# Northern Trinity / Woodbine Aquifer
# Groundwater Availability Model

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The Texas Water Development Board

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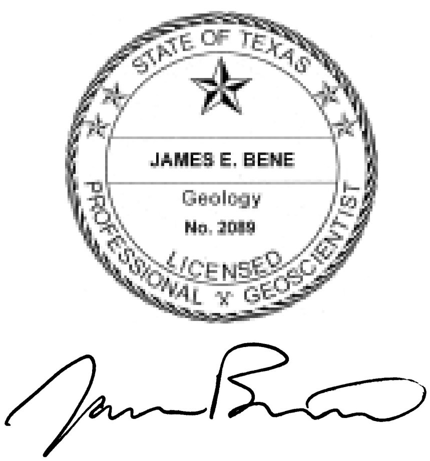



The seals appearing on this document were authorized by James E. Bené, P.G. 2089 and Robert Harden, P.E. 79290 on August 31, 2004.

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# ABSTRACT

The Trinity/Woodbine aquifer system (Trinity/Woodbine) is one of the most extensive and highly utilized groundwater resources in Texas. This report documents a three-dimensional, numerical groundwater flow model of the northern portion of the Trinity/Woodbine, which extends from Central Texas to southern Oklahoma and Arkansas. The model was developed as part of the Texas Groundwater Availability Modeling (GAM) program to evaluate groundwater availability over a 50-year planning period and predict water level response to potential droughts and future pumping.

Although useable water may be obtained from most of the Cretaceous sediments in the model area, there are four aquifer units that are, in general, the most prolific formations within the Trinity/Woodbine system. These include: the Hosston, Hensell, Paluxy, and Woodbine aquifers, and are the focus of this project. Groundwater regimes within these units range from water-table conditions in outcrop zones to artesian conditions at depth where the sand-rich aquifers are confined by low permeability clay and carbonate-rich units that bracket and separate the aquifer sediments.

Extensive development of the Trinity aquifer began in the late 1800's when numerous, artesian, flowing wells were completed in the Trinity throughout central and northern Texas. The practice of leaving flowing artesian Trinity/Woodbine wells uncapped combined with the newfound availability of fresh water led to regional artesian pressure declines, and many wells ceased flowing by the early 1900's. Because of this, an interval of reduced groundwater production in the Trinity/Woodbine was experienced in the region through the 1930's. This period was followed by many decades of increased groundwater withdrawal in many areas of Central and North-Central Texas to meet the local water demands of a growing Texas population. However, since the mid-1970s and the development of surface water resources throughout the study area, demand for groundwater has decreased in some areas, and ground-water levels in some areas have risen or stabilized in response to this trend (Kaiser, 2002).

The construction of the Northern Trinity/Woodbine GAM required the collection and analysis of a relatively large volume of hydrologic and geologic information. All structural data included in the model were derived from the examination of geophysical logs on file at the United States Geological Survey (USGS), the Texas Commission on Environmental Quality (TCEQ), and Texas Water Development Board (TWDB) archives. Where verification against geophysical log records was possible, structural data assembled by previous authors were incorporated into model data sets. Data pertaining to aquifer water levels and hydrologic characteristics, water usage, surface/groundwater interaction, and recharge/discharge relationships were assembled from various

sources and reevaluated for the purposes of the model. Comprehensive metadata files have been completed on all source data used in the GAM, and are supplied with this report.

Simulation of fluxes into and out of the model was accomplished with several MODFLOW packages including: 1) Recharge, 2) Evapotranspiration, 3) Streamflow-Routing, 4) River, and 5) Well. Modification of average annual precipitation by soil permeability and land use factors provided the basic input for the Recharge Package, which was used to simulate infiltration of precipitation to the modeled aquifers. Streambed baseflow fluxes were simulated using the Streamflow-Routing Package, while due to MODFLOW technical issues the River Package was used to reproduce reservoir/groundwater interaction in the GAM. The Evapotranspiration Package simulated the extraction of groundwater from the system by various, near-surface processes including evaporation of soil moisture, plant transpiration, seeps/springs, and stream/groundwater interaction not specifically modeled by the Streamflow-Routing Package. Groundwater pumpage to wells completed in the modeled hydrostratigraphic units was accomplished using MODFLOW's Well Package.

The hydraulic conductivity values input into the model were derived in a multi-step process. The hydraulic conductivity values assigned to each primary aquifer layer (Woodbine, Paluxy, Hensell, and Hosston) varied according to the net sand thickness recorded during analysis of geophysical logs within the model area. Statistical correlations relating pumping test transmissivity and net sand thickness were calculated and utilized to extrapolate initial Kh values to all regions of the model. Once initial conductivity surfaces were generated and input into the model, modification of layer conductivity during the calibration/verification phase of model development was found to improve simulation accuracy.

Calibration of the model was accomplished in three phases. First, a transitional model was constructed that simulated the change in aquifer water levels during the 100-year interval between 1880 and 1980. The results of this model were calibrated to measured 1980 water levels and estimated river/stream baseflows. Construction of the 100-year model was necessary because extensive use of the Trinity/Woodbine during the late 1800's likely depressed aquifer water levels prior to the earliest measurements, making calibration of a steady-state model to pre-development water levels not possible for this project. Following calibration to the transitional period, the model was calibrated to the aquifer conditions recorded during the 1980's. Verification of simulated changes in aquifer head and streamflows during the interval between 1990 and 2000 constituted the final phase of model calibration. In both the transitional and the transient calibration/verification models, the total root mean squared (RMS) residual of each modeled aquifer was less than 10 percent of the measured head drop across the unit for the period simulated.

Following calibration and verification, six simulations of aquifer response to projected groundwater demands (as developed by the TWDB and applicable Regional Water Planning Groups) were performed with the model. In general, the results of these simulations indicate that water levels will remain relatively stable in outcrop zones, while artesian pressures will rise by several hundred feet in the major pumping centers in response to a planned decrease in pumpage from these aquifer units over the next 50 years. While future decreases in pumpage represent a possible future use scenario, it is also possible that use will not decrease and that water levels will remain at or near current levels for many decades. The predictive simulations also provide a comparison of water levels between average rainfall and drought-of-record conditions. However, the difference in regional water levels between average rainfall and drought-of-record conditions was minimal, with most of the differences being less than one foot.

# 1.0 INTRODUCTION

In order to supply Texas resource planners and policy makers with reliable tools for assessing the aquifer response associated with groundwater use over a 50-year planning period, the Texas Legislature instituted the Groundwater Availability Modeling (GAM) program during the 76$^{th}$ Legislative Session in 1999. The Northern Trinity and Woodbine aquifer system (Trinity/Woodbine) currently supplies groundwater to large, heavily–populated, as well as rural regions of North, North-Central and Central Texas. Accordingly, this aquifer was included as part of the GAM program. This report describes the processes completed and results derived from the Northern Trinity/Woodbine GAM project.

Covering over 30,000 square miles, the Trinity/Woodbine is one of the most extensive sources of groundwater in Texas. Although they are not always distinguishable from one another in geologic section, the four primary aquifers that comprise the system (Hosston, Hensell, Paluxy, and Woodbine) extend from southwestern Arkansas to the Colorado River in Central Texas. The northern portion of the aquifer system has supplied the vast majority of groundwater to all or part of 55 counties in the region for more than a century, which has resulted in artesian pressure declines, especially near population centers such as Temple, Waco, Fort Worth, Dallas, and Sherman. Because the Trinity/Woodbine is structurally complex and encompasses a relatively large area, the long-term aquifer response associated with groundwater use is not always readily apparent. For this reason, resource policy makers require a tool that can be used to assist in quantifying the effects related to the ongoing development of aquifer resources in the region. While not applicable in every situation, groundwater flow models are one of the most useful tools for evaluating these effects. However, it should be noted that no model replicates exactly the groundwater conditions found in a given aquifer, and that the discrepancies that exist between simulated and measured aquifer water levels have a direct correlation to the accuracy and density of hydrologic and geologic data describing that aquifer system as well as the spatial and temporal scale of the model.

The construction and implementation of reliable groundwater models is a multi-step process. These steps include: 1) data collection and conceptual model development, 2) model design and construction, 3) model calibration/verification, 4) model sensitivity analyses, and 5) use of the model for predictive purposes. The development of a basic understanding and appreciation of the fundamental processes that drive groundwater flow in an aquifer is paramount in this procedure. This overall understanding is defined as a conceptual model, and affects all other model construction tasks, as well as the interpretation of model predictions. In its most basic form, the conceptual model identifies and defines the hydrostratigraphic units of interest, their recharge and discharge relationship, hydraulic properties and boundary conditions. An in-depth assessment of pertinent geologic structure, lithology and stratigraphy, physiography, groundwater uses, surface/groundwater interaction, and climate of the model region is necessary to properly define the hydrodynamic conceptual model of the Trinity/Woodbine. Model design involves the process of determining the best way to apply the fundamental principles of the conceptual model to the framework of the numerical model. Calibration and verification of the model entails an iterative progression of the assessment of simulation accuracy (as compared to historical water level measurements), followed by adjustment of aquifer parameters and the conceptual model when required. Once calibration goals are met or exceeded, the model is subjected to a sensitivity analysis. During this procedure, model input parameters are systematically varied and the simulation results are monitored. In this way, the magnitude of the error inherent in the simulation(s) can be estimated. Following successful implementation of the previous steps, the model may be employed as a tool that can be used for the prediction of likely water level changes resulting from specific groundwater development scenarios.

In keeping with State water planning policy, the Northern Trinity/Woodbine GAM was developed with input from the stakeholders through stakeholder advisory forums. All data sets and models developed during this project are available to regional water planning groups, river authorities, groundwater conservation districts, and private citizens for the evaluation of groundwater availability in the Northern Trinity/Woodbine aquifer. Digital information related to this project has been posted online at http://www.twdb.state.tx.us/gam/trnt_n/trnt_n.htm.

# 2.0 STUDY AREA

The Northern Trinity/Woodbine aquifer system is composed of four sandy aquifer units confined and separated by relatively impermeable clay and carbonate units. All of these units form a wedge of sediments that dip and thicken to the south and southeast toward the Gulf of Mexico. Trinity/Woodbine sediments crop out in a north-south trending belt in the southern portion of the study area, shifting to an east-west trending belt near the Texas-Oklahoma border. The study area (active model area) is defined as the region bounded by the updip limit of the aquifer outcrop in the north and west, the Colorado River in the south, and the Luling-Mexia-Talco Fault Zone to the east.

The study area (Figures 2.1 and 2.2) covers more than 30,000 square miles and extends from Central Texas to approximately 40 miles north of the Red River, and includes all or part of 46 Texas, nine Oklahoma, and five Arkansas counties. As illustrated by Figures 2.3 and 2.4, all or portions of nine groundwater conservation districts and six regional planning groups fall within the region. Major cities within the study area include Dallas, Fort Worth, Arlington, Waco, and Austin, with a combined population of more than six million residents. In addition, the model encompasses all or part of numerous river basins (Figure 2.5); major basins include: the Red River, Sulphur River, Sabine River, Trinity River, Brazos River, and Colorado River Basins.

