parallel to the ancestral Gulf of Mexico about 150 miles inland from the present Gulf Coast enabling the carbonate platform deposits of the Edwards Group sediments to accumulate to the northwest behind the protection of the reef. Other structural shelf elements that formed behind the Stuart City Reef Trend and controlled the depositional environments and lithologic characteristics of the Edwards Group formations include the Central Texas Platform, the San Marcos Arch, the Devils River Reef Trend on the edge of the Maverick Basin, and the Fort Stockton Basin (Figure 2-13). Prior to the deposition of Upper Cretaceous Del Rio, Buda, Boquillas, and Austin Group sediments, much of the Central Texas Platform was sub-aerially exposed allowing for an initial karstification of Lower Cretaceous carbonate sediments (Barker and others, 1994).

Cenozoic

Towards the end of the Cretaceous and beginning of the Tertiary Periods, the Laramide orogenic event and the dissolution of Upper Permian sediments, resulted in the structural collapse and erosion of overlying Triassic and Cretaceous sediments along the Pecos

River Valley (Barker and others, 1994). These sediments were then redeposited as the Cenozoic Pecos Alluvium throughout the Tertiary and into the Quaternary Periods. During the mid-Tertiary Period, regional uplift and continued deposition of sediments into the Gulf of Mexico provided tensional stresses along the ancient Quachita fold belt. Consequently, the development of the Balcones Fault Zone occurred and displaced Cretaceous and Lower Tertiary sediments by 900 to 1,200 feet (Barker and others, 1994). The Ogallala sediments were deposited over a portion of the Edwards–Trinity sediments from the northern region of the plateau during the late Tertiary Period. The headward erosion of streams has reduced the plateau into its current form throughout the Quaternary.

Previous Investigations

Previous studies on the Edwards–Trinity (Plateau) aquifer began with county-wide studies by the Texas Board of Water Engineers, the Texas Water Commission, the Texas Department of Water Resources, the Texas Water Development Board, and the U.S. Geological Survey. The Texas Department of Water Resources was the first to publish regional study reports on the Trans-Pecos (Rees and Buckner, 1980) and Plateau (Walker, 1979) portions of the Edward-Trinity aquifer. During the late 1980s, the U.S. Geological Survey (USGS) began a Regional Aquifer Systems Analysis (RASA) program for the Edwards–Trinity aquifer system that resulted in the publication of the most recent and comprehensive reports on the aquifer system model (Bush, 1986; Kuniansky, 1989; Kuniansky, 1990; Barker and Ardis, 1992; Ardis and Barker, 1993; Bush and others, 1993; Barker and others, 1994; Bush and others 1994; Barker and Ardis, 1996) as well as a single-layer finite element steady-state numerical groundwater model (Kuniansky and Holligan, 1994). The USGS has also published a groundwater atlas for Oklahoma and Texas that includes a very informative executive summary of the Edwards–Trinity aquifer system (Ryder, 1996). Currently, the Texas Water Development Board is conducting a comprehensive study to develop a state-of-the-art two-layer finite difference numerical groundwater model of the Edwards–Trinity aquifer system with a final report due for publication in 2004. Information on this most recent modeling study is maintained at the following Web address: http://www.twdb.state.tx.us/gam/.

Hydrogeologic Setting

The hydrogeologic setting provides for an understanding of the aquifer system's physical parameters, stress variables, and their interactions. Physical parameters include aquifer characteristics that remain constant over relatively long periods of time such as the hydrostratigraphy, structural geometry, hydraulic properties, steady-state water levels, and regional groundwater flow. Stress variables include aquifer characteristics that fluctuate over time such as recharge, well discharge, and natural interactions between groundwater and surface water such as springs, streams, and lakes.

Hydrostratigraphy

The hydrostratigraphy represents the vertical and lateral organization of the various hydrogeologic units of the Edwards–Trinity (Plateau) aquifer system and is shown in the stratigraphic chart on Figure 2-12 and discussed below.

Paleozoic

The Hickory, the Ellenburger–San Saba, and the Marble Falls aquifers are hydraulically connected to the Edwards–Trinity aquifer along the eastern margin of the plateau surrounding the Llano uplift. The Permian age Capitan and Rustler sediments are hydraulically connected to the Edwards–Trinity sediments in the Trans-Pecos portion of the aquifer (Bush and others, 1994). In general, most of the underlying Paleozoic rocks provide for a relatively impermeable base for the Edwards–Trinity aquifer sediments (Barker and Ardis, 1992).

Triassic

The Dockum Group consists of the Lower (Tecovas Formation), Middle (Santa Rosa Formation), and Upper (Chinle Formation) members (Walker, 1979). Only where the Chinle Formation is missing, allowing for the Basal Cretaceous sands to be in hydraulic communication with the underlying Santa Rosa Formation, is the Santa Rosa Formation considered to be an aquifer (Walker, 1979).

Cretaceous

The Trinity Group sediments are composed of the Lower, Middle, and Upper Trinity aquifer units in the southeastern portion of the plateau (Ashworth, 1983). The Lower Trinity consists of Hosston Sand (Sycamore Sand in the outcrop), Sligo Formation, and Hammett Shale. The Middle Trinity consists of the Cow Creek Limestone, Hensel Sand, and the lower member of the Glen Rose Limestone. The Upper Trinity consists of the upper member of the Glen Rose Limestone (Mace and others, 2000). In the Trans-Pecos region of the plateau, the Trinity Group sediments are composed of the Yearwood Formation and the Cox Sandstone. Elsewhere on the plateau, the Trinity Group sediments are composed of the Basal Cretaceous Sand, the Glen Rose Limestone, and the Maxon Sand. The Basal Cretaceous Sand and Maxon Sand are sometimes lumped together and referred to as the Antlers Sand or Trinity Sands in the northern plateau area where the Glen Rose Limestone is absent.

The Edwards Group and equivalent sediments consist of the Fredericksburg and Lower Washita Group sediments. The Fredericksburg Group consists of the Finlay Formation within the Fort Stockton Basin; the Fort Terrett Formation within the Central Texas Platform; the Devils River Formation within the Devils River Reef Trend; the West Nueces and McKnight formations within the Maverick Basin; and the Kainer Formation within the San Marcos Arch. The Lower Washita Group sediments are composed of the Boracho Formation within the Fort Stockton Basin; the Segovia Formation within the

Central Texas Platform; the Devils River Formation within the Devils River Reef Trend; the McKnight and Salmon Peak formations within the Maverick Basin; and the Person Formation within the San Marcos Arch.

The Upper Cretaceous sediments include the upper most section of the Washita Group sediments (the upper confining Del Rio Clay and the Buda Limestone) along with the Eagal Ford Group (Boquillas Formation) and the Austin Group sediments.

Cenozoic

The Cenozoic Pecos Alluvium aquifer is hydraulically connected to the Edwards–Trinity (Plateau) aquifer in the northwestern edge of the aquifer. The Upper Tertiary Ogallala Formation is hydraulically connected only in the northern-most portion of the Edwards–Trinity (Plateau) aquifer.