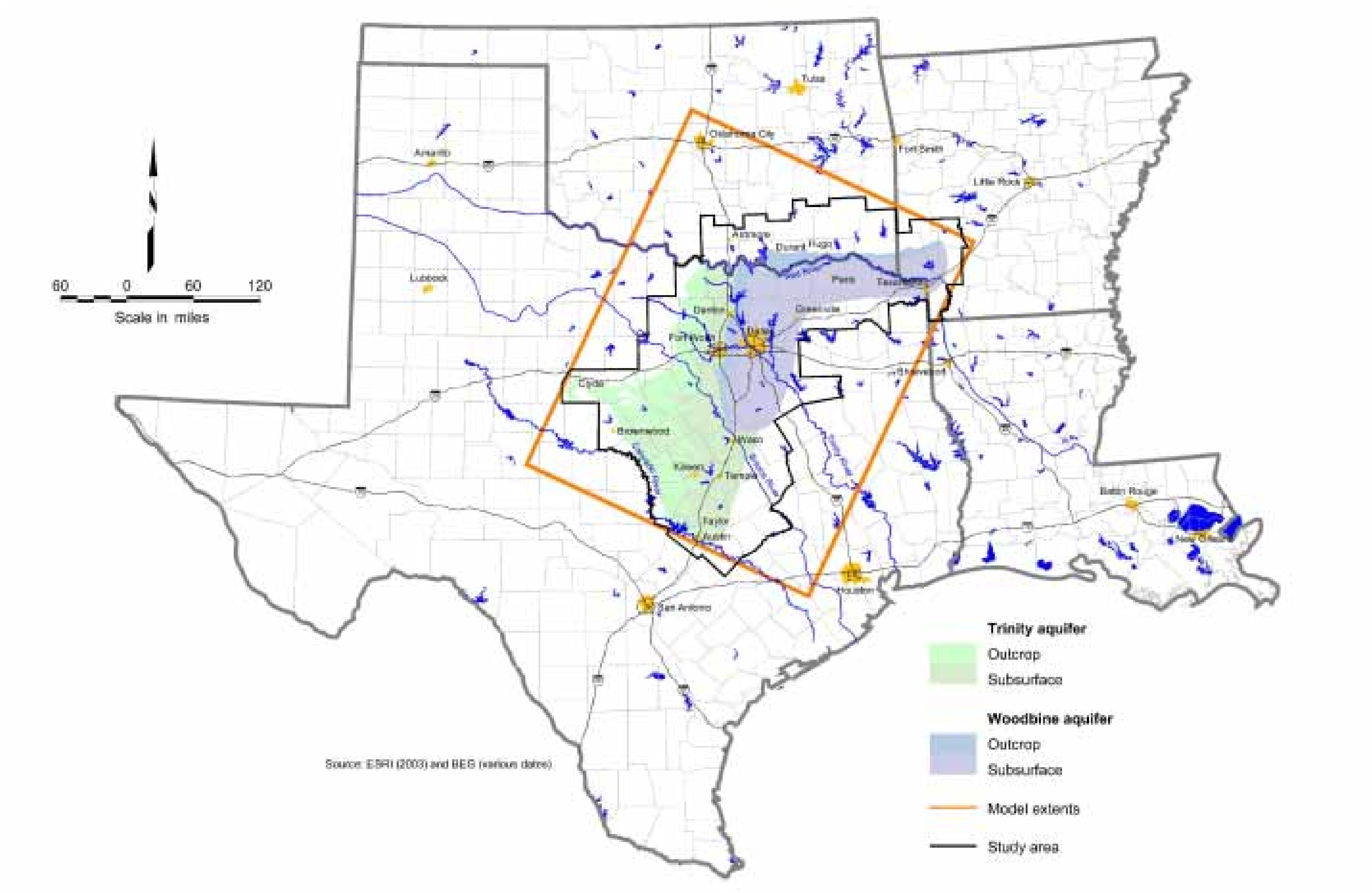


**Figure 2.1 Study Region Location Map No. 1**

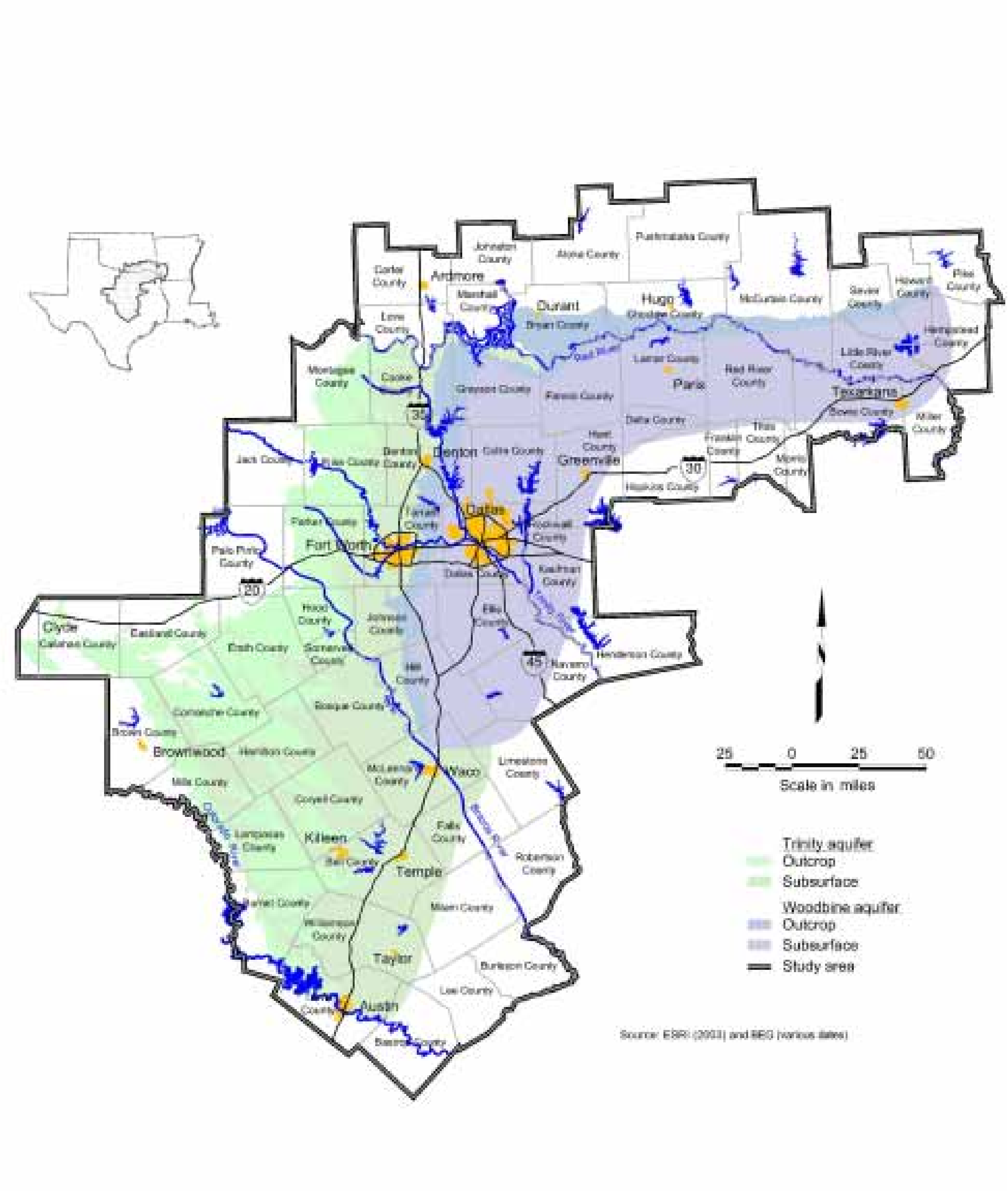


**Figure 2.2 Study Region Location Map No. 2**

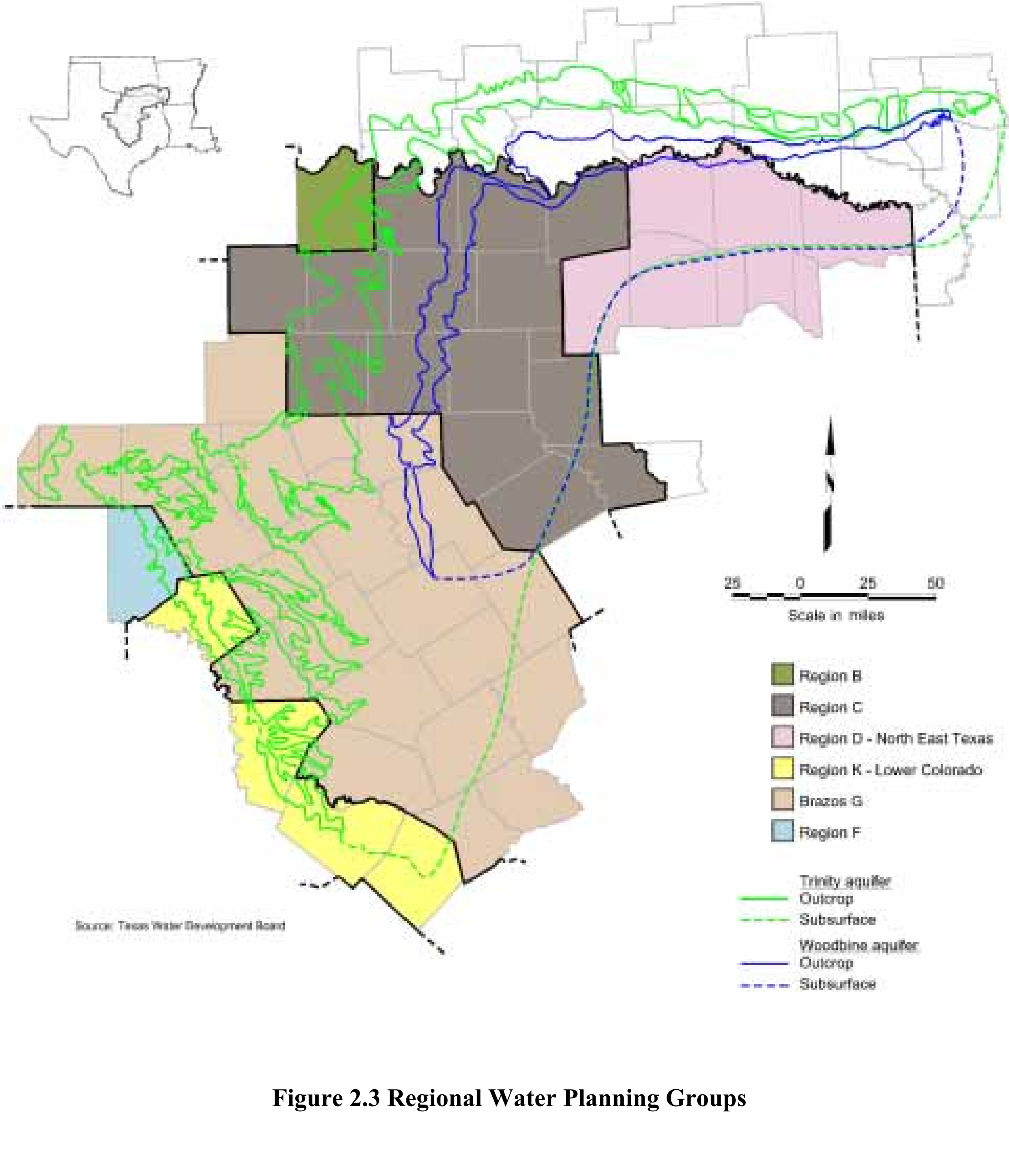


**Figure 2.3 Regional Water Planning Groups**

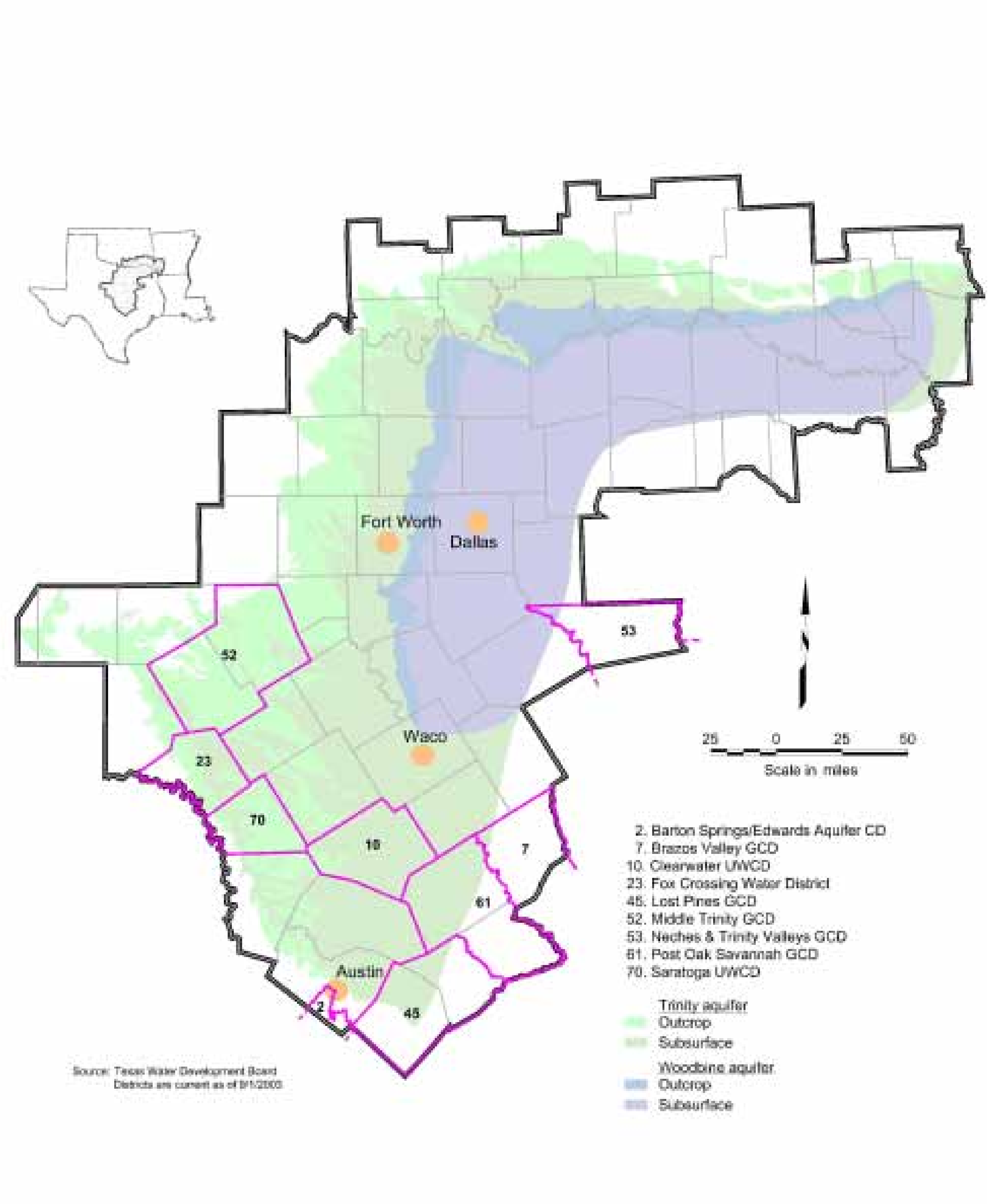


**Figure 2.4 Groundwater Conservation Districts**

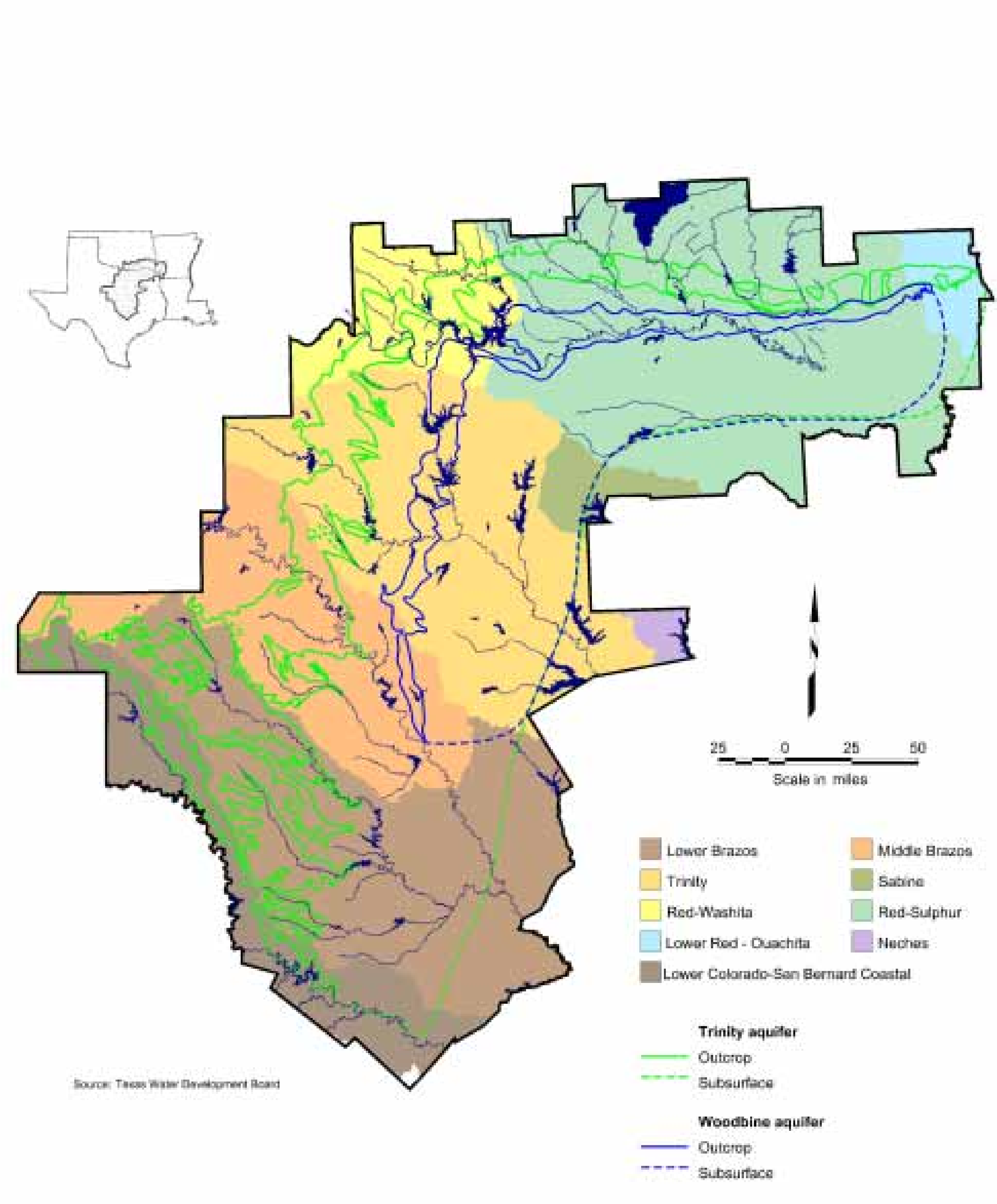


**Figure 2.5 River Basins**

## 2.1 Physiography and Climate

The study region lies in portions of the Coastal Plains, Central Lowlands, and the Great Plains (Figure 2.6). Gently rolling grasslands are common in the southern portion of the study region. In the central portion of the study region, the physical features include high-relief areas with well-defined dendritic drainage patterns. Within northeastern areas, the topography can be described as gently rolling grasslands, forestland, and low floodplains. Soils are generally calcareous clay, sandy loam, and clay loam, with a wide range of vegetation that includes bunch grass, mesquites, pine, elm, live oak, juniper, and pecan trees.

Ground surface elevations range from about 2,200 feet above mean sea level in the far-western areas to approximately 300 feet above mean sea level in the east (Figure 2.7). Drainage of the study region is generally to the southeast through watersheds defined by the Bosque, Brazos, Colorado, Lampasas, Leon, Navasota, Paluxy, Red, Sabine, Sulphur, and Trinity Rivers and their tributaries (Dutton et al., 1996; Klemt et al., 1975).

The climate is humid subtropical within the study area, and is characterized by long, hot summers and mild to moderate winters. The average annual gross lake surface evaporation rate is approximately 55 inches per year (in/yr) (Figure 2.8). Records provided by the National Weather Service (NWS) indicate that the average minimum temperature during winter months is 33° F and generally occurs in early to mid January. The average maximum temperature for summer is 96° F, which commonly occurs from late July to mid August. As shown in Figure 2.9, the mean annual temperature within the study area ranges between 66 and 68 degrees F.

Rainfall records from the NWS and the Texas Water Development Board (TWDB) in the study area were used to develop precipitation characteristics and to evaluate the spatial and temporal variability across the Trinity/Woodbine Formations. The TWDB has classified numerous NWS and other participant precipitation stations into quads throughout the state and assembled complete rainfall records for thousands of stations from 1940 to 2000. For this study, more than 190 stations in 20 quads throughout 52 counties covering Texas and Oklahoma were used to construct a historical rainfall record from 1940 to 2000 (Figure 2.10)

The region is characterized by a spatial distribution of precipitation that decreases in vertical bands from east to west with a distinct gradient geographically parallel to the IH 35 corridor. Average rainfall from 1960 to 2000 across the outcrop was 38 in/yr with an average maximum in the northeast of about 55 in/yr and an average low in the west of about 30 in/yr (Figure 2.11). The southern edge of the model area has seen historical annual lows of about 13 in/yr, while the eastern portion of the aquifer outcrop has received historic high annual rainfall of over 72 in/yr. The smallest amount of precipitation fell across the region in 1963, with an average of just under 23 inches. The trend of decreasing rainfall to the west is likely attributable to increasing topographic elevation and increasing distance from the Gulf of Mexico.

Analysis of 3-year moving averages and Palmer Drought Indexes shows that the only consecutive years of drought in the region occurred between 1954 and 1956. The low consecutive periods of rainfall are evident in the hydrographs of Quads 410, 509, 709, and 710. Precipitation has a bimodal distribution with most rainfall coming in the spring and fall months.