Structural Geometry

The initial base depositional surface of the Cretaceous sediments is generally flat and tilted towards the Gulf of Mexico. Consequently, the Edwards–Trinity sediments form a wedge that thickens from the north and northwest towards the south and southeast. The exceptions to this structural trend are in the areas near the Llano Uplift and the Trans-Pecos Basin and Range. The Llano Uplift is a tectonic structural high that has persisted throughout the geologic history of the region. Edwards–Trinity sediments were deposited over this structural high and later removed by erosion. The Trans-Pecos Basin and Range is the result of a more recent geologic event, the Laramide Orogeny, which uplifted and block faulted the Edwards–Trinity sediments into mountain ranges and graben basins. The wedge of Cretaceous sediments pinches out beneath the Ogallala sediments in the northern portion of the plateau (Barker and Ardis, 1996). The wedge of Cretaceous sediments is faulted and offset along the south and southeast by the Tertiary Balcones Fault Zone system. Most of the Edwards Group sediments and portions of the Upper Trinity sediments have been removed in the canyonland areas of the Texas Hill Country. A small portion of the Edwards–Trinity (Plateau) aquifer is confined in Val Verde and Kinney counties beneath the Upper Cretaceous Del Rio Clay. The semi-permeable Upper Cretaceous sediments of the Buda Limestone and Boquillas Formation form a thin cap over the Edwards Group in the central and southwestern portions of the aquifer.

Data were collected from several sources and merged within a Geographic Information System (GIS) for analysis. By using geostatistical techniques within the GIS framework, structural surfaces were developed for the tops and bottoms of both the Edwards and Trinity aquifer units (Figures 2-15 and 2-16). The base of the Trinity sediments shows a paleo-valley coincident with the lower Pecos River (Figure 2-15). In addition, a local high exists near the intersection of Schleicher, Menard, Sutton, and Kimble counties. The base of the Edwards sediments also shows the same local high in addition to the Maverick Basin along the southwestern portion of Val Verde County (Figure 2-16). The structural surfaces show a steep gradient along the Balcones Fault Zone that generalizes the fault

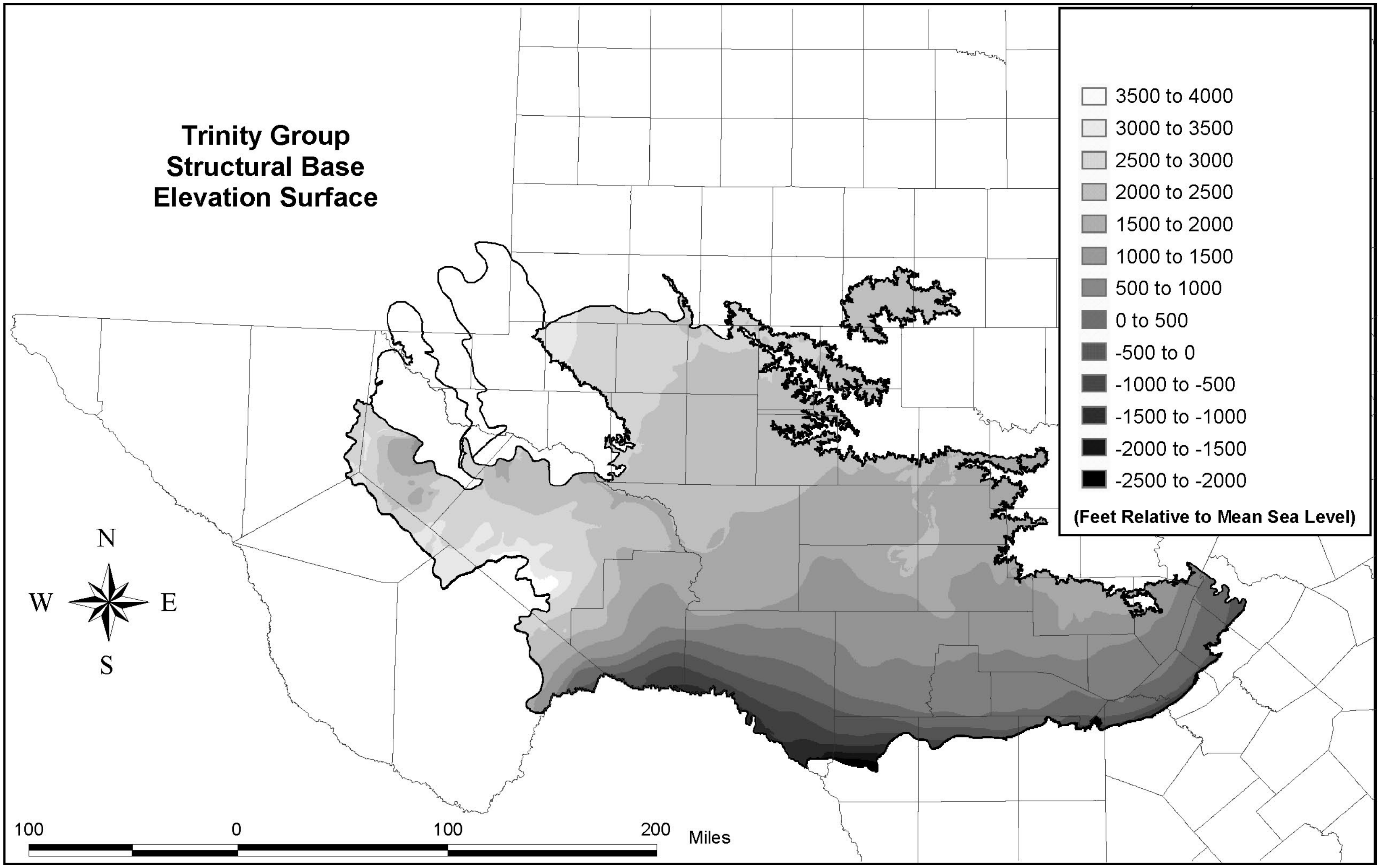


Figure 2-15: Interpolation of the base of the Trinity aquifer unit.