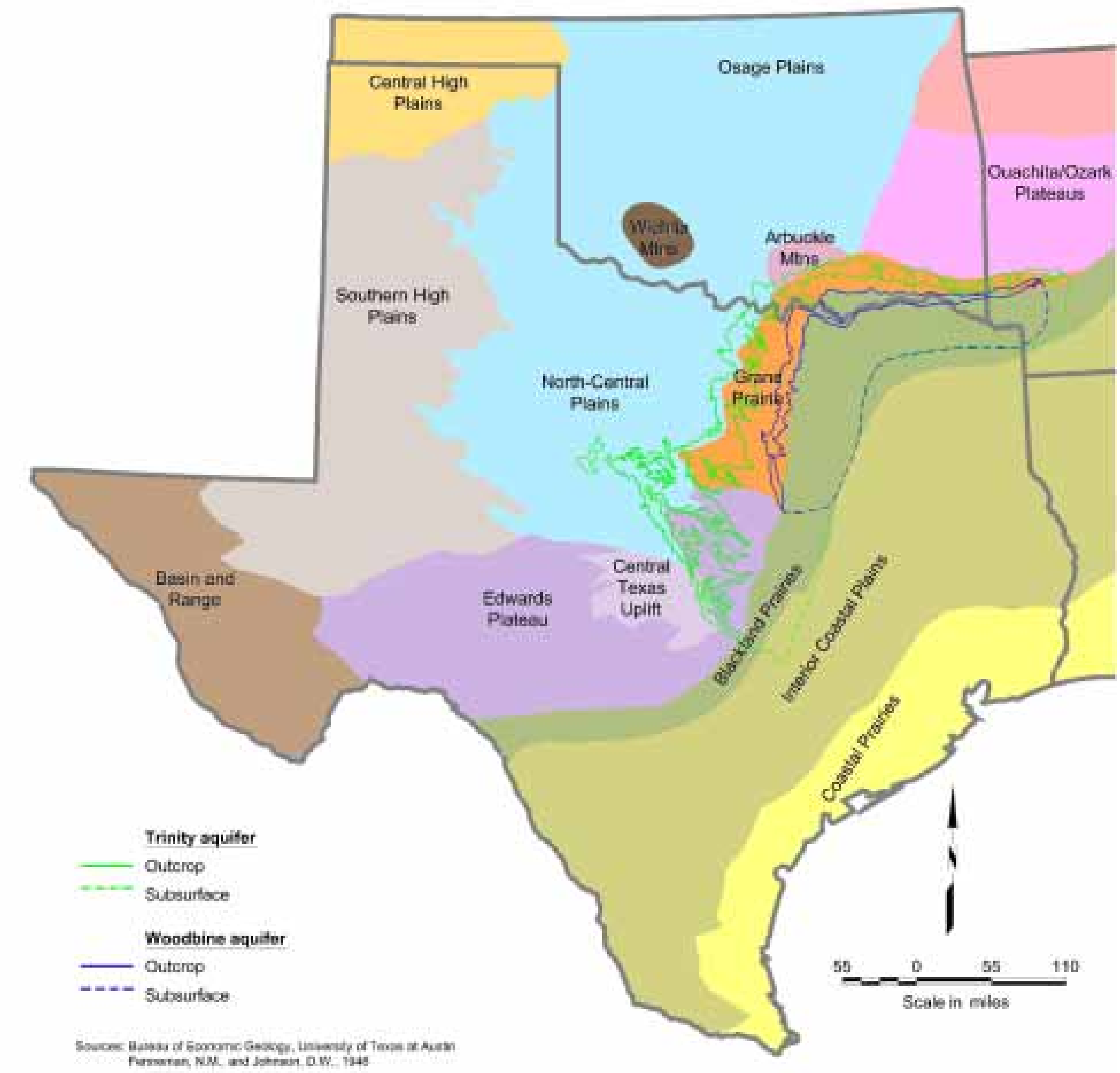


**Figure 2.6 Physiographic Provinces**

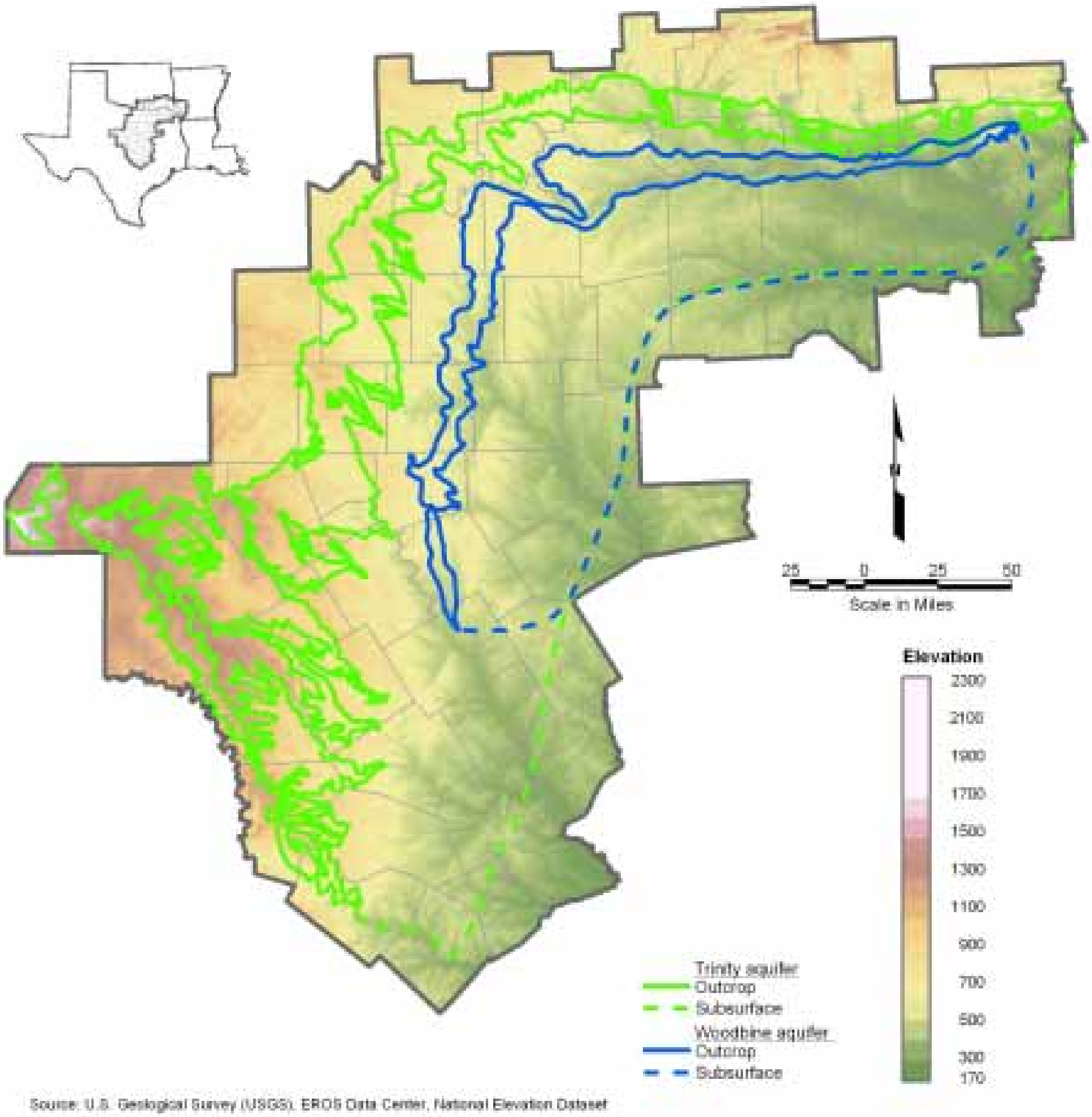


**Figure 2.7 Ground Level Elevation**

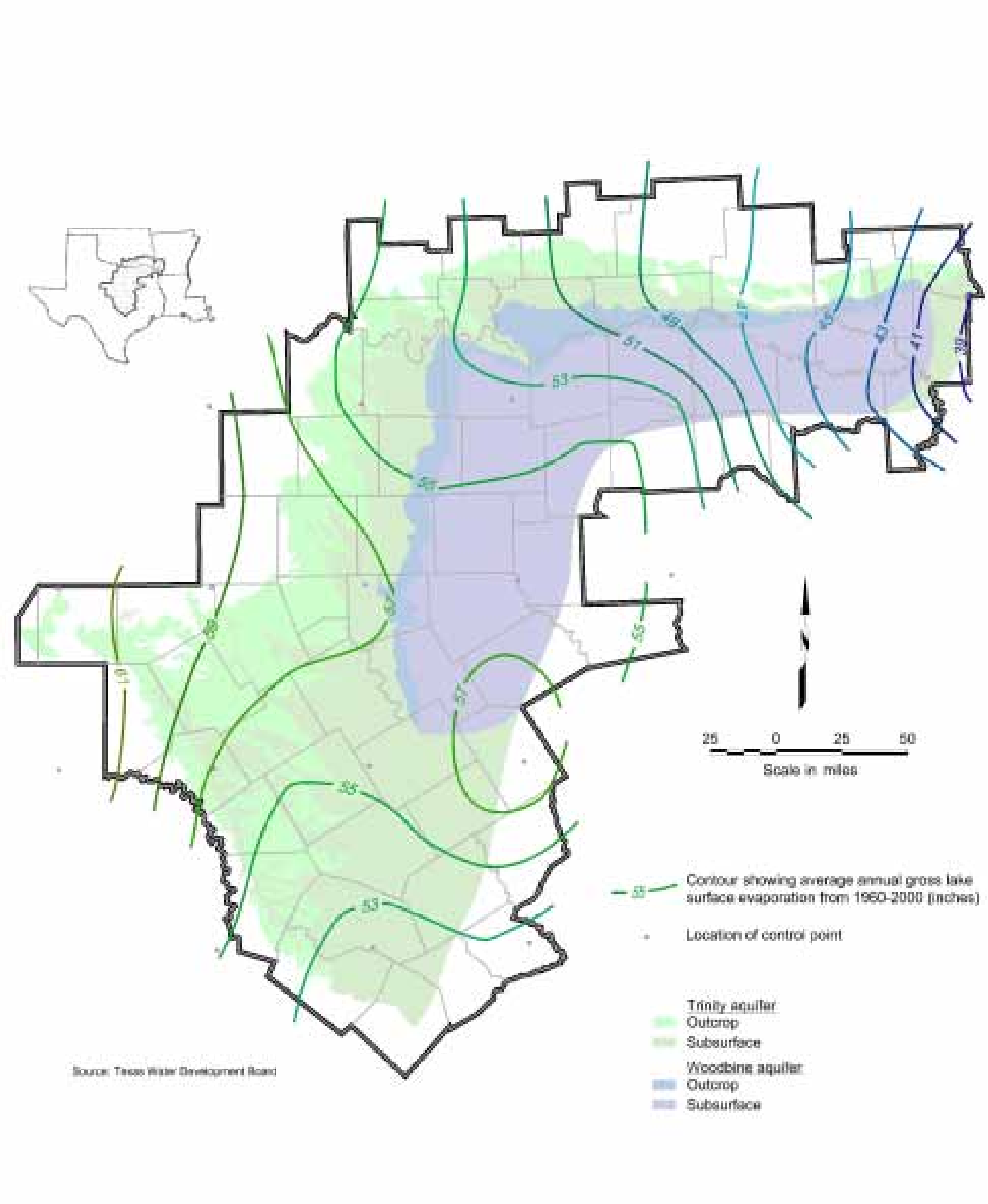


**Figure 2.8 Average Annual Gross Lake Evaporation**

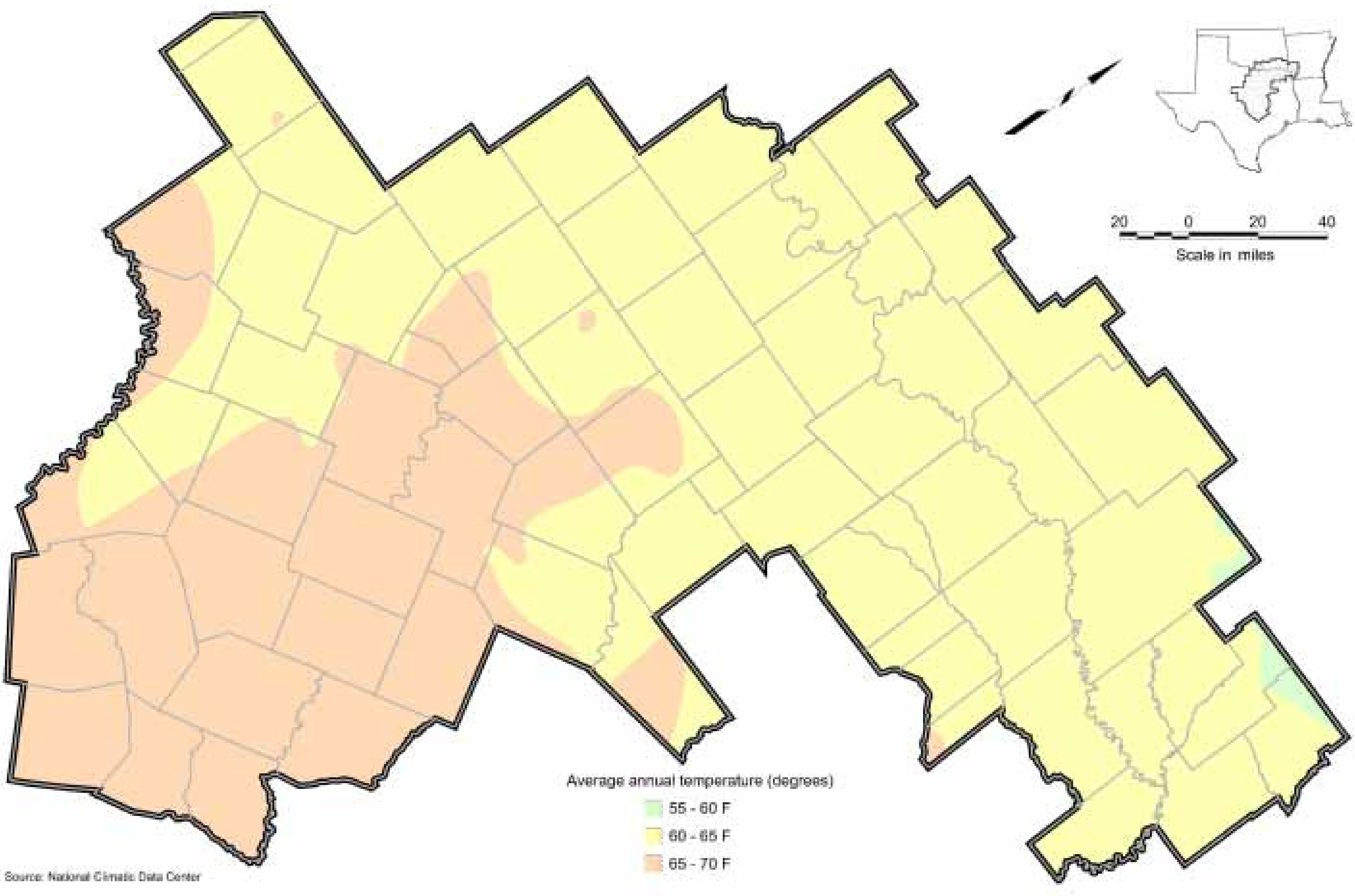


**Figure 2.9 Average Annual Temperature**

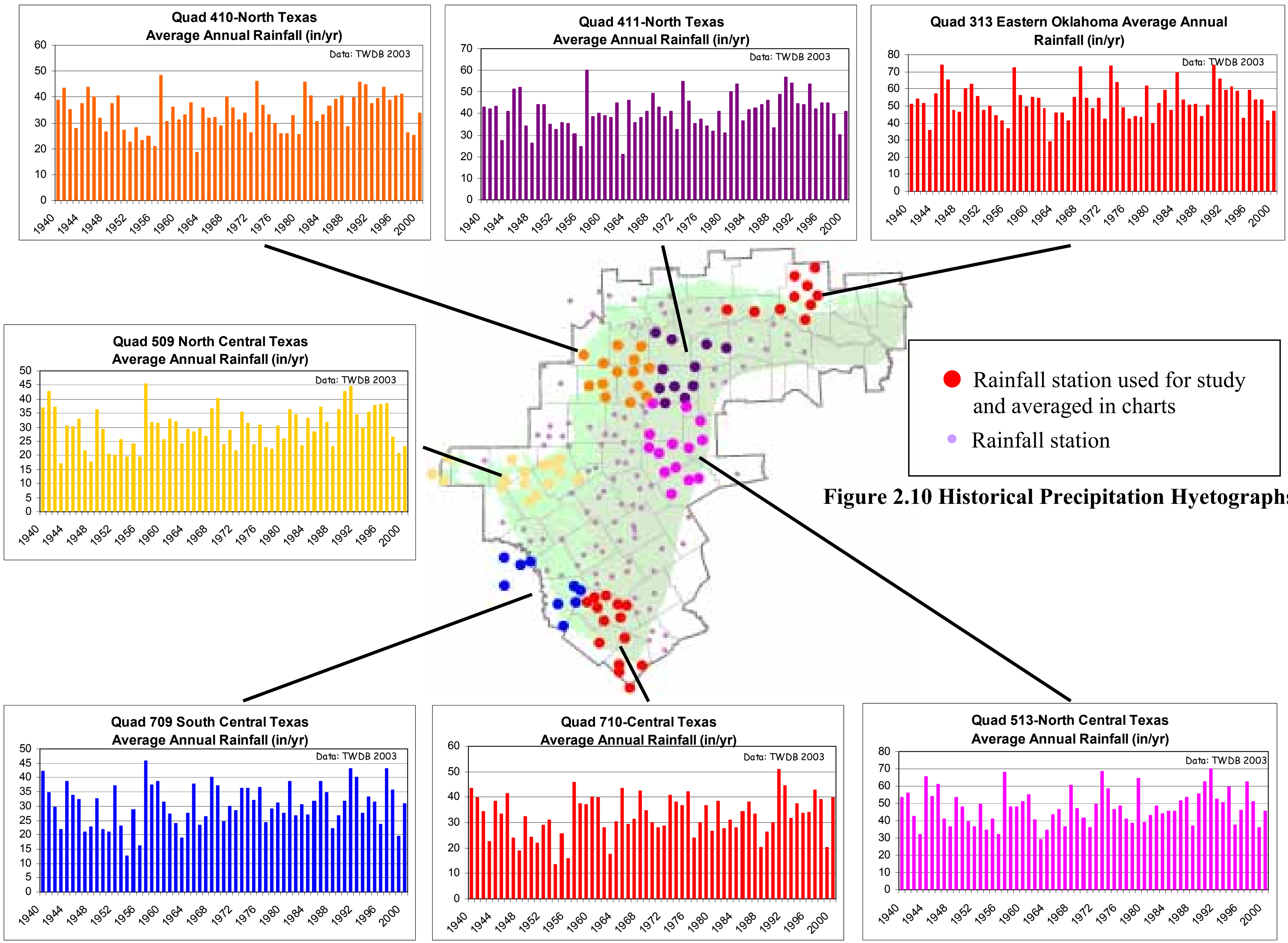


**Figure 2.10 Historical Precipitation Hyetographs**

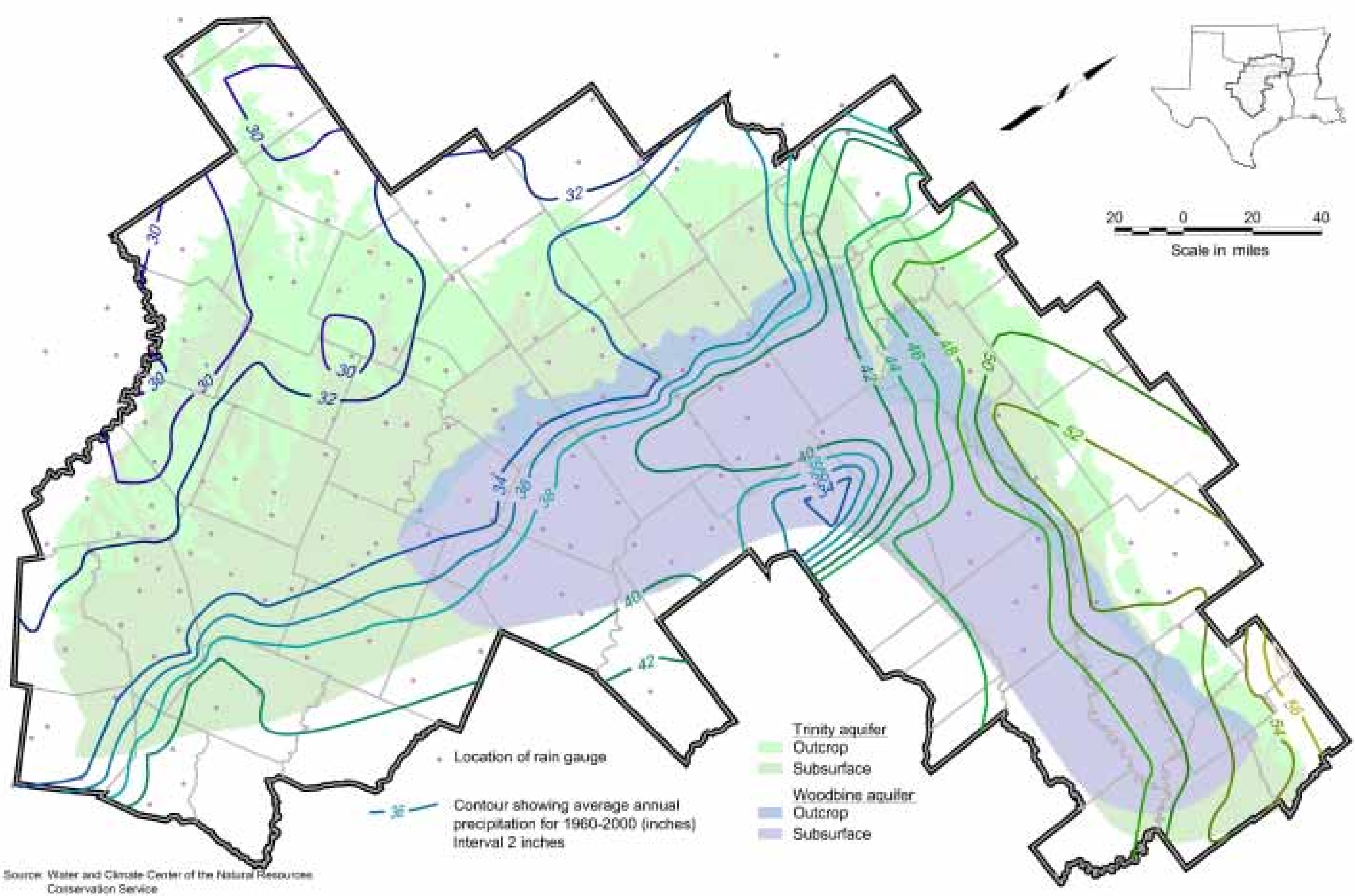


**Figure 2.11 Average Annual Precipitation**

## 2.2 Geology

The Cretaceous sediments that comprise the Northern Trinity/Woodbine aquifer system extend from a small section of western Arkansas and southern Oklahoma through much of the northeastern quarter of Texas. Deposited upon a relatively flat erosional surface (paleoplain) carved into truncated, metamorphosed Paleozoic strata during the Triassic and Jurassic, these sediments form a southeastward-thickening wedge from Central Texas outcrop areas to the East Texas Basin (Nordstrom, 1982). The Trinity/Woodbine sediments were deposited throughout the Comanchean Series and the early Gulfian Series, and are subdivided (from oldest to youngest) into the Trinity, Fredericksburg, Washita, and Woodbine Groups (Hill, 1901). Trinity/Woodbine sediments were laid down in a variety of terrestrial and marine depositional environments. Because of the large degree of variability in thickness and lithology exhibited by these formations over the model extent, the geologic nomenclature describing the Trinity/Woodbine is complex, often varying with author, date, and region. In order to standardize the process of data collection and model construction, the following nomenclature was adopted for this GAM project. The Lower Trinity is defined as all formations below the Glen Rose including (from lower to upper) the Hosston/Sligo, Pearsall/Cow Creek/Hammett, and Hensell members of the Travis Peak Formation, while the Upper Trinity is defined as the Glen Rose and Paluxy Formations where defined (see Figures 2.12 and 2.13). Figures 2.14 through 2.18 illustrate the regional stratigraphic relationships of the Trinity/Woodbine units.

Extending from McLennan County at its southern edge to the Red River in the north, the Woodbine Formation was deposited in the late Cretaceous (Gulfian Series). The Woodbine is composed of sand, silt, clay, and some gravel, and ranges in thickness from less than 100 feet in the south to over 600 feet in northern downdip areas. South of McLennan County in Central Texas, where the thick sands of the Woodbine are no longer present, the Pepper Shale is equivalent to the Upper Woodbine (Adkins and Lozo, 1951). The Woodbine is divided into two members from oldest to youngest: the Dexter Member and the Lewisville Member. These members are composed chiefly of sediments deposited in fluvial, high-destructive deltaic, and shelf-strandplain depositional systems. The Ouachita Mountains in Southern Oklahoma and Arkansas served as the source of Woodbine sediments, which were subsequently deposited into the actively subsiding East Texas Basin (Oliver, 1971). The Woodbine is unconformably overlain by the Eagle Ford Group throughout most of the study area, which acts as a confining unit to the Woodbine (Yelderman, 2002). The Eagle Ford is comprised predominantly of shale with thin beds of limestone and bentonite, and increases in thickness from about 150 feet in the south to greater than 500 feet in northern Texas. As shown in Figure 2.19, the net sand content of the Woodbine is also greatest in downdip areas in northern Texas. In this region, the sand thickness increases from less than 100 feet near the outcrop to over 400 feet near the Luling-Mexia-Talco Fault Zone (Section 4.2).

The Fredericksburg and Washita Groups separate the Paluxy from the overlying Woodbine Formation. The Fredericksburg Group is comprised of the Walnut Formation, Comanche Peak, and Edwards Formations in southern areas. In the northern portion of the model area, the carbonate facies of the Fredericksburg is generally classified as the Goodland Formation, which forms a very distinct contact on geophysical logs with the Kiamichi Clay, defined herein as the basal unit of the Washita Group. Deposited during late Comanchean times, the Washita Group is subdivided into various formations with very complex stratigraphic nomenclature, depending upon region and author. The Fredericksburg and Washita Groups consist primarily of limestone, dolomite, marl, and shale facies (Leggat, 1957), and have a combined thickness ranging from about 450 to 900 feet in the model area.

The Lower Cretaceous Paluxy Formation consists of sand, silt, and clay, deposited unconformably atop the underlying Trinity Group sediments. Separated from the Lower Trinity aquifers by the Glen Rose Formation throughout most of the southern section of the study area, the Paluxy merges with and generally becomes indistinguishable from the Hensell and Hosston in the north and northwest. The boundary with the overlying clay-rich Walnut Formation is characterized as a gradational, interfingering contact, which suggests time-equivalent deposition (Atlee, 1962). The Ouachita and Arbuckle Mountains in Oklahoma provided the source of Paluxy sediment, which was redeposited in fluvial, deltaic, and strandplain depositional environments in northeastern Texas (Caughey, 1977). The Paluxy increases in total thickness from a featheredge in the southern portion of the study area to greater than 600 feet in the north and northwest. Similarly, the net sand thickness (as derived in this study from geophysical logs) grows from just a few feet in the south to more than 250 feet in northern Texas (Figure 2.20). The sands and silts that comprise the Paluxy are composed primarily of fine-grained, friable, quartz grains, which are, in general, well sorted, poorly cemented, and crossbedded (Klemt et al., 1975).