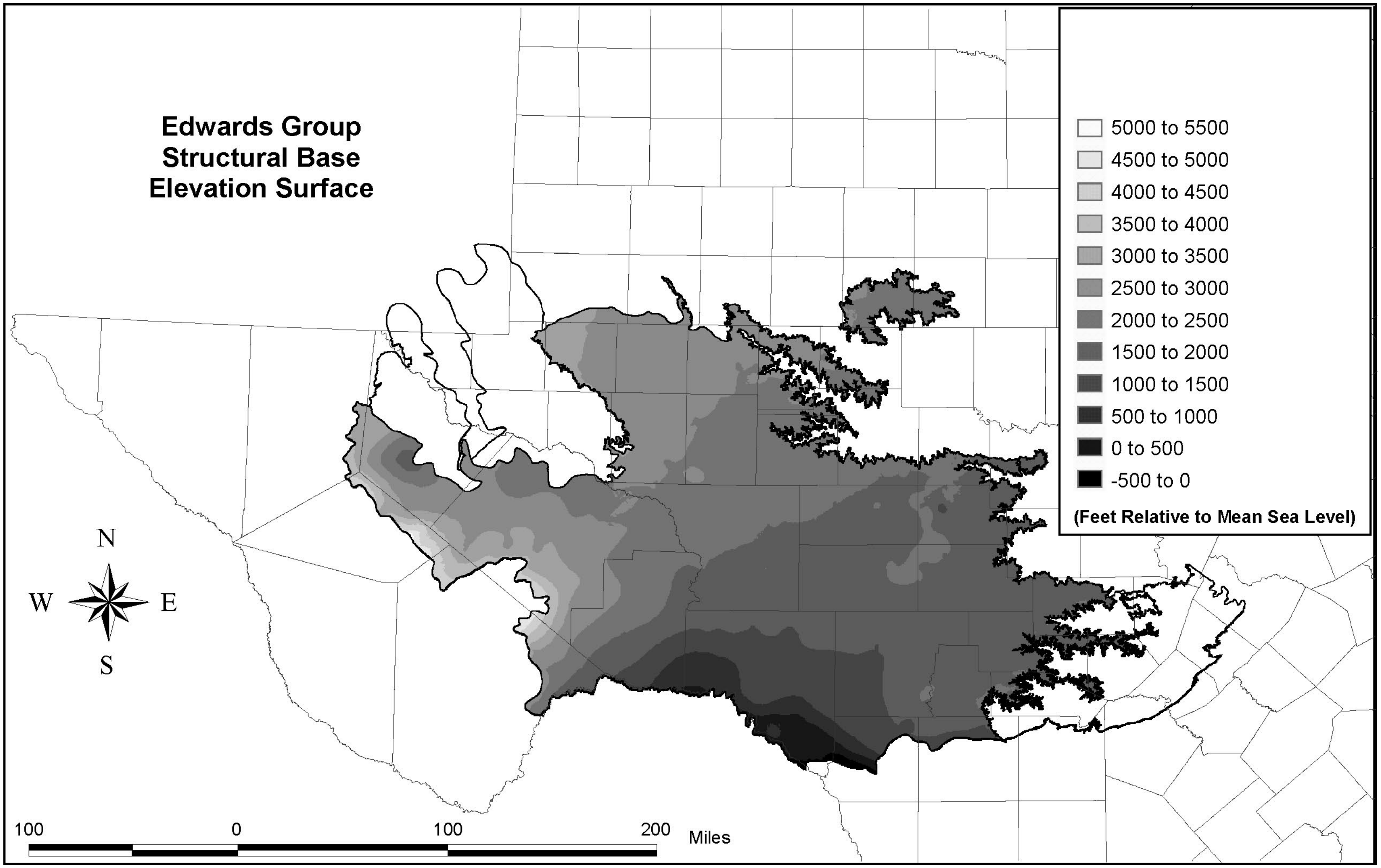


Figure 2-16: Interpolation of the base of the Edwards aquifer unit.

system rather than actually representing the abrupt stair-stepped offsets of the individual faults.

Hydraulic Properties

The Edwards–Trinity (Plateau) aquifer is hydraulically connected to four major aquifers: (1) the Cenozoic Pecos Alluvium, (2) the Ogallala, (3) the Trinity, and (4) the Edwards (Balcones Fault Zone). The Edwards–Trinity (Plateau) aquifer is also hydraulically connected to several minor aquifers: (1) the Dockum, (2) the Capitan Reef Complex, (3) the Rustler, (4) the Hickory, (5) the Ellenburger-San Saba, (6) the Lipan, and, to a very small degree, (7) the Marble Falls.

The saturated thickness of less than 100 feet to greater than 800 feet for the Edwards–Trinity (Plateau) aquifer system generally increases from north to south and varies the greatest along the western margins of the aquifer. Gentle north-south trending ridges and troughs of the folded Paleozoic base depositional surface combined with the topographic influence on the water table control the variability in saturated thickness (Barker and Ardis, 1996). The aquifer is mostly under water table or unconfined conditions, although the Trinity unit of the aquifer may be semi-confined locally where relatively impermeable sediments of the overlying basal member of the Edwards Group exists (Ashworth and Hopkins, 1995).

Transmissivity is a function of the conductivity of the aquifer sediments and the saturated thickness. The Edwards–Trinity (Plateau) aquifer generally has transmissivity values of less than 5,000 feet squared per day in the north and eastern portions of the aquifer and values between 5,000 and 50,000 feet squared per day in the southern and western portions of the aquifer with an average of less than 10,000 feet squared per day (Barker and Ardis, 1996). Except for areas of significant karst induced permeability, the average hydraulic conductivity of the Edwards–Trinity aquifer sediments is about 10 feet per day based on transmissivity and saturated thickness distributions (Barker and Ardis, 1996).

Specific-capacity test data were collected from the Texas Commission on Environmental Quality (TCEQ) and analyzed to calculate hydraulic conductivity values for both the Edwards and Trinity aquifer units. The spatial locations of these specific capacity data are limited to the area of a standard two and one-half minute quadrangle. An assumption was made to locate the specific-capacity data to the center of their respective quadrangle. Pumping-test data were then collected from the TWDB groundwater database and analyzed to calculate hydraulic conductivity for both Edwards and Trinity aquifer units. In addition, one or more pumping tests were conducted in almost every county of the aquifer system by TWDB staff during 2000. The pumping test data had unique latitude and longitude coordinates assigned to them. The calculated conductivity data were then analyzed and spatially interpolated using geostatistical techniques (Figures 2-17 and 2-18).

The geometric mean of the hydraulic conductivity for the Edwards aquifer unit was calculated at about 6.5 feet per day. The median hydraulic conductivity for the Trinity

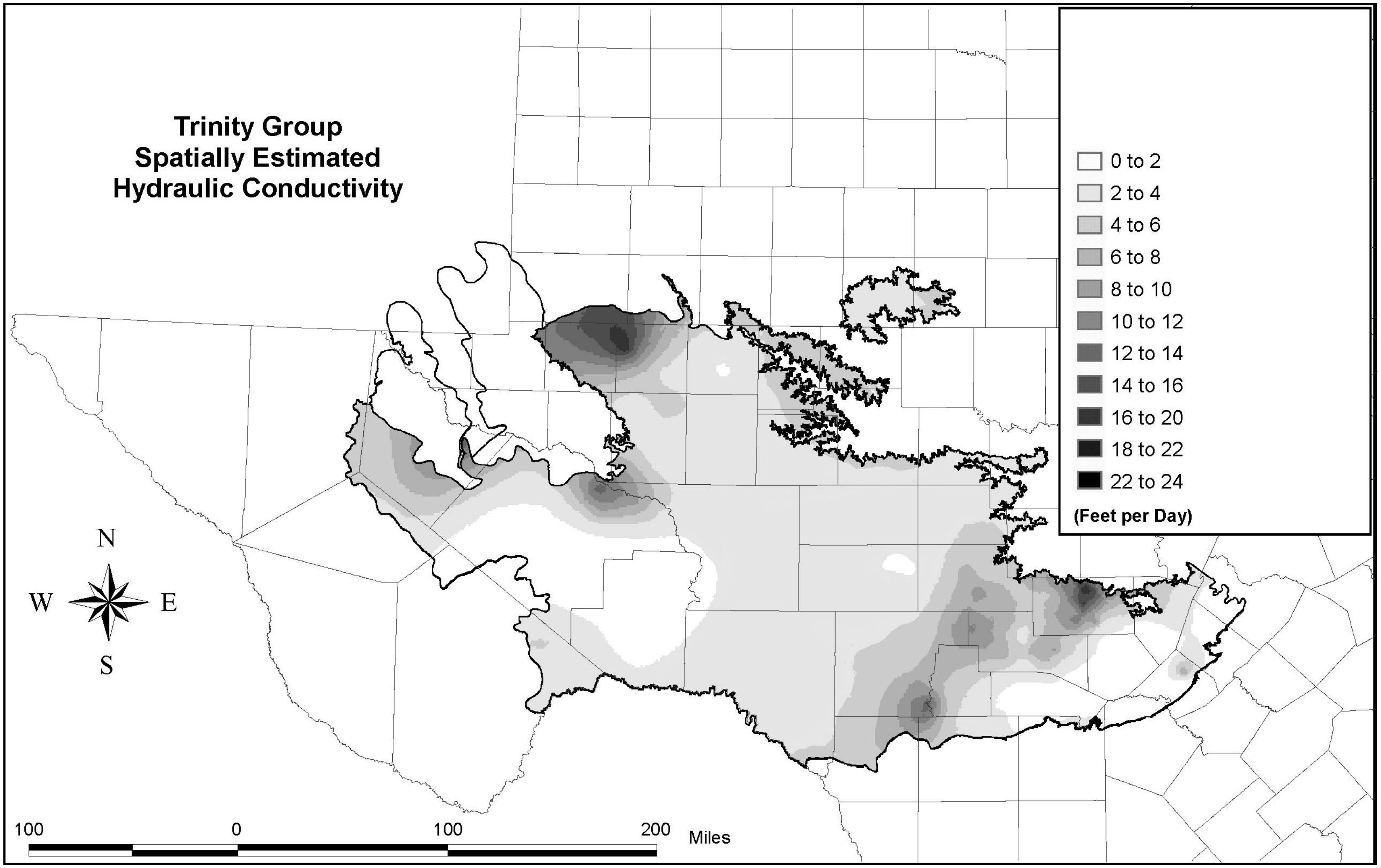


Figure 2-17: Estimated spatial interpolation of hydraulic conductivity for the Trinity aquifer sediments.

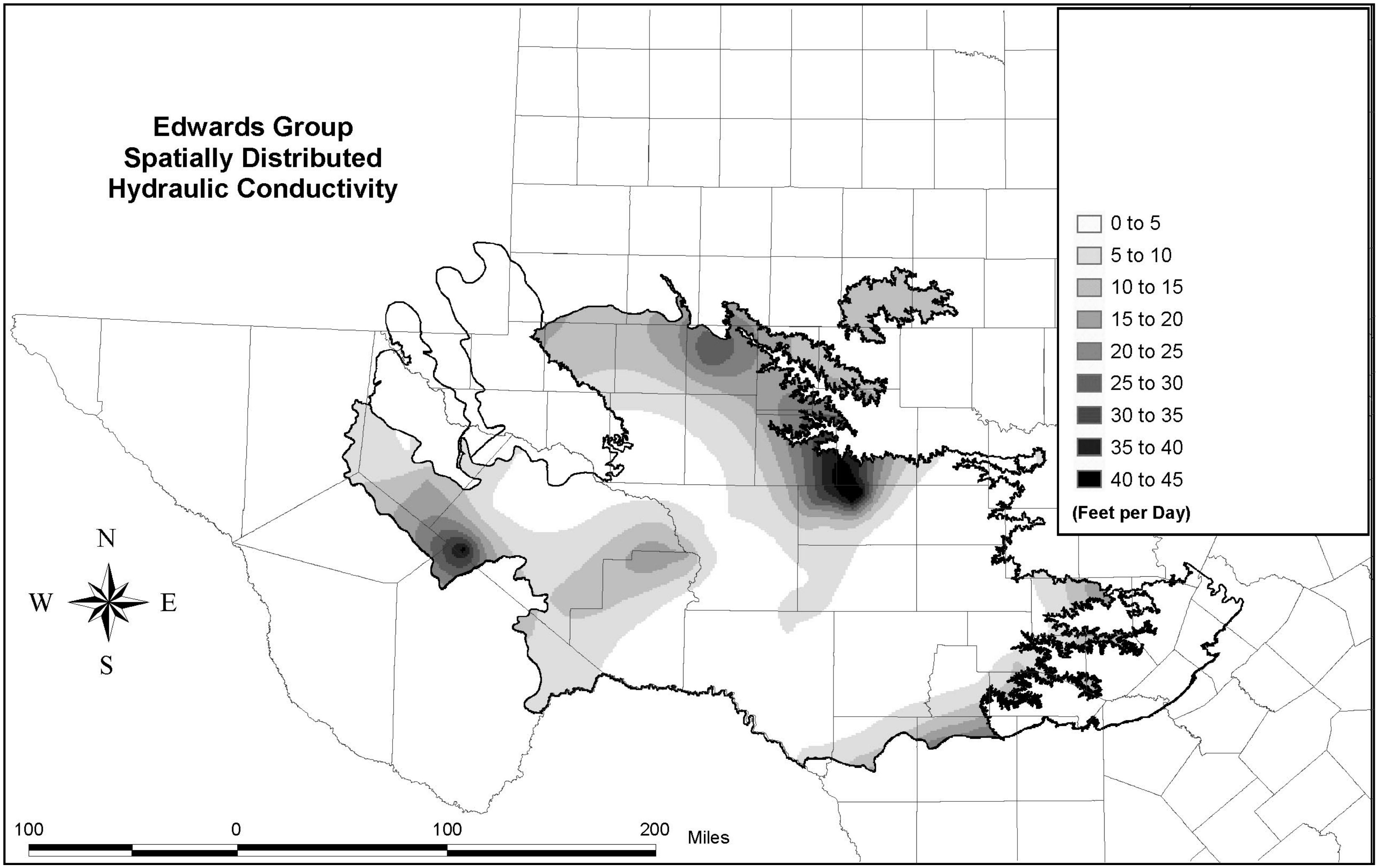


Figure 2-18: Estimated spatial interpolation of hydraulic conductivity for the Edwards aquifer sediments.

aquifer unit was calculated at about 2 feet per day for the southern part of the aquifer and about 4.5 feet per day for the northern part of the aquifer. Two different median hydraulic conductivity values were calculated for the Trinity aquifer unit because of the difference in sediment composition between the southern and northern parts of the aquifer unit. The southern part of the aquifer is composed of the shale, sand, and limestone transgressive-regressive sequence of the Lower, Middle, and Upper Trinity whereas the northern part is composed of the Trinity Sands.