The Glen Rose Formation lies below the Paluxy Formation throughout most of the model area. Conformable and gradational with the underlying Travis Peak Formation, the Glen Rose strata were deposited on a laterally extensive shelf area known as the Central Texas Platform. The Glen Rose is composed primarily of dense, finely crystalline limestone with varying amounts of shale, sandy-shale, and anhydrite distributed throughout the unit. The type, volume, and distribution of sediments were controlled primarily by eustatic cycles, which resulted in the alternation between classic tidal flat depositional environments during regressive stages, and deeper marine (neritic) environments during transgressive periods (Davis, 1974). The Glen Rose carbonates are present throughout most of the study area, but pinch out in the west and northwestern portions of the model domain. In regions where the unit is defined, the thickness is variable, but averages about 500 feet throughout the study area.

The Cretaceous strata underlying the Glen Rose Formation have traditionally been designated as the Twin Mountains Formation in northern Texas and the Travis Peak Formation in Central Texas. The Travis Peak is comprised of three members: the Hosston/Sligo Member, the Pearsall/Cow Creek/Hammett Member, and the Hensell Member. In general, the assignment of Twin Mountains has been applied in regions where the contacts between the individual members are ambiguous, while the assignment to the Travis Peak Formation is made when the boundaries between subdividing members are well defined, although this is not always the case. Additional nomenclatural ambiguity results in northern sections where the definition between the Hensell and Hosston is not clear and the carbonates of the Glen Rose Formation are not distinguishable. In these areas, the sediments separating the sands of the Paluxy and the Lower Trinity are (by default) attributed in geologic nomenclature either to the Paluxy or to the Twin Mountains/Travis Peak. Where this occurs, the combined Paluxy-Twin Mountains/Travis Peak strata are referred to as the Antlers Sand.

The Hensell Member was defined by Hill (1901) and is designated as the uppermost, sandy, subdivision of the Travis Peak Formation. The lithologic makeup of the Hensell is similar to that of the Hosston, containing a large percentage of fine to coarse-grained sand interbedded with shales and, in the basal section, pebbly conglomerate lenses (Boone, 1968). Hensell sand deposits exhibit poor cementation and common cross-beds (Nordstrom, 1987). The Hensell does not generally exhibit the basinward thickening of sand deposits seen in other Trinity/Woodbine aquifer units. Instead, the sand thickness of the Hensell is relatively uniform, ranging between 50 to 100 feet throughout most of the region (Figure 2.21). Source rock for the Hensell was derived from regions located to the north and west of the study area, which were eroded and redeposited to the southeast within fluvial and deltaic depositional regimes (Hall, 1976).

The Pearsall/Cow Creek/Hammett Member separates the Hensell and Hosston/Sligo Members of the Travis Peak Formation. This composite member defines the carbonate and clay-rich clastic sediments deposited during early Comanchean times. Predominantly composed of limestone in downdip areas, the carbonate facies of the Cow Creek gradually thins and pinches out in the western (updip) portion of the study area. Where the Cow Creek limestones are not present, the shales of the Cow Creek and Hammett Members coalesce and become indistinguishable as separate units. Updip of this convergence zone, the argillaceous composite unit is defined as the Pearsall Member. The

Pearsall/Cow Creek/Hammett averages 100 to 200 feet thick, and is generally distinguishable on geophysical logs in the south, but is not clearly defined in northern portions of the study area.

The Hosston/Sligo Member of the Travis Peak Formation represents the first sequence of preserved Cretaceous deposits in the study area. Composed primarily of fossiliferous, dolomitic limestone with interbedded shale, the Sligo is the downdip, marine equivalent to the Hosston Sand (Klemt et al., 1975). Ranging in thickness from 0 to 130 feet, the Sligo is thickest in eastern, downdip areas, and grades into sandstone and shales that become indistinguishable from the Hosston west of the Waco area. In the outcrop, the Hosston Sand is interpreted to be equivalent to the Sycamore Sand (Stricklin et al., 1971) as defined by earlier researchers. This unit is composed of thin to massively bedded, fine to medium grained orthoclase-rich quartz sand interbedded with sandy clay (Boone, 1968). As illustrated in Figure 2.22, the net sand thickness of the Hosston averages about 175 feet in the model area, with a maximum of about 500 feet in downdip areas. Because the Hosston/Sligo was deposited upon valleys and ridges that existed in the pre-Cretaceous surfaces, the total thickness of deposition varies in the study region. In general, local Hosston/Sligo deposits are thicker in valley areas, while locally thinner deposits are found in areas where the underlying strata formed ridges. Within the model area as a whole, the total thickness of the Hosston sand averages about 240 feet, with deposits in downdip portions of the study area exceeding 1,500 feet in thickness.

Two major fault zones displace Trinity/Woodbine sediments: 1) the Luling-Mexia-Talco Fault Zone, and 2) the Balcones Fault Zone. These zones significantly affect the flow within the aquifer system, which in turn influences the quality and availability of Trinity/Woodbine groundwater. Sections 4.1 and 4.2 discuss the geologic history and occurrence of these features in the model area.

| System | Series | Groups | Formation: North | Formation: South | Approximate Maximum Thickness: North | Approximate Maximum Thickness: South |
|---|---|---|---|---|---|---|
| **Tertiary** | Undifferentiated | | | | | |
| **Cretaceous** | Gulfian | Navarro | Undifferentiated | Undifferentiated | 800 | 550 |
| | | Taylor | | | 1500 | 1,100 |
| | | Austin | | | 700 | 600 |
| | | Eagle Ford | | | 650 | 300 |
| | | Woodbine | | | 700 | 200 |
| | Comanchean | Washita | Grayson Marl | Buda, Del Rio | 1,000 | 150 |
| | | | Mainstreet, Pawpaw, Weno, Denton | Georgetown | | 150 |
| | | | Fort Worth, Duck Creek | | | |
| | | | Kiamichi | Kiamichi | | 50 |
| | | Fredericksburg | Goodland | Edwards | 250 | 175 |
| | | | | Comanche Peak | | 150 |
| | | | Walnut Clay | Walnut Clay | | 200 |
| | | Trinity | Antlers – Paluxy | Paluxy | 400 | 200 |
| | | | Antlers – Glen Rose | Glen Rose | 1,500 | 1,500 |
| | | | Antlers – Twin Mountains | Travis Peak – Hensell | 1,000 | 1,800 |
| | | | | Travis Peak – Pearsall/Cow Creek/Hammett | | |
| | | | | Travis Peak – Hosston/Sligo | | |
| **Paleozoic** | Undifferentiated | | | | | |

Source: Klemt et al., 1975; Nordstrom, 1987.

**Figure 2.12 Stratigraphic Diagram**

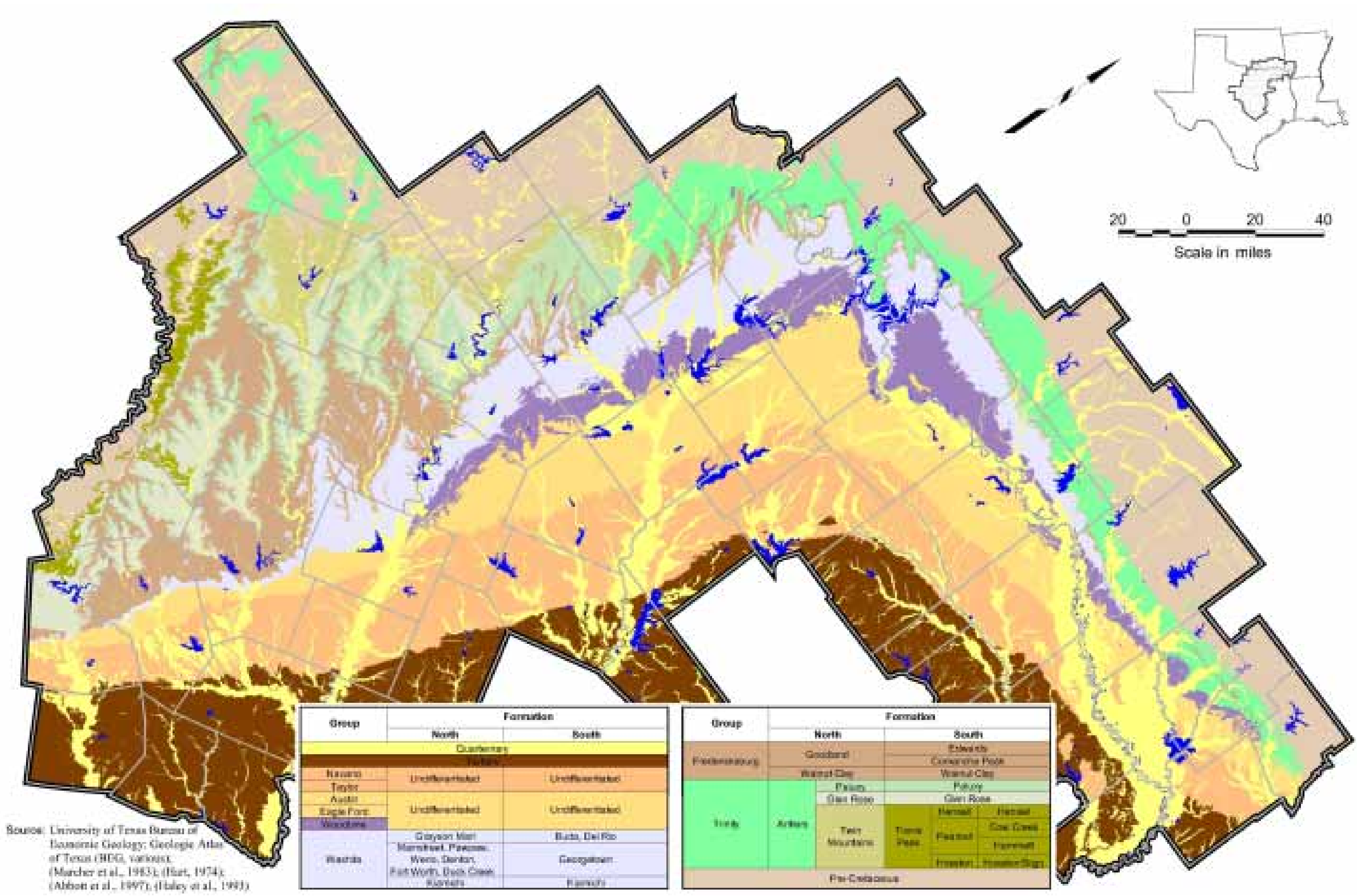


**Figure 2.13 Surface Geology**

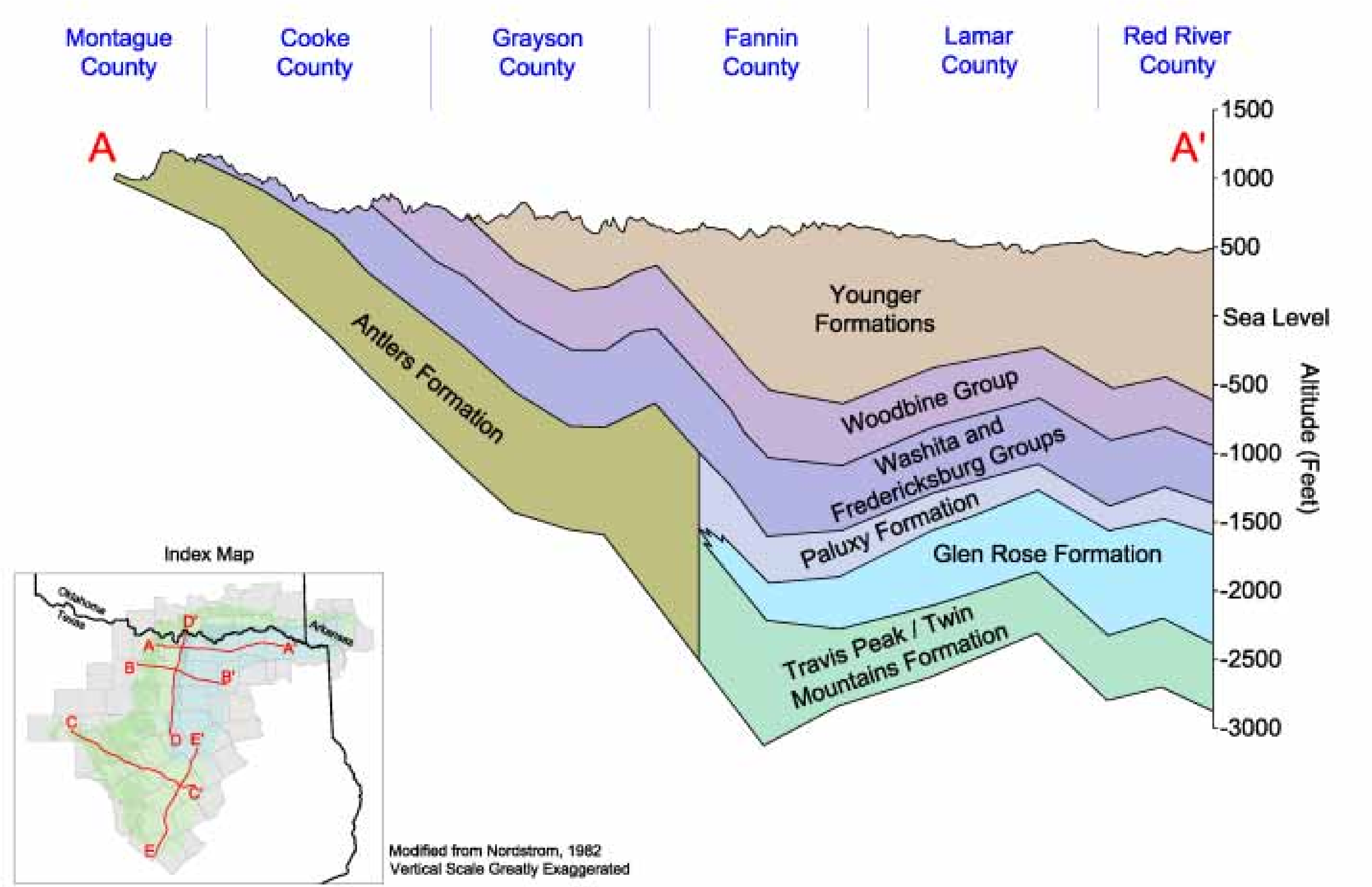


**Figure 2.14 Generalized Geologic Section A - A'**

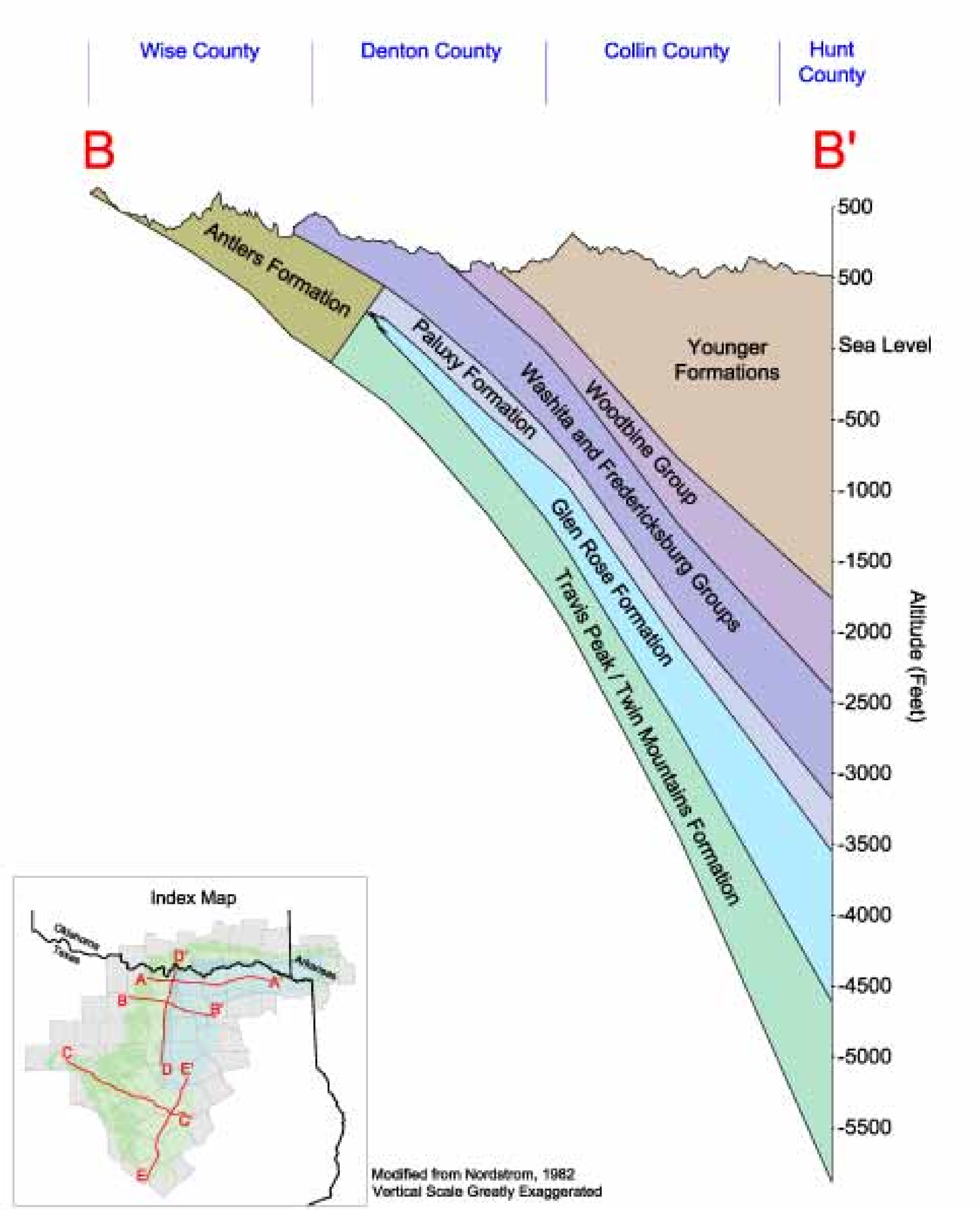


**Figure 2.15 Generalized Geologic Section B - B'**

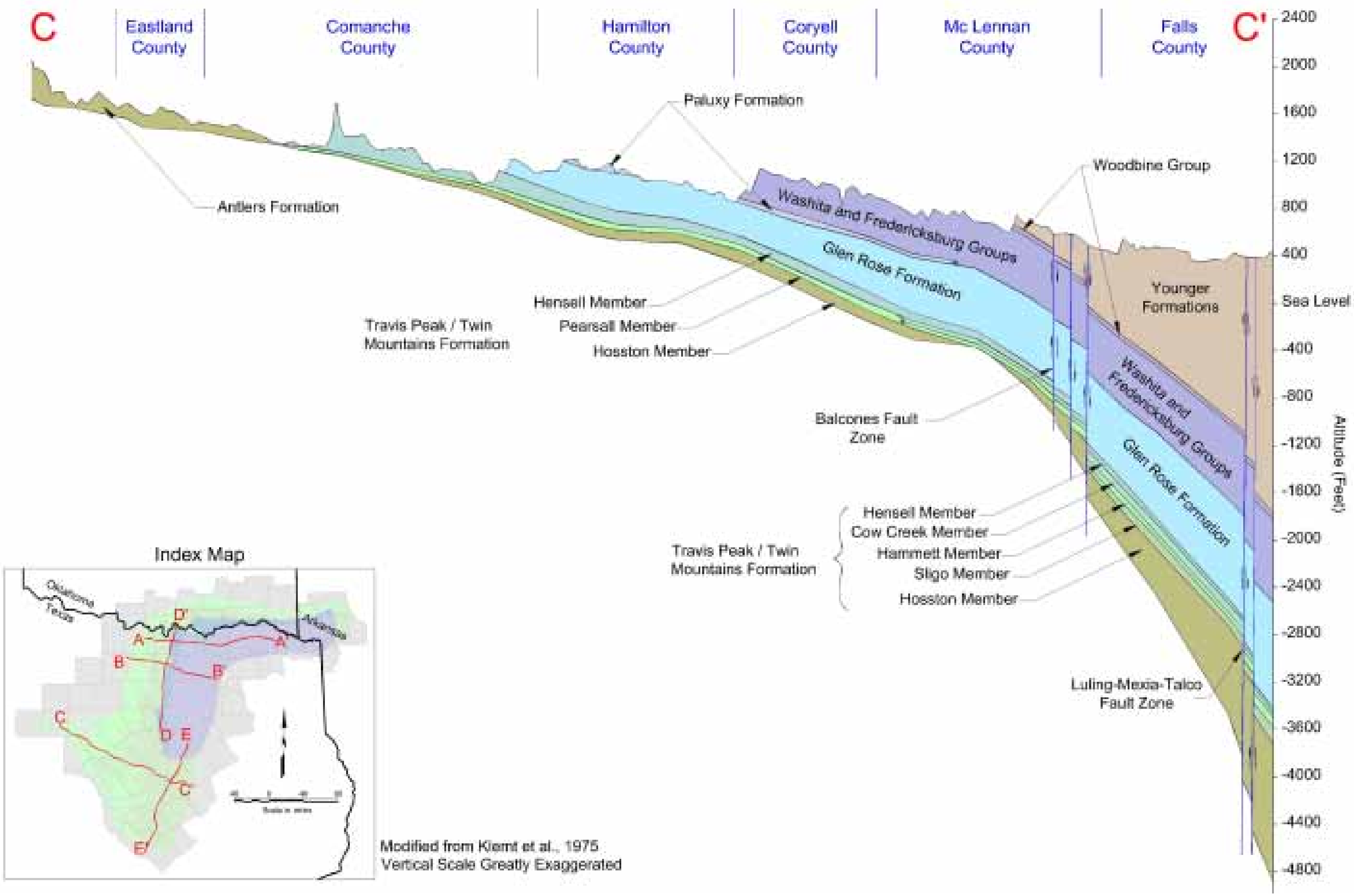


**Figure 2.16 Generalized Geologic Section C - C'**

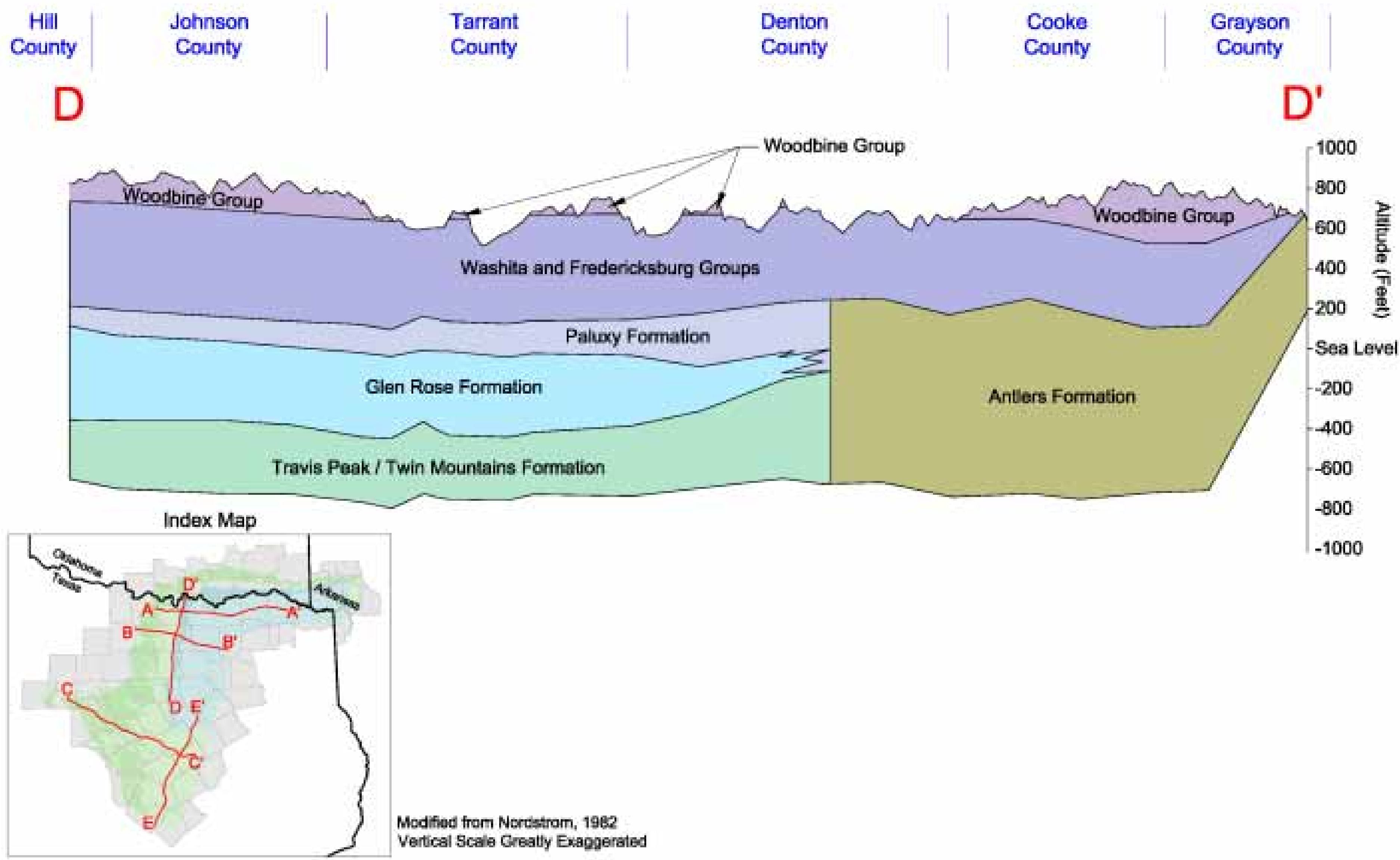


**Figure 2.17 Generalized Geologic Section D - D'**

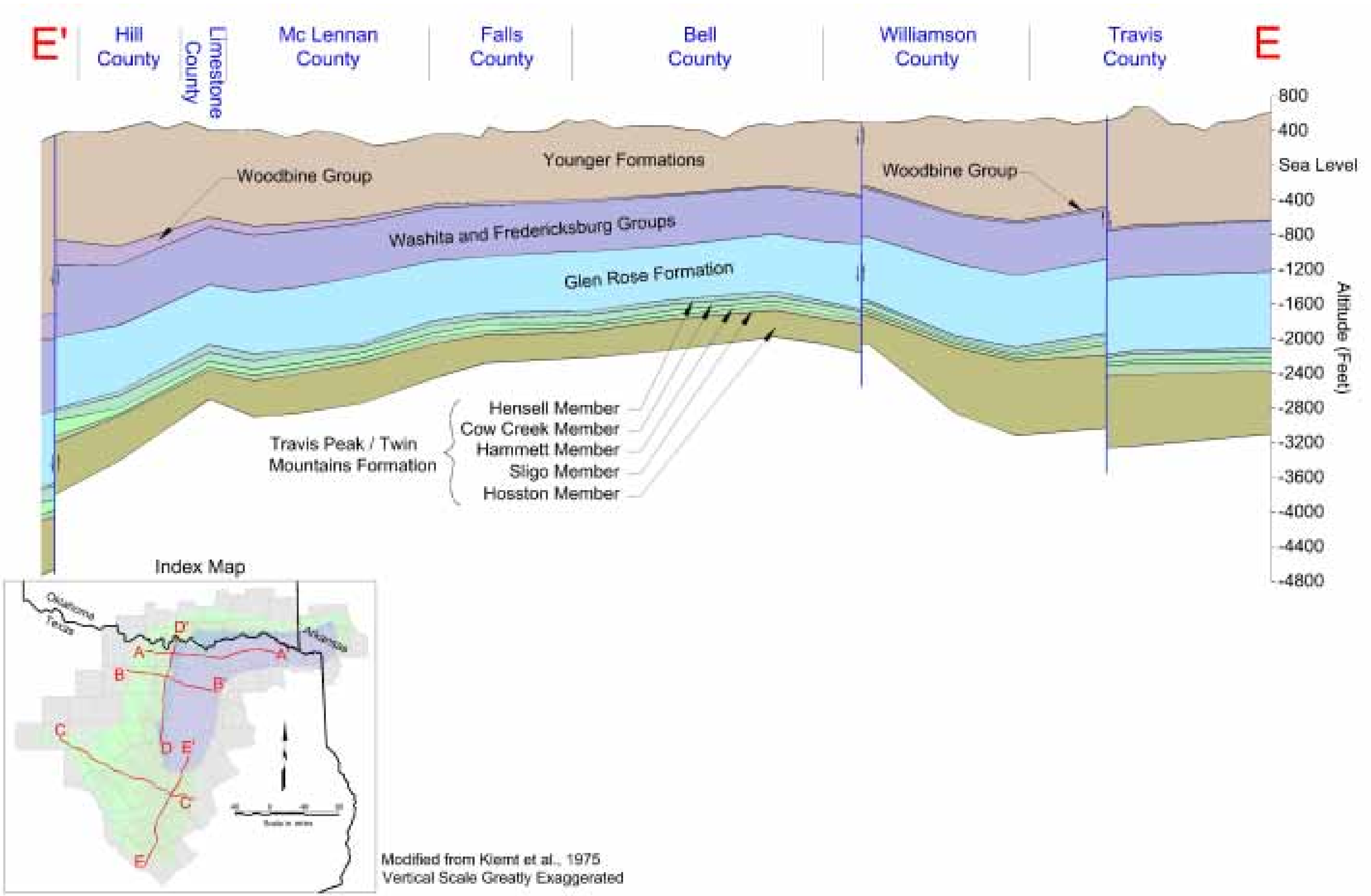


**Figure 2.18 Generalized Geologic Section E - E'**

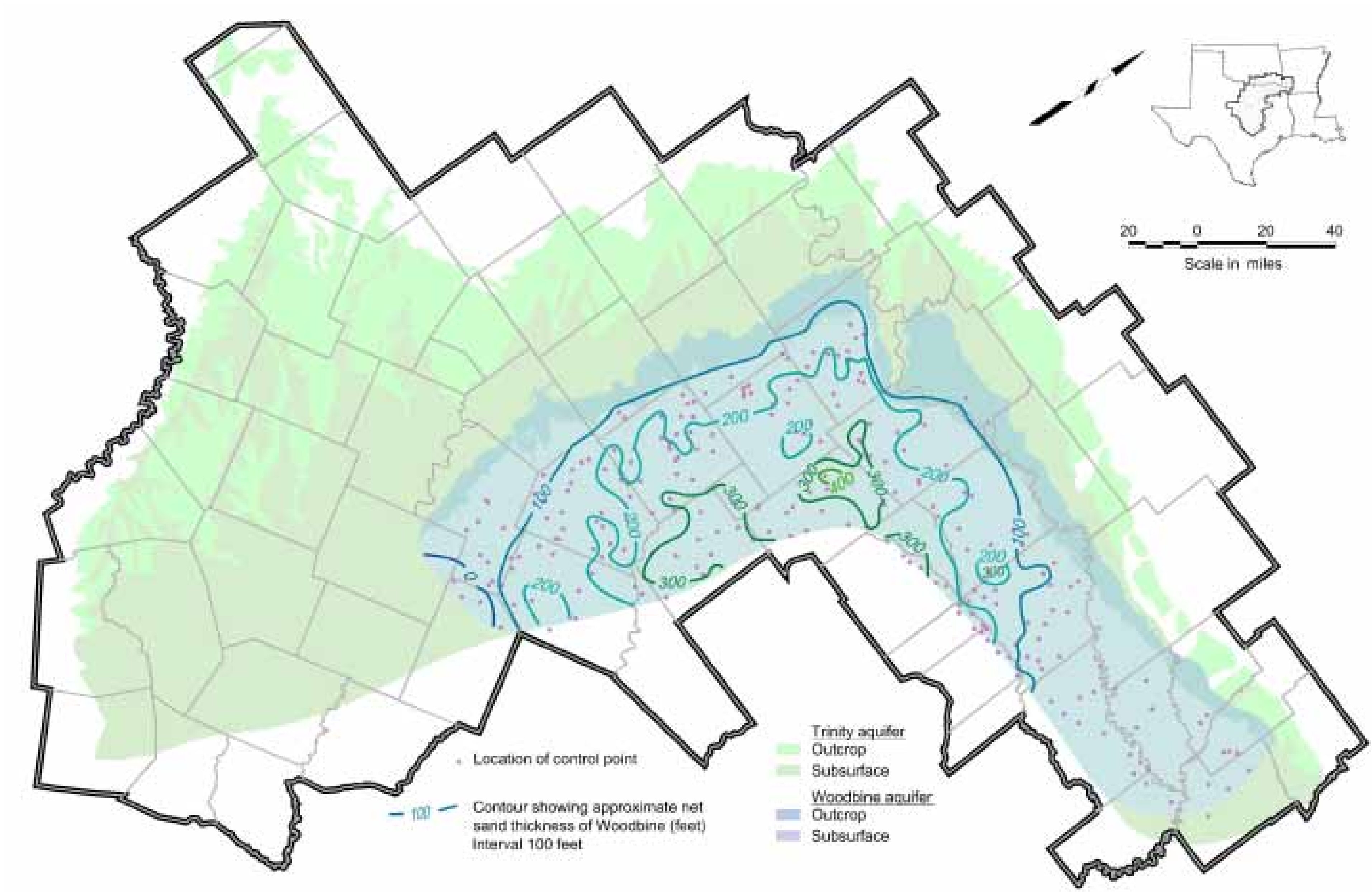


**Figure 2.19 Net Sand Thickness of the Woodbine**

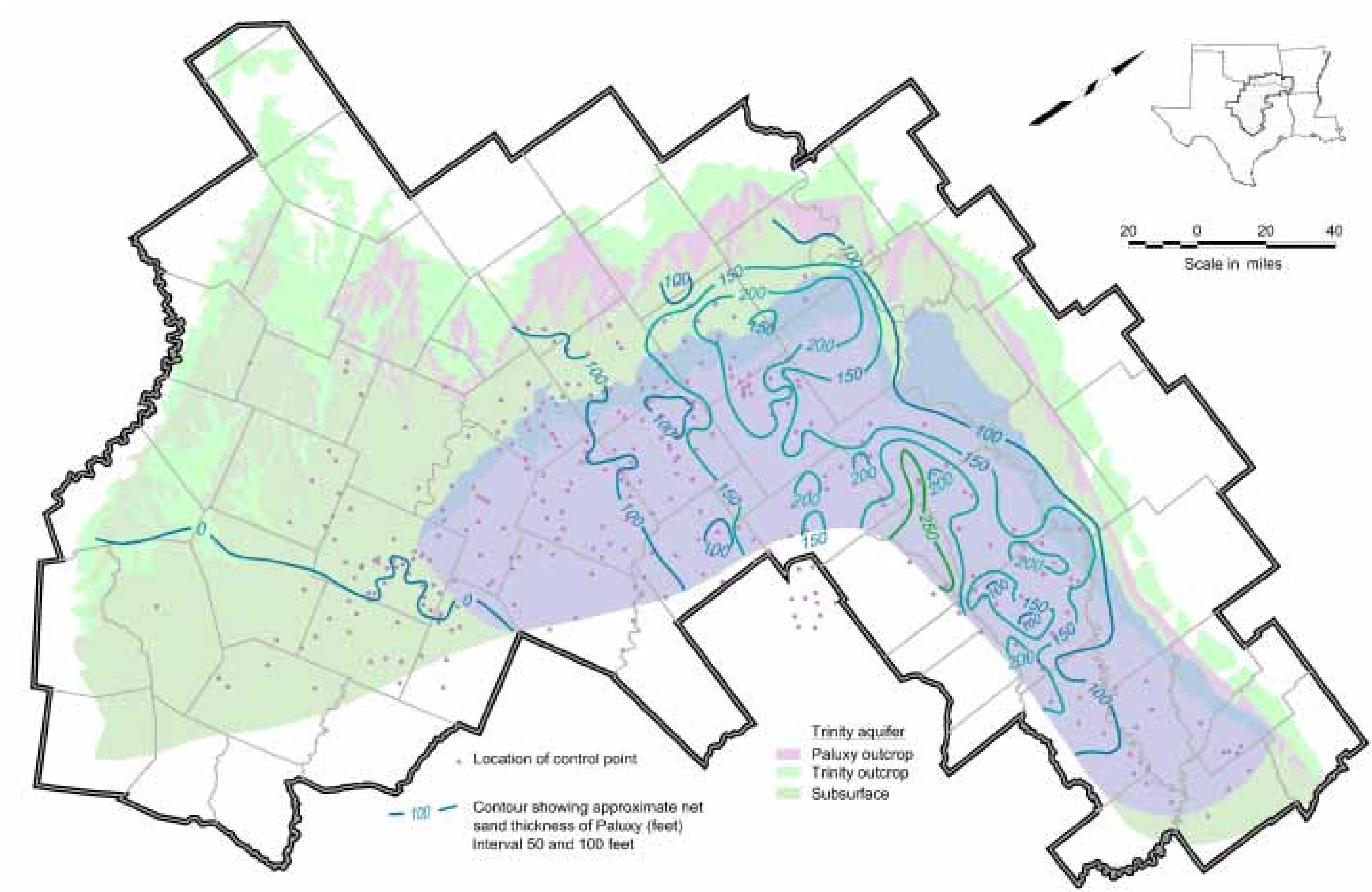


**Figure 2.20 Net Sand Thickness of the Paluxy**

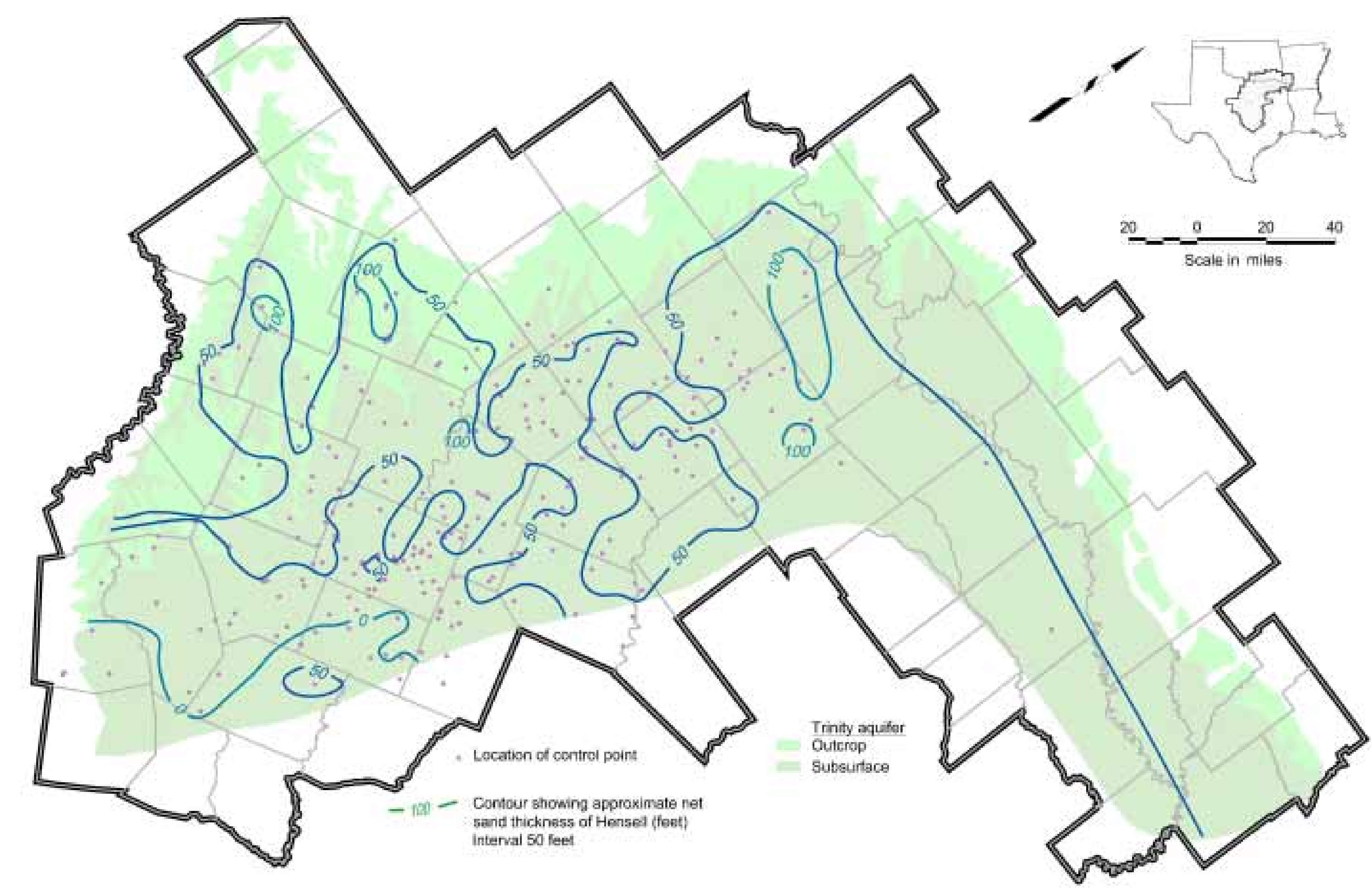


**Figure 2.21 Net Sand Thickness of the Hensell**

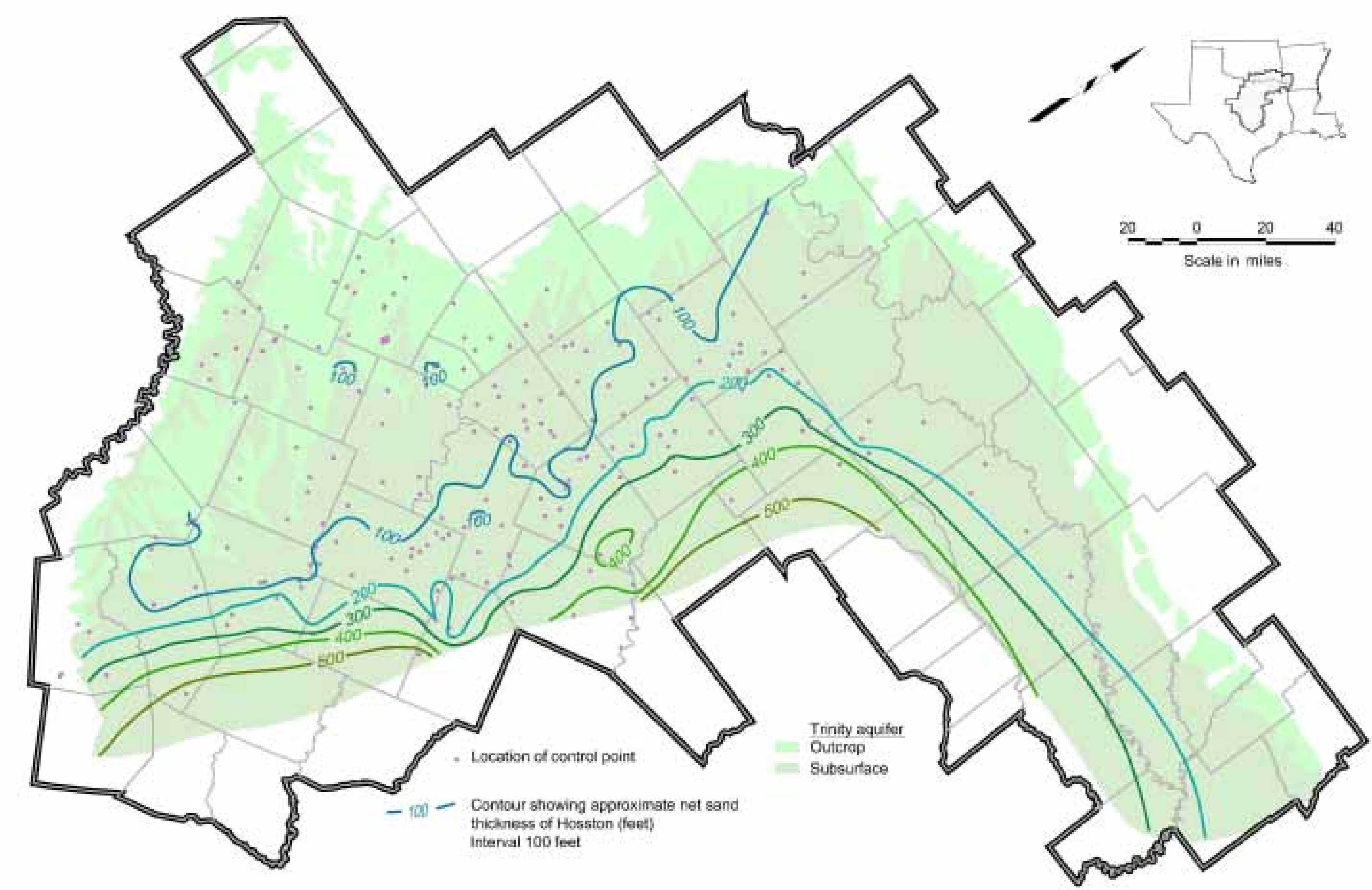


**Figure 2.22 Net Sand Thickness of the Hosston**

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# 3.0 PREVIOUS WORK

For more than one hundred and fifty years, previous investigators have researched the northern section of the Trinity/Woodbine aquifer and published numerous reports, models, and maps on the geology and hydrology of the system. The following is a brief summary of the works of these authors and their contribution to the study of the Trinity/Woodbine.

One of the first studies of the Cretaceous rocks in central and northern Texas was conducted in the interval from 1845 to 1847 by the German geologist Ferdinand Roemer, who investigated the region as a precursor to German settlement later in the 19th Century (Mosteller, 1970). A few years later, G. G. Shumard, Jules Marcou, and B. F. Shumard also conducted investigations of the Lower Cretaceous fossils and stratigraphy (Shumard, 1860). Building upon the work conducted by these previous researchers, R. T. Hill (1901) published some of the most enduring descriptions of the Cretaceous stratigraphy and sediment characteristics in north-central Texas in the late 1800's and early 1900's. In the 1930's, Adkins (1933) studied and reported on the Trinity/Woodbine strata, while the (Texas) State Board of Water Engineers compiled drillers logs, water level data, and water quality data on wells located in many northern and central Texas counties.

Population growth encouraged increased development of groundwater resources in Texas during the mid 20th Century. Concurrently, C.V. Theis' (1935) methods of calculating water level declines were coming into widespread use. These circumstances fostered a period of increased interest by researchers and State agencies in the hydrogeologic properties of the aquifers that comprise the Trinity/Woodbine in North-Central Texas. George and Rose (1942) described the groundwater resources in the region surrounding Fort Worth, emphasizing the changes that occurred in Trinity and Paluxy water levels during the previous decades. Livingston (1945) and Sundstrom (1948) reported aquifer test results for the Texas State Board of Water Engineers. The stratigraphy of the Woodbine in the Waco region was studied in detail by Adkins and Lozo (1951) and the sediment characteristics of the Woodbine in the Arlington area were reported by Dodge (1952). Leggat (1957) presented a very thorough appraisal of the geology and groundwater resources of Tarrant County in the late 1950's.

Scientific and economic interest in the Trinity/Woodbine continued to grow during the 1960's and 1970's. As a result, numerous county and regional studies were funded by the Texas Board of Water Engineers, the Texas Water Commission, and the Texas Water Development Board (TWDB). These include: Harden (1960), Baker (1960), Peckham et al. (1963), Bayha (1967), Thompson (1967), Myers (1969), Thompson (1969), and Thompson (1972). Klemt et al. (1975, 1976) reports include numerous maps detailing the regional structure, and sand content of the Trinity/Woodbine aquifers, as well as the historical water levels and groundwater quality attributable to the individual strata. In 1960, Davis with the Oklahoma Geological Survey published a bulletin reporting the stratigraphy and aquifer characteristics of the Trinity/Woodbine in southern Oklahoma. Researchers at Baylor University also focused on the Cretaceous deposits in North-Central Texas during that time. Baylor Geological Studies Bulletins published during the 1960's and 1970's pertaining to various aspects of the Trinity/Woodbine include: Holloway (1961), Atlee (1962), Henningsen (1962), Boone (1968), Mosteller (1970), Bain (1973), Hayward (1978), and Owen (1979). Investigators at the University of Texas Bureau of Economic Geology (BEG) also showed an interest in Cretaceous sediments during the 1970's, publishing several works that not only sought to define the extent and properties of the deposits, but to determine the depositional environments that dictated the geometry and distribution of various strata. Oliver (1971) reported that the Woodbine sediments were likely deposited within fluvial and deltaic depositional regimes. Hall (1976) described the processes thought to have determined the structure and sediment characteristics of the Lower Trinity (Travis Peak Formation) in north-central Texas. Caughey (1977) published a thorough assessment of the specific environmental settings that may account for the distribution of Paluxy sediment facies. Woodruff et al. (1979) studied the physical and chemical properties of the Trinity/Woodbine near the Luling-Mexia-Talco Fault Zone in order to quantify the aquifers' potential for geothermal use.

State and federally funded research of geology and hydrology of the Cretaceous sediments in North-Central Texas continued during the 1980's. Hart and Davis (1981) with The Oklahoma Geological Survey published available hydrogeologic data applicable to the Antlers Sand in southern Oklahoma. Nordstrom (1982, 1987) provided tables and maps of the occurrence, availability, and chemical quality of the groundwater in the North-Central Texas area. Groundwater availability studies conducted by Brune and Duffin (1983) and Price et al. (1983) reported on conditions in Travis and Callahan Counties, respectively.

During the last two decades of the 20$^{th}$ century, the volume of new work pertaining to Trinity/Woodbine diminished, however several very useful reports and models were generated from a variety of sources. Baker, B. B., et al. (1990) evaluated the water resources in the northern Texas portion of the study area. The evaluation focused on the geologic framework of the Cretaceous sediments, water-level declines in the Antler, Twin Mountains, and Paluxy Formations, and the Woodbine Group, and projected water demands through the year 2010. A detailed tabulation of the groundwater quality characteristics was published by Beynon for the TWDB in 1991. Duffin and Musick (1991) completed an assessment of the water resources near Bell, Burnet, Travis, and Williamson Counties. In 1993, Reutter summarized the well and water quality data pertaining to the Woodbine outcrop for the United States Geological Survey. Mace et al. (1994) discussed and constructed maps of the estimated predevelopment potentiometric surfaces associated with the Woodbine, Paluxy, and Trinity Aquifers. Ashworth and Hopkins (1995) summarized ground-water pumpage and use data from the major and minor aquifers of Texas. Wilkins of the Oklahoma Water Resources Board published a brief report of the hydrologic conditions of the Cretaceous aquifers in southern Oklahoma in 1998. Langley (1999) provided an update to the Baker et al. (1990) evaluation of water resources in part of north-central Texas, which focused on the Antlers, Twin Mountains, Paluxy and Woodbine Formations. Transformations in the groundwater conditions seen in Trinity aquifers during the 1987 to1997 interval in the region near Bastrop, Bell, Burnet, Lee, Milam, Travis, and Williamson were reported by Ridgeway and Petrini (1999). One of the most recent works was completed by Mace et al. (2000), who developed a three-dimensional, numerical ground-water model depicting the availability of groundwater in the Trinity aquifer in the Texas Hill Country for the GAM program.