Water Levels and Regional Groundwater Flow

Although water levels of the Edwards–Trinity aquifer system are influenced by climate, they have remained fairly constant except in areas of the northern and western plateau where a general trend of declining water levels has occurred as a result of increased irrigation pumpage (Ashworth and Hopkins, 1995). Steady-state water levels for the Edwards–Trinity aquifer were analyzed to gain an understanding of the regional groundwater flow within the aquifer system. Water level data from the TWDB groundwater database were queried for the first winter measurements of each well record available for both the Edwards and Trinity aquifer units and excluding measurements taken during the 1930s and 1950s drought years. The water-level data were queried with the assumption that they would have minimal influence from climate and pumpage, thus representing steady-state aquifer conditions. The water-level data were then entered into a GIS for inspection against the structural surfaces of their corresponding aquifer units. The quality controlled water level data were then analyzed and interpolated into potentiometric or water level surfaces for both the Trinity and Edwards aquifer units using geostatistical techniques (Figures 2-19 and 2-20).

The Pecos River has a very significant influence on groundwater flow in the western half of the aquifer system. Some groundwater flow in this part of the aquifer occurs as cross-formational flow from the eastern flanks of the Trans-Pecos mountains into the Cenozoic Pecos Alluvium Aquifer. Regional groundwater flow east of the Pecos River is generally from the northwest towards the southeast. A regional groundwater divide coincident with the surface topography and trending from the northwest in Ector county to the southeast near the common boundary of Real, Kerr, and Edwards counties separates flow towards the Colorado River from flow towards the Pecos River and Rio Grande.

Trinity water levels in the west show a steep gradient towards the Pecos River and towards the Rio Grande. An area of anomalous low water levels appears in the central part of the Reagan-Glasscock county boundary, historically an area of concentrated groundwater irrigation. Anomalous low water levels are also visible within an area of concentrated oil production in central west Midland County. To the north and east of the Pecos River, the Trinity water levels have a more gentle and subdued surface with only the lower Devils River in southern Val Verde County having an apparent effect on the water level surface. Trinity water levels continue with the gentle surface gradient south towards the Balcones Fault Zone and southeast into the Hill Country.

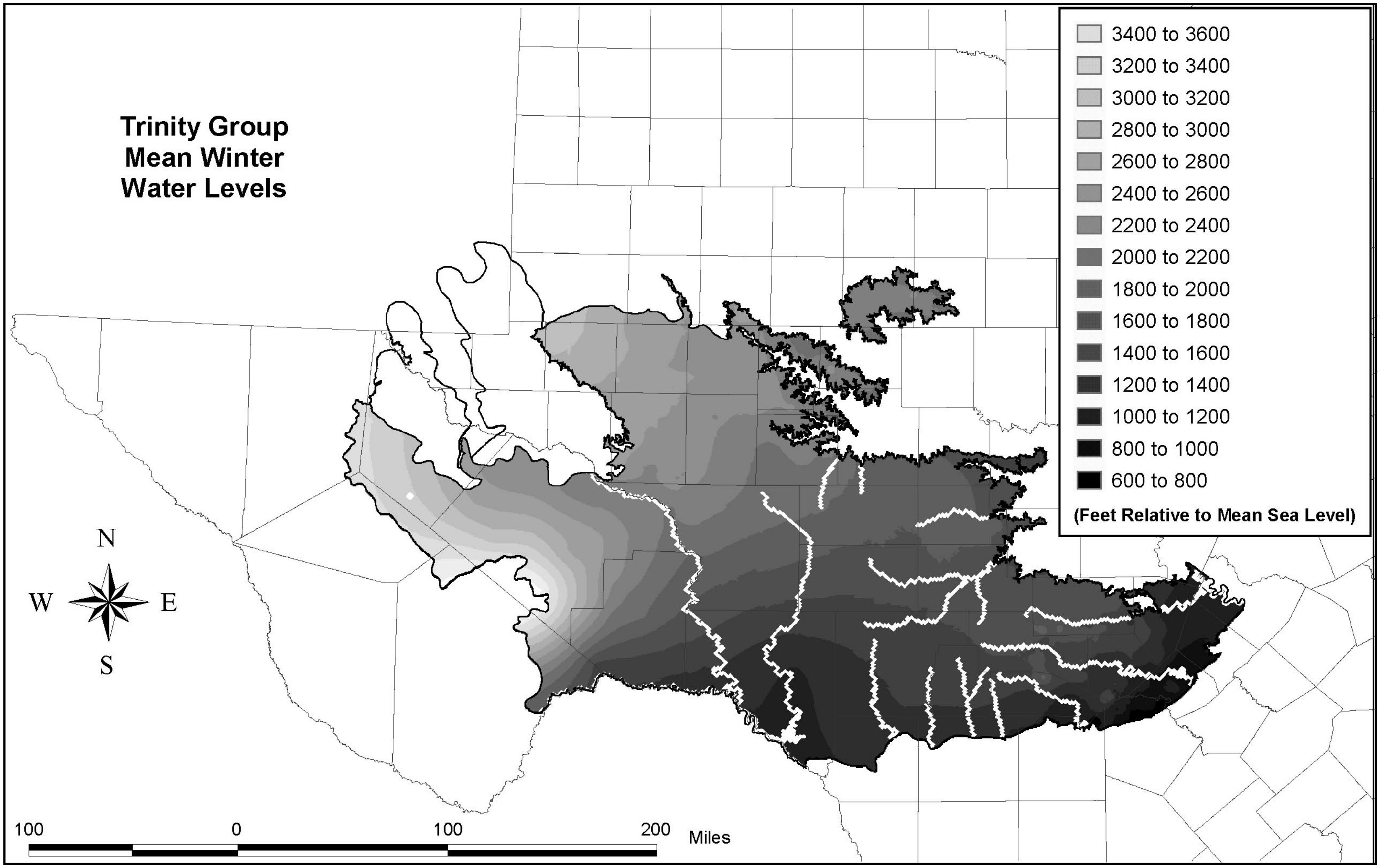


Figure 2-19: Historical mean winter water levels for the Trinity aquifer unit.