Prior studies of the Trinity/Woodbine include two regional-scale models that are incorporated within the GAM footprint (Figure 3.1). The first was constructed by Morton (1992), and simulated groundwater movement in the Antlers aquifer and overlying units in Oklahoma and northeastern Texas. The model utilized a relatively coarse grid distribution that varied within the study area, averaging about 2 miles by 3 miles near the Red River in northern Texas. Three layers were included in the model: 1) the Quaternary alluvium and terrace deposits, 2) the Cretaceous sediments overlying the Antlers, and 3) the Antlers aquifer. Morton sought to predict aquifer water level changes in response to expected future withdrawals during the interval between 1990 and 2040; however, due to the small amount of historical pumpage in the region, Morton was unable to test and calibrate the model to transient pumping stresses.

Dutton et al. (1996) evaluated the geologic and hydrogeologic framework of regional aquifers in North-Central Texas and constructed a numerical flow model of the region. The model covers all or parts of 24 counties and utilized 3 layers to explicitly model the Twin Mountains, Paluxy, and Woodbine aquifers. The confining units that separate the aquifers (Fredericksburg/Washita and Glen Rose) were implicitly modeled through modification of the vertical leakance between aquifer units. The model was calibrated to historical water levels and subsequently used to predict aquifer water level changes during the interval between 2000 and 2050.

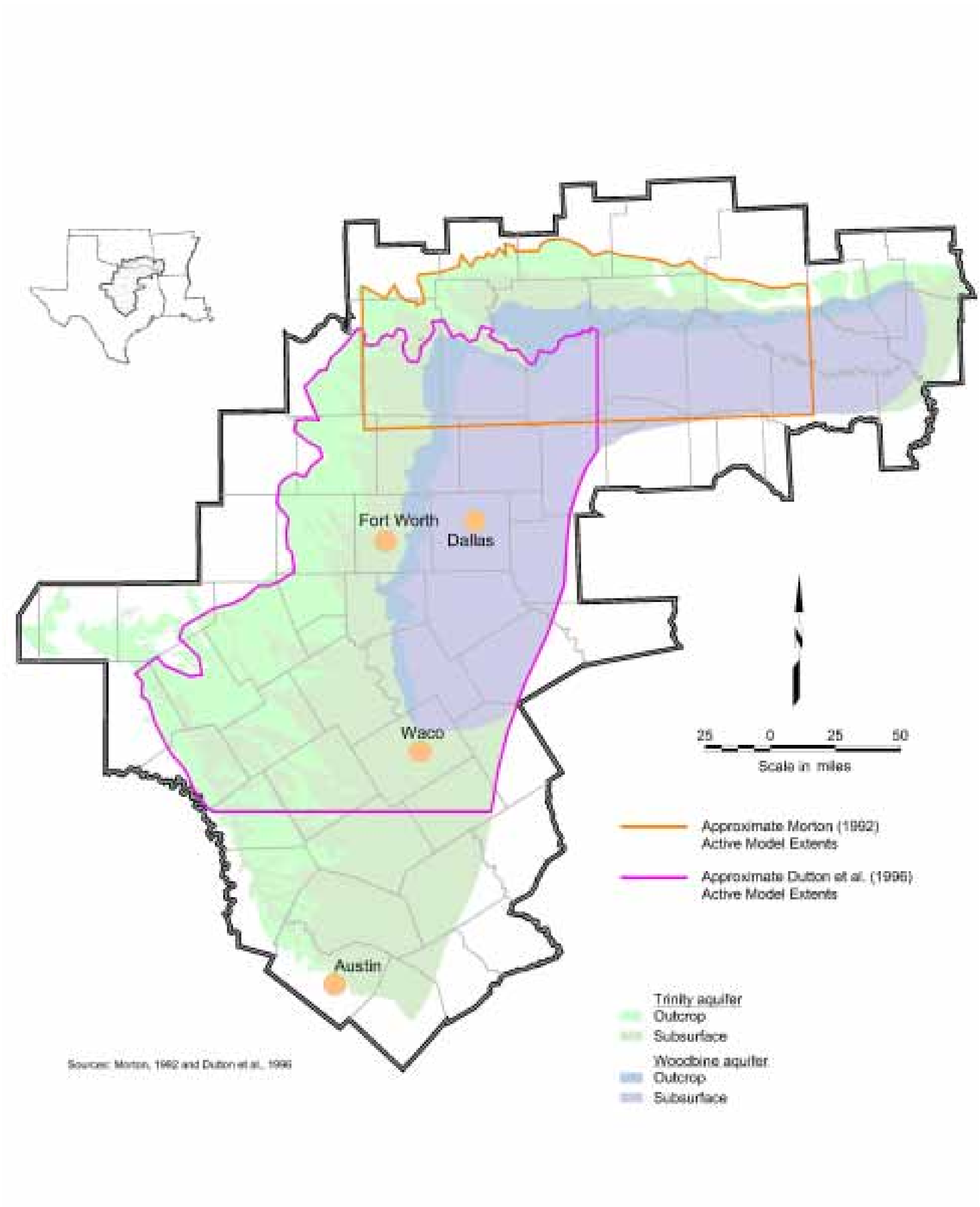



**Figure 3.1 Previous Model Extents**

# 4.0 HYDROLOGIC SETTING

The complex interactions between numerous and diverse factors influence groundwater flow within the Trinity/Woodbine. These factors include the geometry and hydraulic properties of aquifer and confining strata, regional topography, structural framework, groundwater chemistry, and the modes of possible recharge and discharge. This section describes the significant components affecting groundwater flow, which collectively are defined as the hydrologic setting. A review and analysis of data collated from previous investigations (see Section 3.0), as well as data collected for this project, is the basis for the following characterizations.

## 4.1 Hydrostratigraphy

Throughout most of the model region, the Trinity/Woodbine is composed of four, semi-distinct, sand-rich aquifer units. These units are, from oldest to youngest: the Hosston and Hensell Members of the Travis Peak Formation, the Paluxy Formation, and the Woodbine Formation. Five relatively impermeable layers confine and separate the aquifer strata. In order from oldest to youngest these confining units are: the pre-Cretaceous formations (Precambrian to Jurassic), the Pearsall/Cow Creek/Hammett Member of the Travis Peak Formation, the Glen Rose Formation, the Fredericksburg/Washita Groups, and the Eagle Ford Formation. In general, the Trinity/Woodbine forms a southeastward dipping and thickening wedge of sediments, which crops out on the western and northern portions of the study area.

As described in Section 2.2, the stratigraphic nomenclature applied to the Trinity/Woodbine is complex. Of primary interest to this study is the often-gradual stratigraphic transformation seen between areas where the members of the Travis Peak Formation (Hosston, Pearsall/Cow Creek/Hammett, and Hensell) are clearly defined, and areas where distinct contacts between hydrologic units are not perceptible (in geophysical logs). In general, the early Comanchean sediments are labeled the Twin Mountains Formation where no well-defined internal boundaries are present, and the Travis Peak Formation in areas where the subdivisions are apparent. Further complexity arises in the northern portion of the study area where the carbonates of the Glen Rose Formation are not distinguishable in geophysical logs. In these areas, the Glen Rose Formation does not exist in geologic literature, and so the Paluxy and Twin Mountains/Travis Peak coalesce (nomenclaturally) to form the combined unit known as the Antlers Sand. However, it is misleading to conclude that the sands of the Paluxy are in direct hydrologic contact with the sands of the upper Twin Mountains/Travis Peak in areas where the Glen Rose is not defined. Review of geophysical logs in these areas suggests that, in general, some thickness of argillaceous sediments usually separates the Paluxy and Twin Mountains/Travis Peak Formations, restricting groundwater flow between them. Figure 4.1 depicts the general association between aquifer nomenclature and regions within the study area, and Figure 4.2 illustrates the regional stratigraphic relationships of the Trinity/Woodbine units.

In clastic aquifers, the distribution and physical properties of sediments has a major influence on groundwater flow. In general, sand-rich and karstic carbonate units transmit water, while sediments composed primarily of clay and carbonate minerals (non-karstic) are much less permeable, and tend to act as aquitards/confining layers. Variations in the physical properties of aquifer sediments produce changes in the number and form of the inter-granular pore spaces that conduct groundwater flow. These pathways are generally maximized in sediments composed of large, well-sorted (homogenous grain size) grains with little or no interstitial cementation, which can fill pore spaces and block groundwater flow. The vertical and horizontal continuity of sand strata also affect the properties of aquifers. Several small but interconnected sand bodies may form a more productive aquifer than a comparable amount of poorly connected sand, and are likely to be less transmissive than a large, continuous sandy layer.

The elevation, thickness, and character of the aquifers that comprise the Trinity/Woodbine aquifer units vary widely with location in the study area. In general, aquifer sediments were eroded from highlands to the north and west of the study area, and redeposited in fluvial, deltaic, and shallow marine environments to the south and east (Hall, 1976; Oliver, 1971; Caughey, 1977). Multiple cycles of sea level transgression/regression coupled with subsidence of the East Texas Basin, and uplift and tilting of the continental platform (Texas Craton) west and north of the Ouachita foldbelt governed the spatial relationship between source rocks and basinal accommodation space. These structural elements played an important role in dictating the geometry, characteristics, and stratigraphy of Trinity/Woodbine sediments.

The youngest of the Cretaceous aquifers within the study area is the Woodbine Formation. Covered by the Eagle Ford, Austin, Taylor, and Navarro Groups, and separated from the Paluxy by the Fredericksburg and Washita Groups, the Woodbine is effectively isolated from the Trinity aquifers below. Like the Paluxy, the primary source-rock regions lay in the northern and northwestern portions of the study area, which resulted in the deposition of thicker sections of sediments in downdip zones near those areas. Like the Trinity aquifers, artesian pressures have declined due to groundwater use, but can be over 1,000 feet above the top of the Woodbine in confined sections of the aquifer.

The Paluxy Formation is confined from above by the Fredericksburg and Washita Groups, and is separated from the Hensell by the relatively thick and impermeable interval consisting of Glen

Rose carbonates in southern areas and Glen Rose equivalent argillaceous sediments in northern portions of the study area. As with the Hensell and Hosston, the Paluxy is well defined in the central model region, but becomes difficult to recognize in geophysical logs in areas where the carbonates of the Glen Rose are not distinguishable. Minimal (generally less than 10 feet) rises and declines have been measured in Paluxy outcrop water table levels, while cones of depression in artesian water levels have been observed beneath heavy use regions surrounding cities in North-Central Texas.