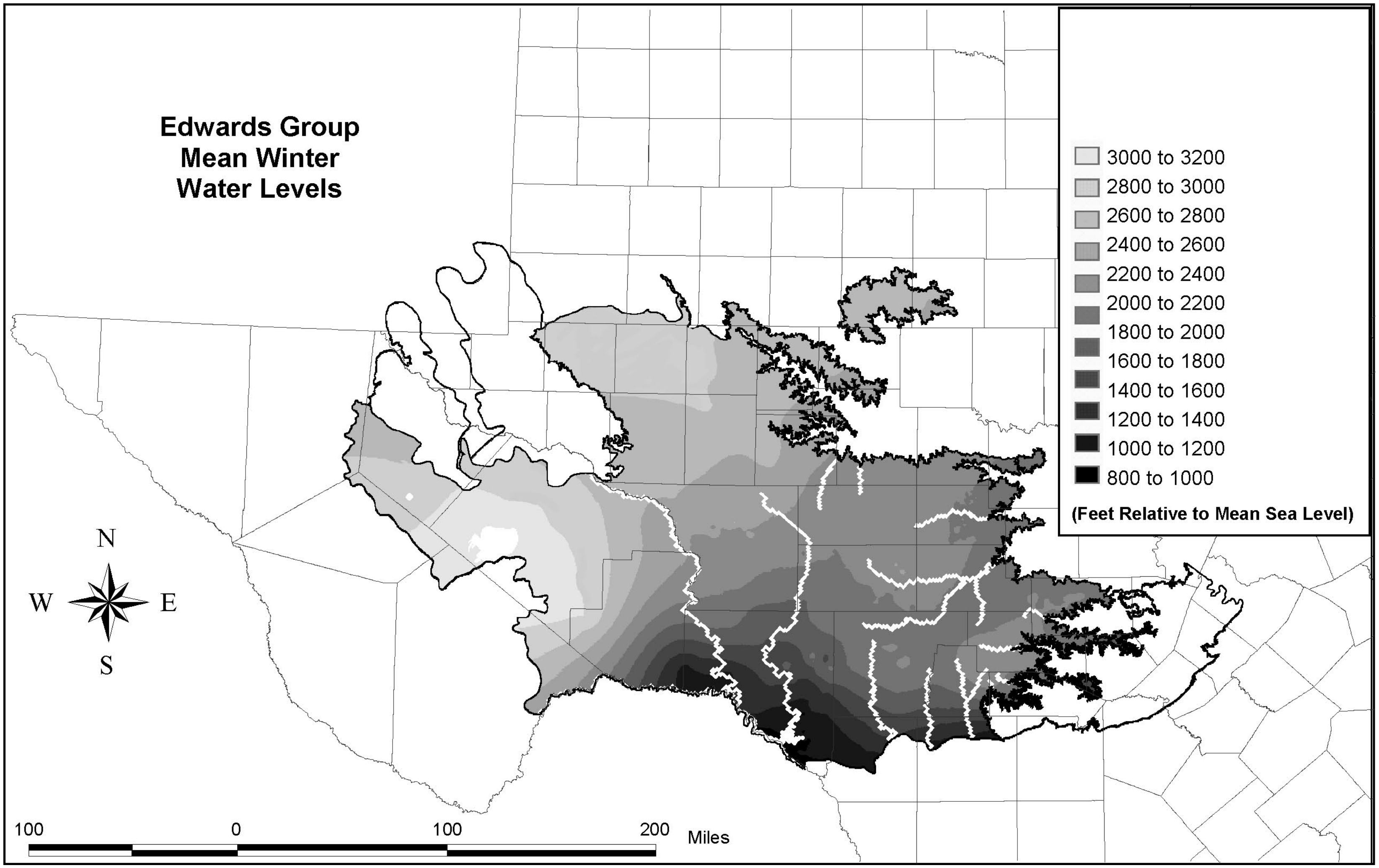


Figure 2-20: Historical mean winter water levels for the Edwards aquifer unit.

Edwards water levels show a steep gradient towards the Rio Grande in Terrell County as well as the southern part of the aquifer just to the north of the Blacones Fault Zone in Kinney and Uvalde counties. Anomalous low water levels appear in southern Reagan County near Big Lake. The central reach of the Devils River affects Edwards water levels in the southeastern corner of Crockett County. A mounding of the water-level surface is visible in the area near the common boundary of Real, Kerr, and Edwards counties forming a southwest-northeast trending saddle shaped valley through northern Edwards and southeastern Kimble counties.

Recharge

Recharge rates vary with climate conditions, surface geology, surface topography, soils, vegetation, and landuse. Most recharge occurs from the infiltration of precipitation over outcrops of the Edwards–Trinity aquifer, from surface runoff into sinkholes, and stream losses from intermittent streams. An uncertain amount of cross-formational flow from the Ogallala aquifer also provides recharge to the Edwards–Trinity aquifer system in the northwestern portion of the aquifer. Induced recharge occurs in Pecos and Reeves counties as a result of water-level declines due to irrigation pumpage from the Cenozoic Pecos Alluvium aquifer (Barker and Ardis, 1996).

Rees and Buckner (1980) estimated recharge over the Trans-Pecos region of the plateau to be between about 0.3 and 0.4 inches per year. Kuniansky (1989) estimated recharge over the eastern portion of the plateau to range between 0.12 and 2.24 inches per year. The simple strategy of using four percent of the mean annual precipitation will be used as an initial estimate for recharge for the main approach of calibrating recharge within the numerical groundwater flow model. The range in estimated recharge values by other investigators in conjunction with reasonable values in aquifer conductivity estimates will be used as limits in the calibration process.

Interactions of Groundwater and Surface Water

Natural discharge from the Edwards–Trinity aquifer occurs mostly along the margins of the aquifer from springs where the water table intersects canyons or surface topography to provide baseflow to streams. Springs also discharge groundwater along the eastern flanks of the Trans-Pecos mountains and the lower Pecos River canyons. As water levels decline in the western portion of the aquifer due to increased irrigation pumpage, spring flows within those areas have also declined. In addition, many small springs that once flowed throughout the plateau have ceased flowing as a consequence of native grasslands being replaced by woody vegetation that consume high amounts of potential recharge and allow other excess rainfall to runoff before it is able to recharge the aquifers.

Most of the intermittent streams high on the plateau lose their flow to the underlying aquifer. The lower reaches of major streams along the northern, eastern, and southern margins of the plateau become gaining, usually when their stream channel elevation falls below the base of the Edwards aquifer unit. Phreatophytes, mostly along major stream valleys, discharge groundwater naturally as evapotranspiration where the water table is shallow enough for the root networks. The Pecos River has perhaps the most prime example of extreme evapotranspiration by invasive salt cedar.

The Edwards–Trinity aquifer interacts with reservoirs or lakes only along the southern margin of the aquifer system. These water bodies initially lost water to the aquifers and raised water levels in their vicinity but have all reached a fairly steady-state condition since the late 1970s. The largest of them is Amistad Reservoir just below the confluence of the Devils River with the Rio Grande in Val Verde County. The remaining lakes are located in the Hill Country just north of the Balcones Escarpment and include Medina Lake on the Medina River in northern Medina County, Canyon Lake on the Guadalupe River in Northern Comal County, and Lake Austin on the Colorado River in Travis County.

Pumping

The Edwards Group sediments provide most of the water in the central, southern, and eastern portions of the plateau while the Trinity Group sediments provide much of the water for the northern and western areas of the plateau in addition to the Hill Country region (Barker and Ardis, 1996). Over three fourths of the total groundwater pumpage from the Edwards–Trinity aquifer is used for irrigation, primarily in the northern and western portions of the aquifer (Figure 2-21). Municipal water suppliers account for the second most common groundwater use followed by minimal use for industrial, mining, livestock, and rural domestic uses. Climate has a significant effect on the amount of groundwater pumpage from the Edwards–Trinity aquifer within areas of irrigation.

Water Quality

Although water quality is typically hard, it is generally fresh except for areas in the Trans-Pecos where groundwater from Permian evaporite sediments and/or oil field brines are able to mix with groundwater from the Edwards–Trinity aquifer (Rees and Buckner, 1980). Water quality is also affected by induced recharge from Pecos River stream losses (Barker and Ardis, 1996). East of the Pecos River, oil field brines and agricultural runoff have a significant effect on the groundwater quality of the northern portion of the Edwards–Trinity aquifer (Walker, 1979). Water quality aspects of the Edwards–Trinity (Plateau) aquifer system are discussed in more detail in later chapters.

Conceptual Model

The conceptual model is a simplified interpretation that provides our best understanding of the aquifer system and defines the hydrostratigraphic units, describes the water budget, and illustrates flow system (Anderson and Woessner, 1992). The conceptual model for the Edwards-Trinity (Plateau) aquifer defines two basic hydrostratigraphic units (Figure 2-22). The lower unit represents the partially confined Trinity aquifer while the upper unit represents the unconfined Edwards aquifer. In addition, the lower Trinity unit is contiguously extended to the southeast to include the Trinity (Hill Country) aquifer.

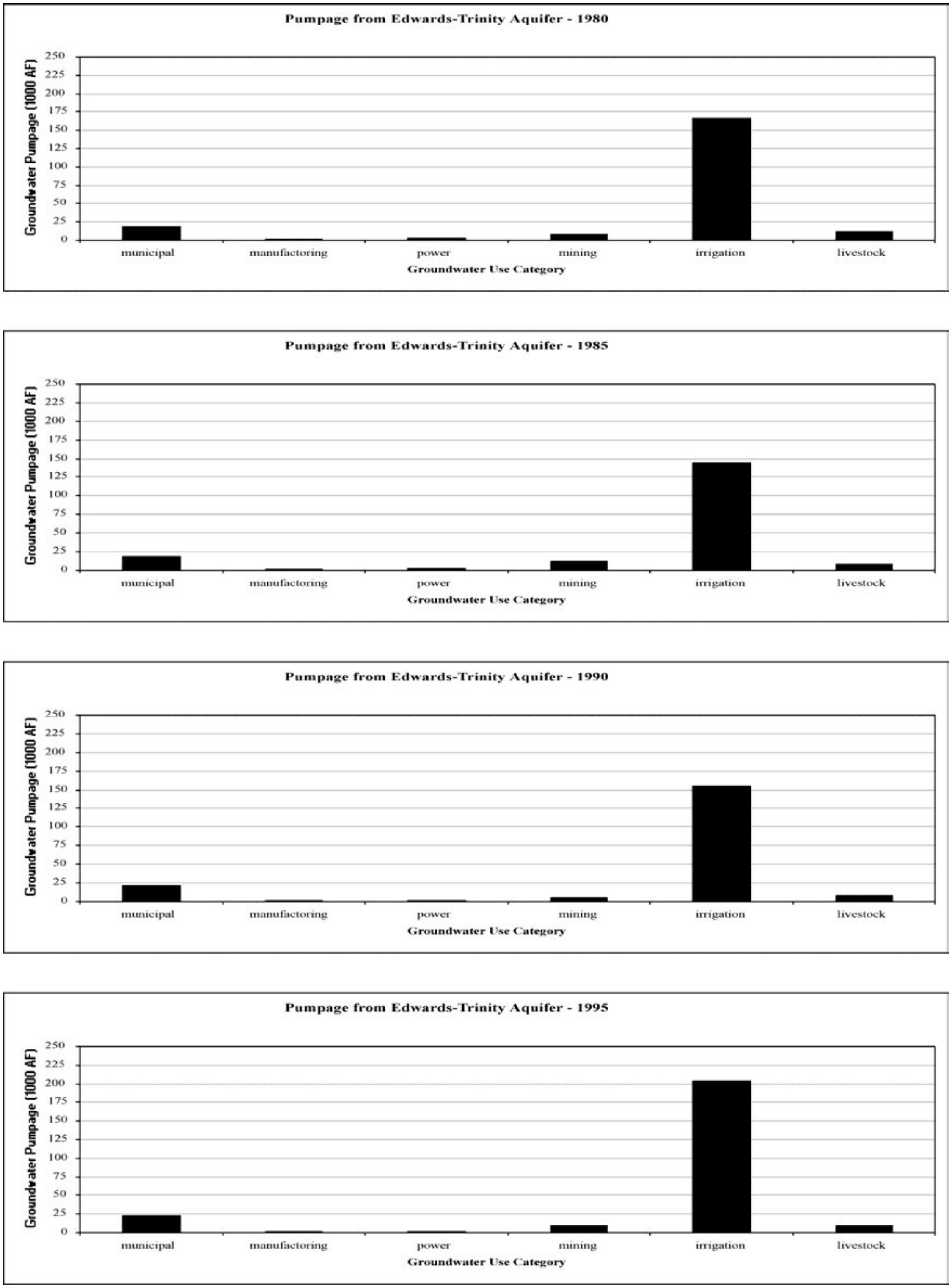


Figure 2-21: Pumpage from the Edwards–Trinity aquifer for 1980, 1985, 1990, and 1995.