The Hensell Member is designated as the uppermost aquifer of the Travis Peak Formation. The Hensell is distinguishable as a separate unit throughout most of the model domain, but becomes less well defined in the northern portion of the study area. Unconfined (water table) groundwater processes dominate in outcrop areas, while artesian pressures of over 3,000 feet above the top of the aquifer have been maintained in downdip zones. Water table levels in the Hensell have remained relatively constant during the 1900's, while downdip water levels show a well-defined cone of depression in the Waco area. However, because hundreds of feet of low permeability materials can hydraulically separate the Hensell from the underlying Hosston and overlying Paluxy, the potentiometric surface exhibited in the Hensell is unique in most regions.

Trinity sediments were deposited on: 1) the eroded, westward-dipping Paleozoic strata of the Texas Craton in the western portion of the study area, 2) the eastward dipping Triassic and Jurassic sediments in the East Texas Basin in the down dip portions of the Study area and 3) the metamorphosed Paleozoic and pre-Cambrian rocks of the Ouachita foldbelt (Flawn, 1961). The Paleozoic and Pre-Cambrian rocks formed the Wichita paleoplain (Hill, 1901), and are composed of relatively impermeable sediments. The topographical relief remaining after erosion of this surface during the early Mesozoic influenced the thickness and geometry of the first aquifer unit deposited during the Cretaceous: the Hosston Member of the Travis Peak Formation.

Commonly known as the "Lower Trinity Sand" or "Second Trinity", the Hosston is recognized as one of the most important aquifers in the region (Klemt et al., 1975; Kaiser, 2002), and has been extensively developed in previous decades. Confined by Pre-Cambrian, Paleozoic, and early Mesozoic strata below and capped by the Pearsall/Cow Creek/Hammett Members of the Travis Peak Formation, the Hosston exhibits large artesian pressures in downdip areas. These pressures have been reduced by groundwater pumpage near the Dallas-Fort Worth and Waco areas. However, based on analysis of water levels in the unconfined (outcrop) zones of the Hosston, it appears that water levels in the outcrop zone have been relatively stable during the last 50 years.

Extensive faulting throughout most of Texas offsets the Trinity/Woodbine sediments, and affects regional groundwater flow. Major fault zones, including the Balcones and the Luling-Mexia-Talco, can exhibit hundreds of feet of displacement effectively juxtaposing vertically distinct hydrostratigraphic units. However, the relatively insoluble character of the Woodbine, Paluxy, Hensell, and Hosston sediments results in the smearing of materials in the fault zone, and precludes significant dissolution of arenaceous fault-zone materials. For this reason, little if any vertical or horizontal interformational flow is thought to occur in fault planes or across faulted sediments (Yelderman, 2002). For this reason, the Luling-Mexia-Talco Fault Zone defines the downdip boundary of groundwater flow.

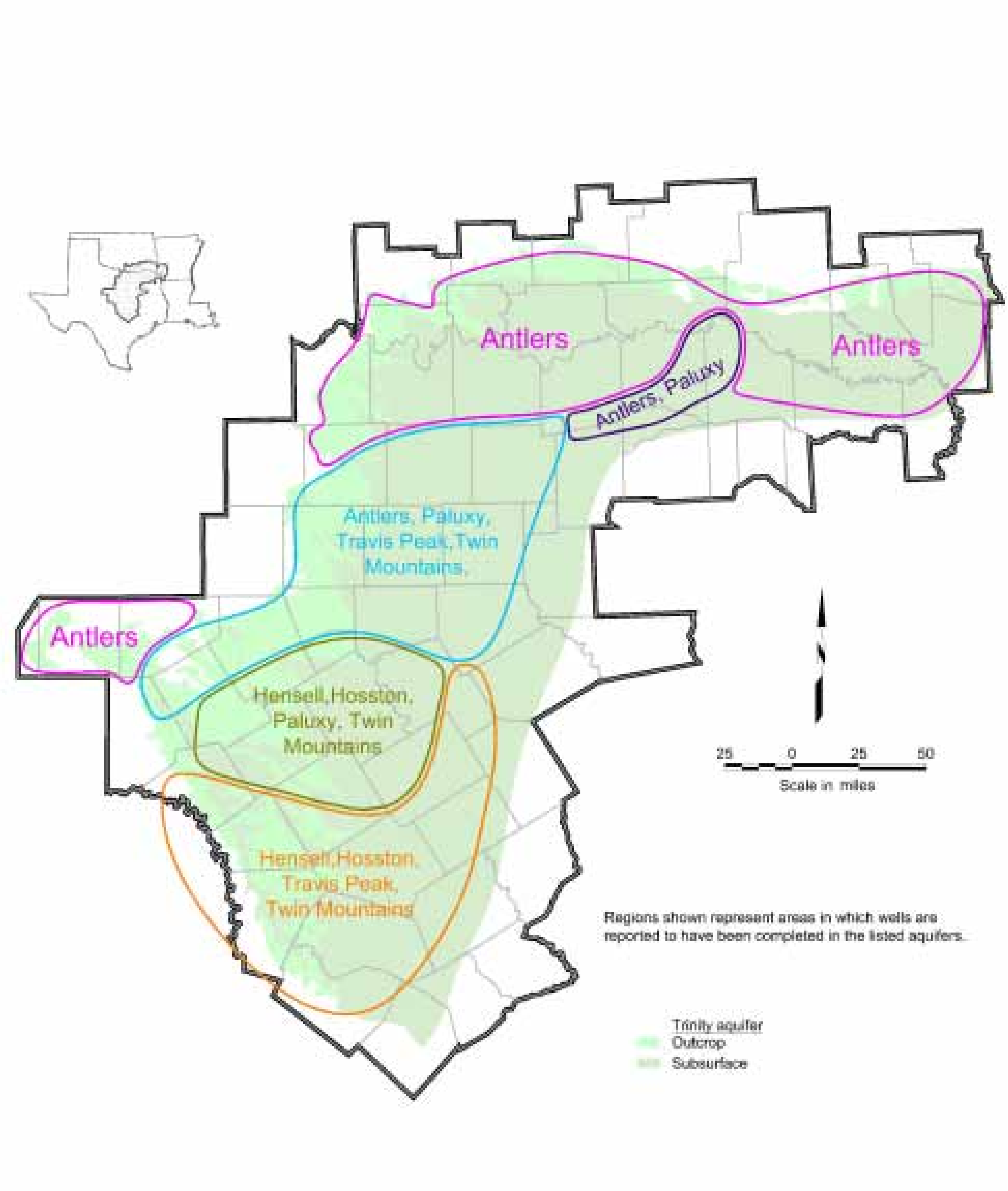



**Figure 4.1 Aquifer Definition by Region (Trinity Group)**

<table>
<tr><th rowspan="2">System</th><th rowspan="2">Series</th><th rowspan="2">Groups</th><th colspan="4">Formation</th><th colspan="2">Approximate Maximum Thickness</th><th rowspan="2">Model Layers*</th></tr>
<tr><th colspan="2">North</th><th colspan="2">South</th><th>North</th><th>South</th></tr>
<tr><td>Tertiary</td><td colspan="8">Undifferentiated</td><td></td></tr>
<tr><td rowspan="17">Cretaceous</td><td rowspan="5">Gulfian</td><td>Navarro</td><td colspan="2" rowspan="5">Undifferentiated</td><td colspan="2" rowspan="5">Undifferentiated</td><td>800</td><td>550</td><td rowspan="4">GHB</td></tr>
<tr><td>Taylor</td><td>1500</td><td>1,100</td></tr>
<tr><td>Austin</td><td>700</td><td>600</td></tr>
<tr><td>Eagle Ford</td><td>650</td><td>300</td></tr>
<tr><td>Woodbine</td><td>700</td><td>200</td><td>1</td></tr>
<tr><td rowspan="12">Comanchean</td><td rowspan="4">Washita</td><td colspan="2">Grayson Marl</td><td colspan="2">Buda, Del Rio</td><td rowspan="4">1,000</td><td>150</td><td rowspan="7">2</td></tr>
<tr><td colspan="2">Mainstreet, Pawpaw, Weno, Denton</td><td colspan="2" rowspan="2">Georgetown</td><td rowspan="2">150</td></tr>
<tr><td colspan="2">Fort Worth, Duck Creek</td></tr>
<tr><td colspan="2">Kiamichi</td><td colspan="2">Kiamichi</td><td>50</td></tr>
<tr><td rowspan="3">Fredericksburg</td><td colspan="2" rowspan="2">Goodland</td><td colspan="2">Edwards</td><td rowspan="3">250</td><td>175</td></tr>
<tr><td colspan="2">Comanche Peak</td><td>150</td></tr>
<tr><td colspan="2">Walnut Clay</td><td colspan="2">Walnut Clay</td><td>200</td></tr>
<tr><td rowspan="5">Trinity</td><td rowspan="5">Antlers</td><td>Paluxy</td><td colspan="2">Paluxy</td><td>400</td><td>200</td><td>3</td></tr>
<tr><td>Glen Rose</td><td colspan="2">Glen Rose</td><td>1,500</td><td>1,500</td><td>4</td></tr>
<tr><td rowspan="3">Twin Mountains</td><td rowspan="3">Travis Peak</td><td>Hensell</td><td rowspan="3">1,000</td><td rowspan="3">1,800</td><td>5</td></tr>
<tr><td>Pearsall/ Cow Creek/ Hammett/ Sligo</td><td>6</td></tr>
<tr><td>Hosston</td><td>7</td></tr>
<tr><td>Paleozoic</td><td colspan="8">Undifferentiated</td><td></td></tr>
</table>

* Blue model layers (Layers 1, 3, 5, and 7) signify the primary aquifer units of this study.

Source: Klemt et al., 1975; Nordstrom, 1987.

**Figure 4.2 Hydrostratigraphic Diagram**

## 4.2 Structure

As shown in Figure 4.3, the model area encompasses a wide range of structural features that affected the deposition of the Trinity/Woodbine. Tectonic plate collisions that occurred during the formation of Pangea in the late Paleozoic uplifted and deformed the preexisting lithology, forming the Ouachita Mountains in what was then the southern margin of the Laurasian paleocontinent. These mountains formed highlands that served as source rock areas for the later deposition of the Trinity/Woodbine system (Caughey, 1977). As Pangea began to break apart during the early Mesozoic, rifting occurred to the southeast of the Ouachita Fold Belt creating low-lying areas that were subsequently flooded in the Jurassic to form the ancestral Gulf of Mexico (Stearn et al, 1979). During this time, the study area was located near the equator, the climate was hot, which, coupled with the relatively restricted flow in the newly formed seaway, promoted the deposition of evaporate minerals.

As the ancestral Gulf widened during the Mesozoic, drainage patterns in the study area shifted to the southeast, and deposition of the Trinity was initiated in the Early Cretaceous. As the Trinity/Woodbine accumulated, the East Texas Basin underwent syndepositional subsidence (Oliver, 1971), which served to foster the formation of the basinward thickening wedge of sediments that characterize the Cretaceous formations in the study area.

Throughout the Cretaceous period, the continued subsidence of the East Texas Basin and the relative stability of the Texas Craton formed a hinge along the Ouachita Fold Belt. The resulting tensional forces during the Tertiary period and possibly during the Cretaceous contributed to the two main fault systems near the Eastern edge of the study area: the Luling-Mexia-Talco and the Balcones Fault Zones. The Luling-Mexia-Talco Fault Zone runs parallel to the Ouachita Structural Belt and marks the updip boundary of the East Texas Basin. The Luling-Mexia-Talco fault system consists primarily of normal faults, the growth of which was accelerated by lateral, basinward creep along the underlying salt deposits deposited in the Jurassic (Jackson, 1982). The Luling-Mexia-Talco Fault Zone has created displacements of more than 700 feet in some areas of Texas. Continued subsidence in the Gulf of Mexico Basin during the Tertiary Period advanced the formation of the Balcones Fault Zone. This zone runs from Austin to north of Waco and consists of a series of high angle normal faults with downthrown blocks toward the Gulf of Mexico. The Balcones Fault Zone has displaced sediments by as much as 400 feet in McLennan County to 600 feet in Travis County.

As illustrated by Figures 4.4 through 4.15, the elevation, thickness, and character of the aquifers that comprise the Trinity/Woodbine aquifer units vary widely with location in the study area. The total thickness of the Woodbine is greater than 600 feet in basinward sections in northern Texas, and averages about 300 feet within the study area (Figure 4.6). The total thickness of the Paluxy varies from greater than 600 feet in northeastern Hunt County just west of the Luling-Mexia-Talco Fault Zone, to a featheredge in Central Texas (Figure 4.9). As shown in Figure 4.12, the total thickness of the Hensell ranges from zero feet in outcrop zones to over 150 feet in downdip areas, and averages about 80 feet in the study area. Like the Woodbine, the total thickness of the Hosston increases relatively uniformly from less than 100 feet in outcrop areas to more than 1,500 feet in southern, downdip zones (Figure 4.15).

All structural data included in the model were derived from the examination of over 1,000 geophysical logs on file at the United States Geological Survey (USGS), the Texas Commission on Environmental Quality (TCEQ), and Texas Water Development Board (TWDB) archives. Depth to formation top and base and net sand thickness was recorded for the Woodbine, Paluxy, Hensell, Hosston, Travis Peak, Twin Mountains, and Antlers units. The total thickness of the hydrologic unit was recorded in instances where both the top and base of the unit was distinguishable on an individual geophysical log. All data were recorded to the nearest foot when possible, however, the poor legibility of many logs only allowed picks to within 10 feet. Logs that could not be read to a 10-foot level of accuracy were not included in this study. The precision of the elevation ultimately assigned to the pick is dependent upon the ground level elevation assigned to the site. Information pertaining to the various methods used to estimate ground level elevation is included with the structure data supplied with this report. The positional accuracy of the picks also varies; similarly to elevation data, information describing the precision of the well location was recorded with the data.