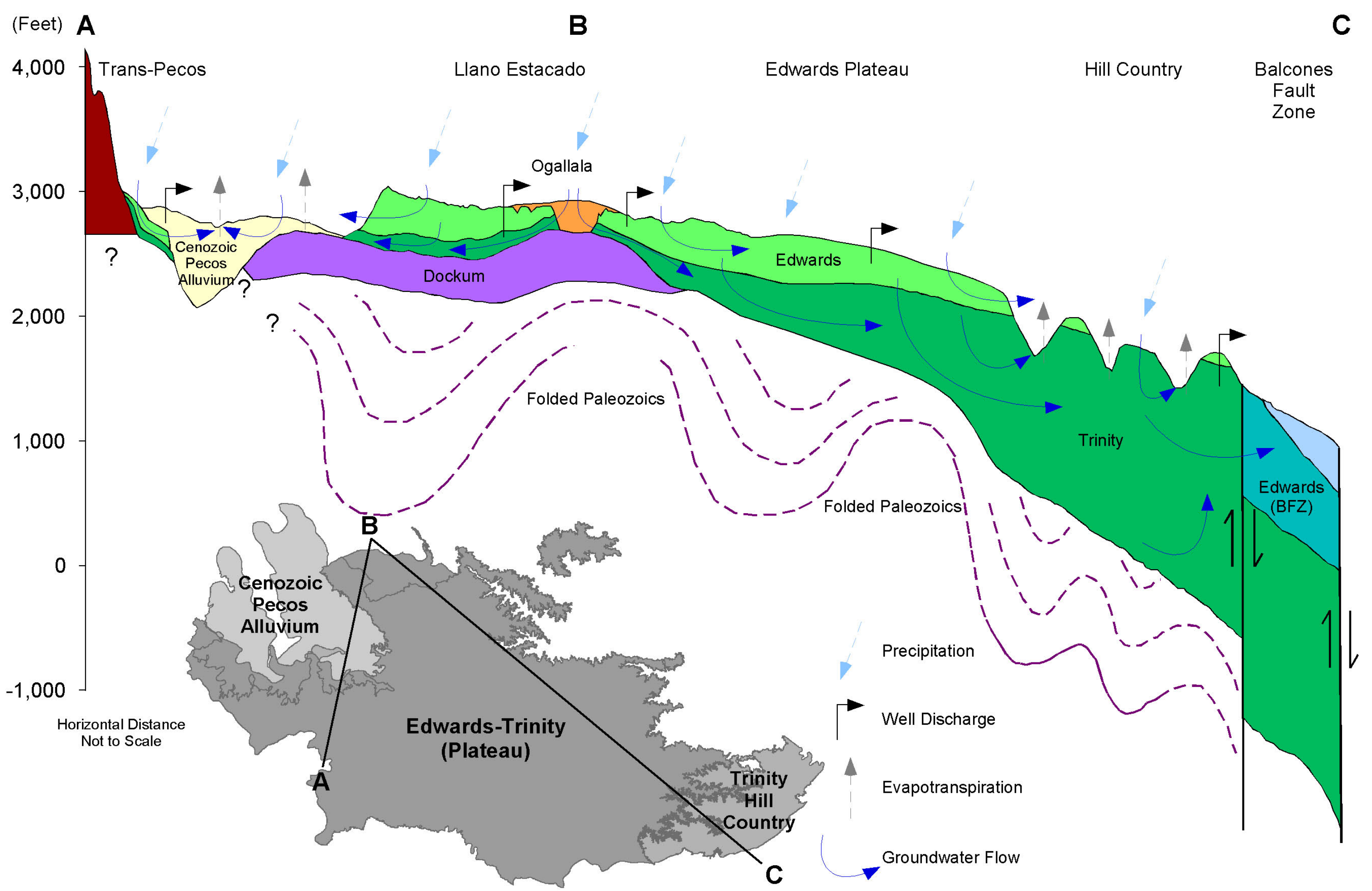


Figure 2-22: Conceptual model diagram of the Edwards–Trinity (Plateau) aquifer system (modified from Kuniansky, 1994).

The Cenozoic Pecos Alluvium aquifer is included in the conceptual model in the Trans-Pecos region.

The water budget incorporates recharge from precipitation as the primary input into the Edwards aquifer unit. However, most of the precipitation returns to the atmosphere as evapotranspiration or exits from the study area as runoff before it can become recharge. Up to four percent of the annual rainfall enters the aquifer system as diffuse recharge over aquifer outcrops or as direct recharge from losing streams on the aquifer outcrops. Some of the recharge that occurs over the Edwards aquifer outcrop flows downward into the underlying Trinity aquifer unit. Yet, most of the recharge that enters into the Edwards aquifer eventually exits the aquifer unit as (1) seeps and springs along the plateau margins to become the headwaters for tributaries of major streams; (2) baseflow to the lower gaining reaches of major perennial streams; (3) evapotranspiration where vegetation is able to tap into the water table; or (4) pumping from wells.

The Trinity aquifer has few outcrops exposed for recharge and consequently receives much of its water from the overlying Edwards aquifer except in the Hill Country where the Edwards Group sediments have been removed by erosion. In the Hill Country area, recharge over the Trinity aquifer outcrops is about four to six percent of annual rainfall. The Trinity aquifer may also receive some water from the adjacent Ogallala aquifer in the northwest as cross-formational flow. The Trinity aquifer loses its water to pumping wells mostly in the Llano Estacado and Hill Country areas. In the Hill Country, water also flows out of the Trinity aquifer as springs and baseflow to gaining streams and as cross-formational flow to the Edwards (Balcones Fault Zone) aquifer. In the Trans-Pecos area, water exits both the Edwards and Trinity aquifers into the Cenozoic Pecos Alluvium aquifer. After the water levels in the reservoirs and lakes reached their capacity, groundwater generally flows from the aquifer units into the reservoirs and lakes.

Lithologic characteristics are the principal control on the permeability of the aquifer units. The Edwards aquifer unit has relatively high vertical and horizontal permeability because of the mostly massive limestone composition of the Edwards Group. The Trinity aquifer unit has a much more variable lithologic composition. The northern half of the Trinity aquifer is thinner and composed of sands. The southern portion of the aquifer is composed of a thick sequence of sand, shale, and limestone. Consequently, the northern part of the Trinity aquifer unit has higher vertical and horizontal permeability than the southern part. Moreover, the southern part has significantly lower vertical permeability than horizontal permeability because of the stratified sequence of lithologic sub-units.

Conclusions

The Edwards-Trinity (Plateau) aquifer is located beneath the Edwards Plateau of central-west Texas, a region characterized as a tableland with thin soils, subhumid to subarid climate and vegetation, and a sparse population. The aquifer system is composed of Early Cretaceous age sediments of the Trinity Group and the overlying Edwards Group.

The TWDB is developing a GAM for the Edwards-Trinity (Plateau) aquifer. A conceptual model was developed as an initial task in the design of a numerical groundwater flow model of the Edwards-Trinity (Plateau) aquifer system. The conceptual model is based on characteristics of the hydrogeologic setting such as the hydrostratigraphy, structural geometry, hydraulic properties, water levels, and regional groundwater flow. The conceptual model defines two hydrostratigraphic units for the aquifer system in which the lower unit represents the Trinity aquifer and the upper unit represents the Edwards aquifer. In addition, the conceptual model incorporates the Edwards-Trinity (Plateau) aquifer with the Trinity aquifer in the Hill Country and Cenozoic Pecos Alluvium aquifer systems because of their unique hydraulic connection. Interactions with vertically and laterally adjacent aquifer systems as well as aquifer stresses such as recharge, well discharge, and natural interactions between groundwater and surface-water features such as springs, streams, and lakes are also represented in the conceptual model.

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