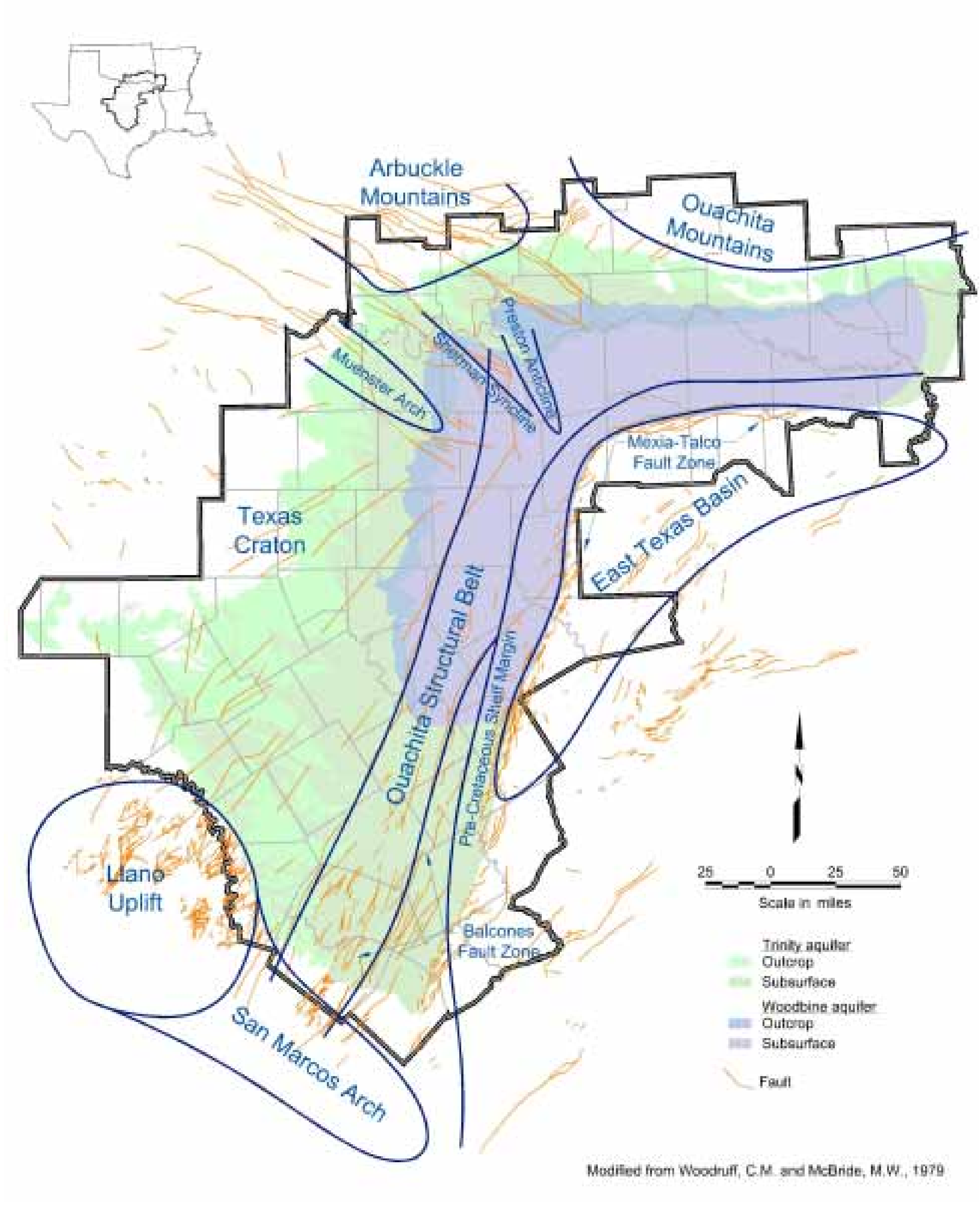



**Figure 4.3 Structural Elements**

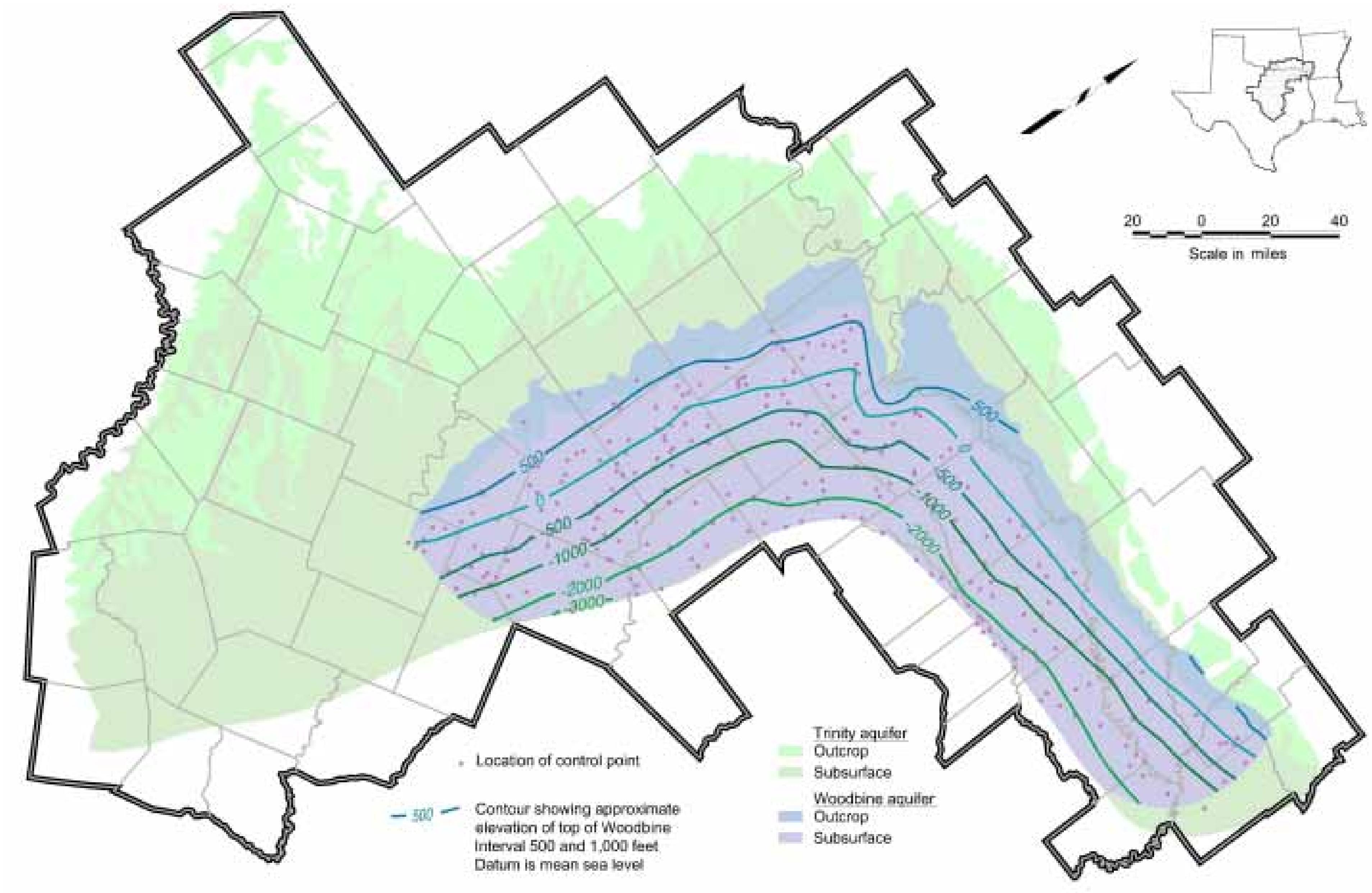



**Figure 4.4 Elevation of the Top of the Woodbine**

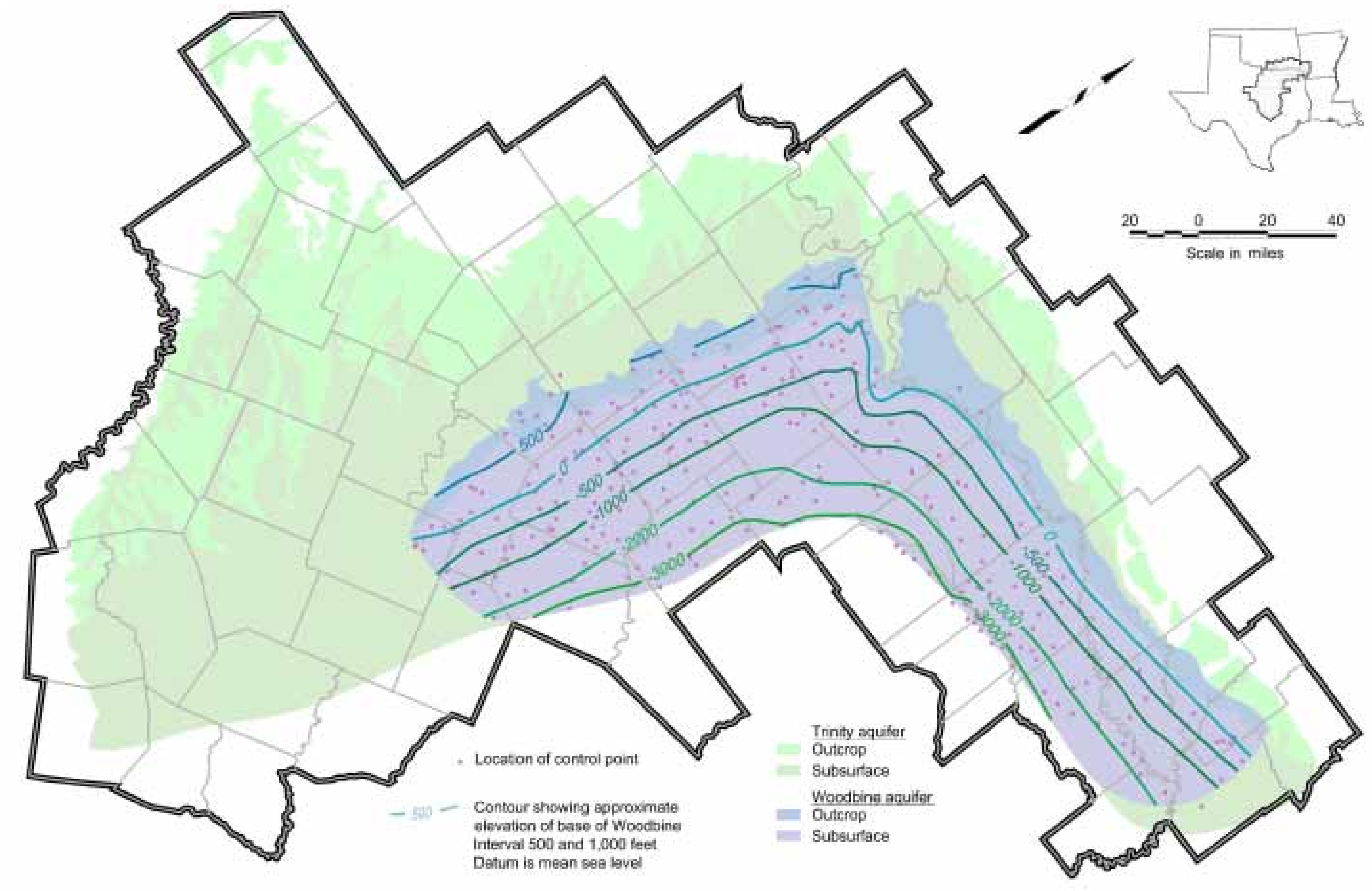



**Figure 4.5 Elevation of the Base of the Woodbine**

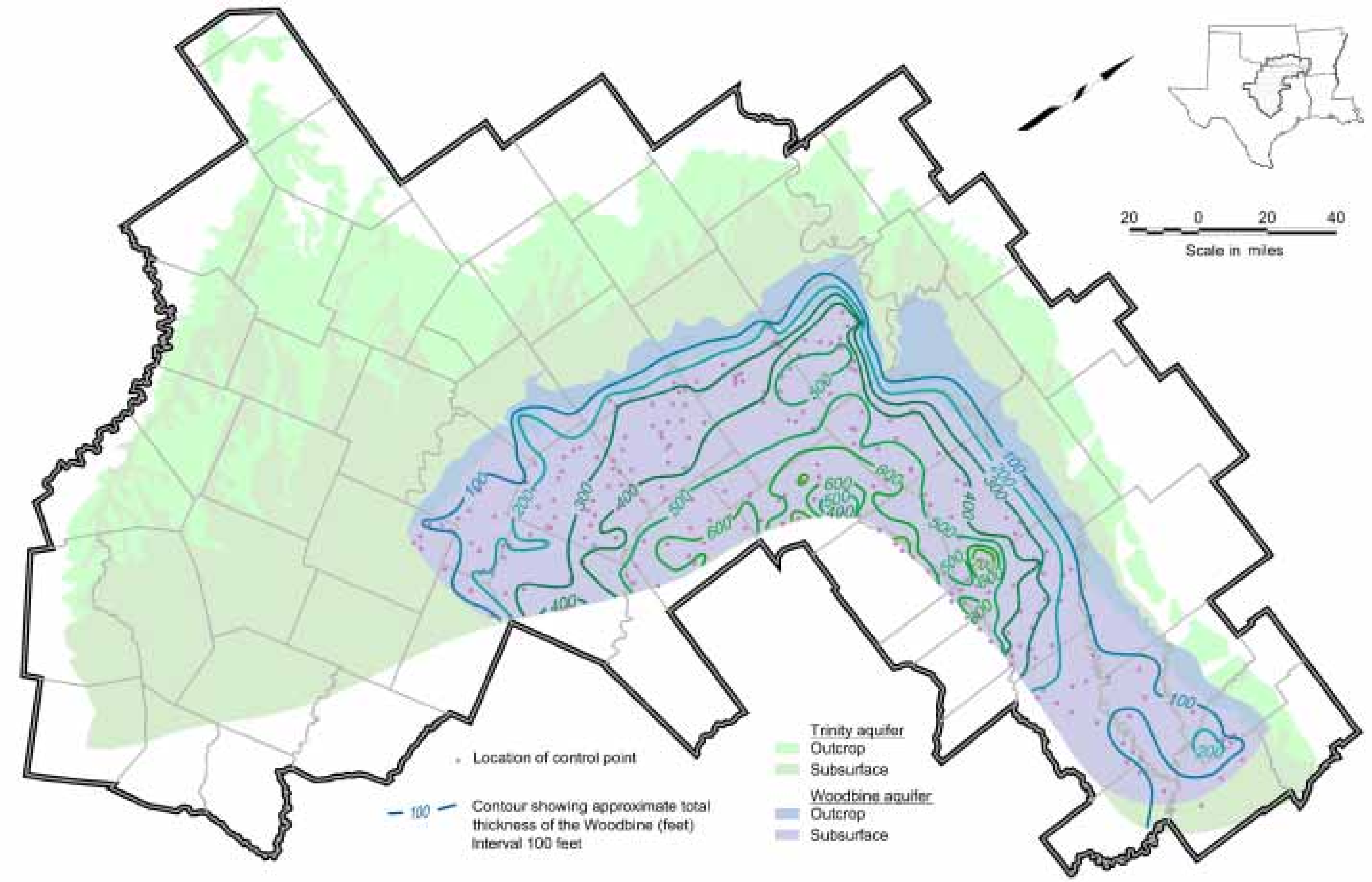



**Figure 4.6 Total Thickness of the Woodbine**

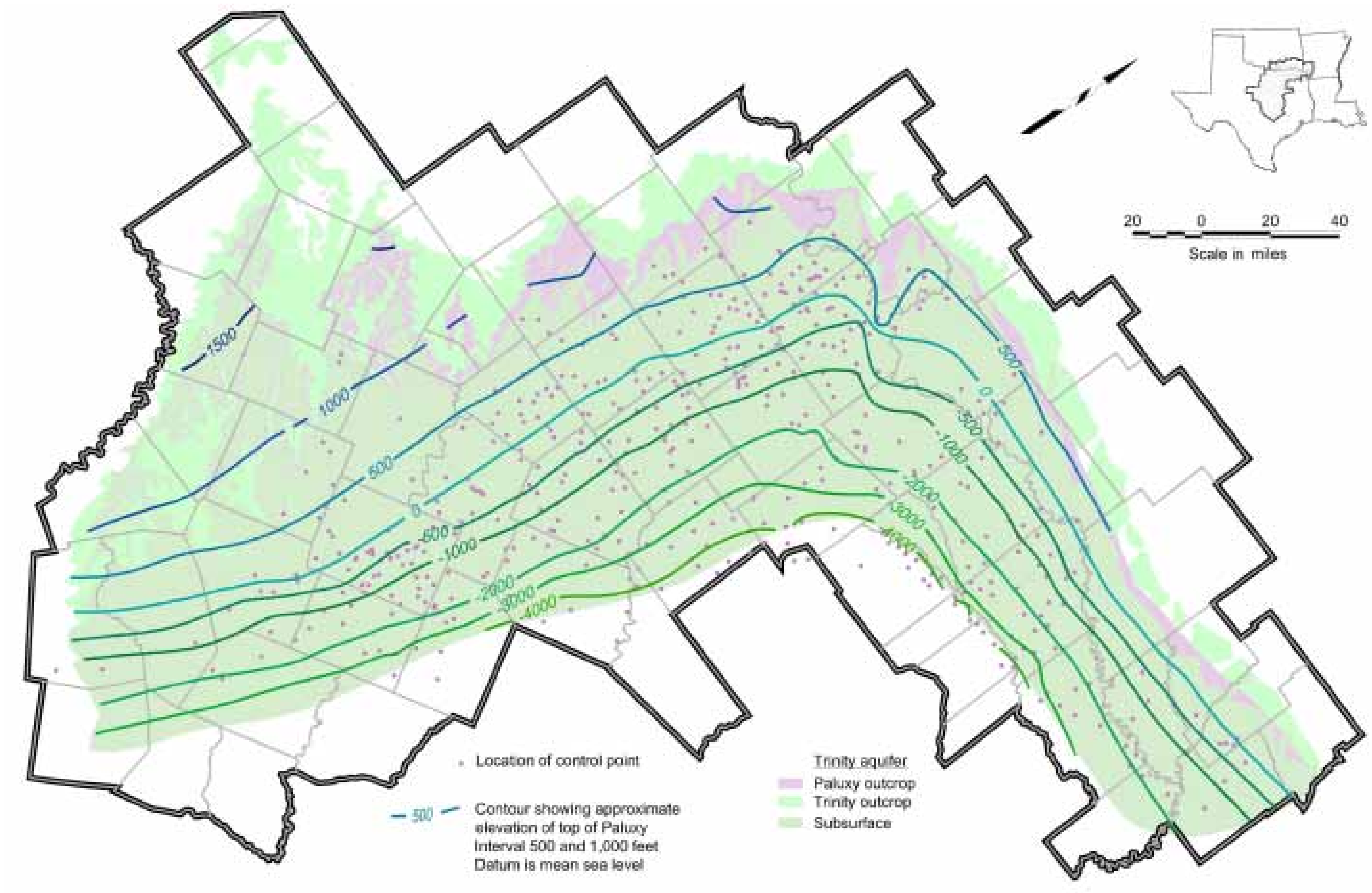



**Figure 4.7 Elevation of the Top of the Paluxy**

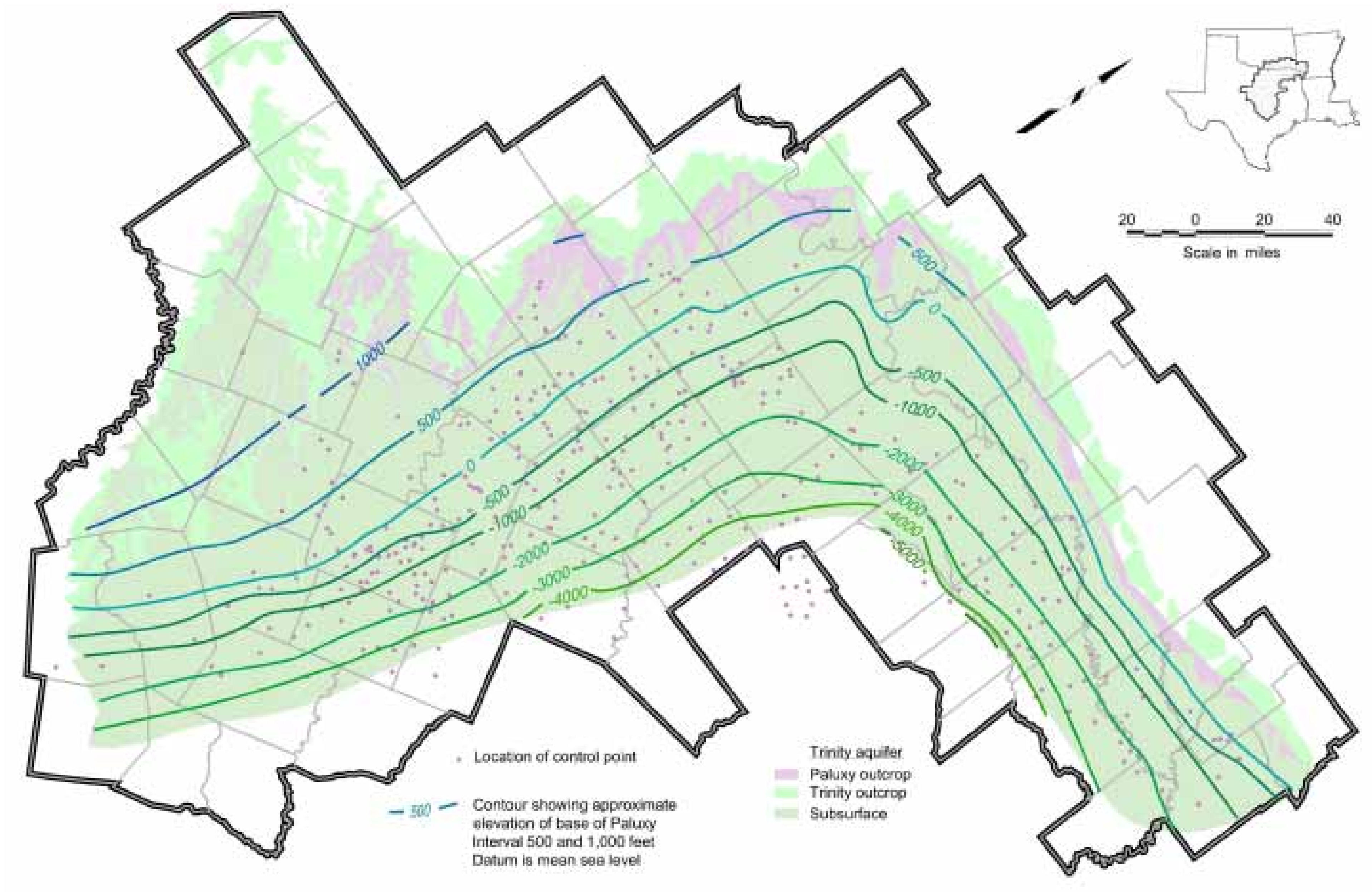



**Figure 4.8 Elevation of the Base of the Paluxy**

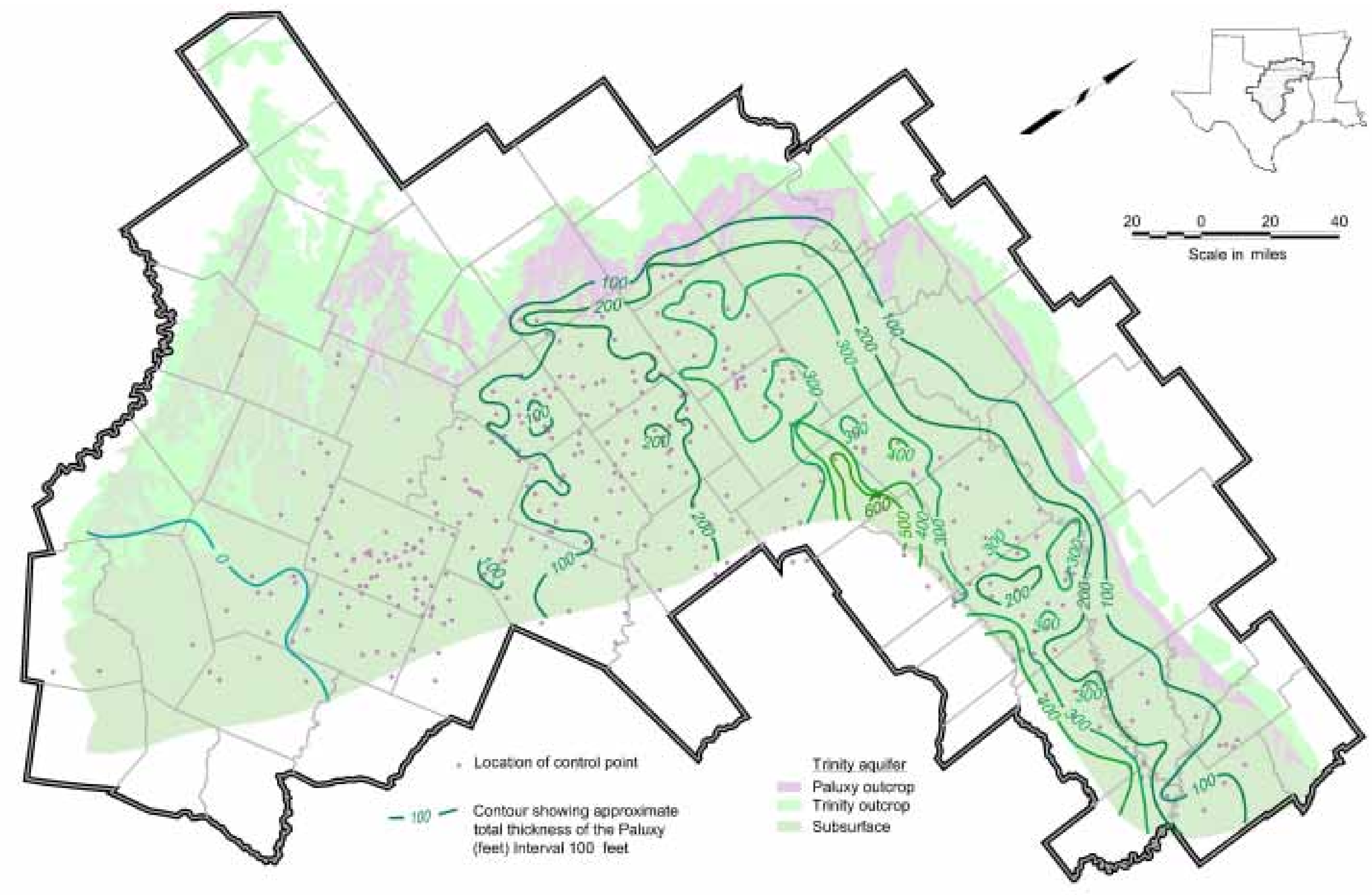



**Figure 4.9 Total Thickness of the Paluxy**

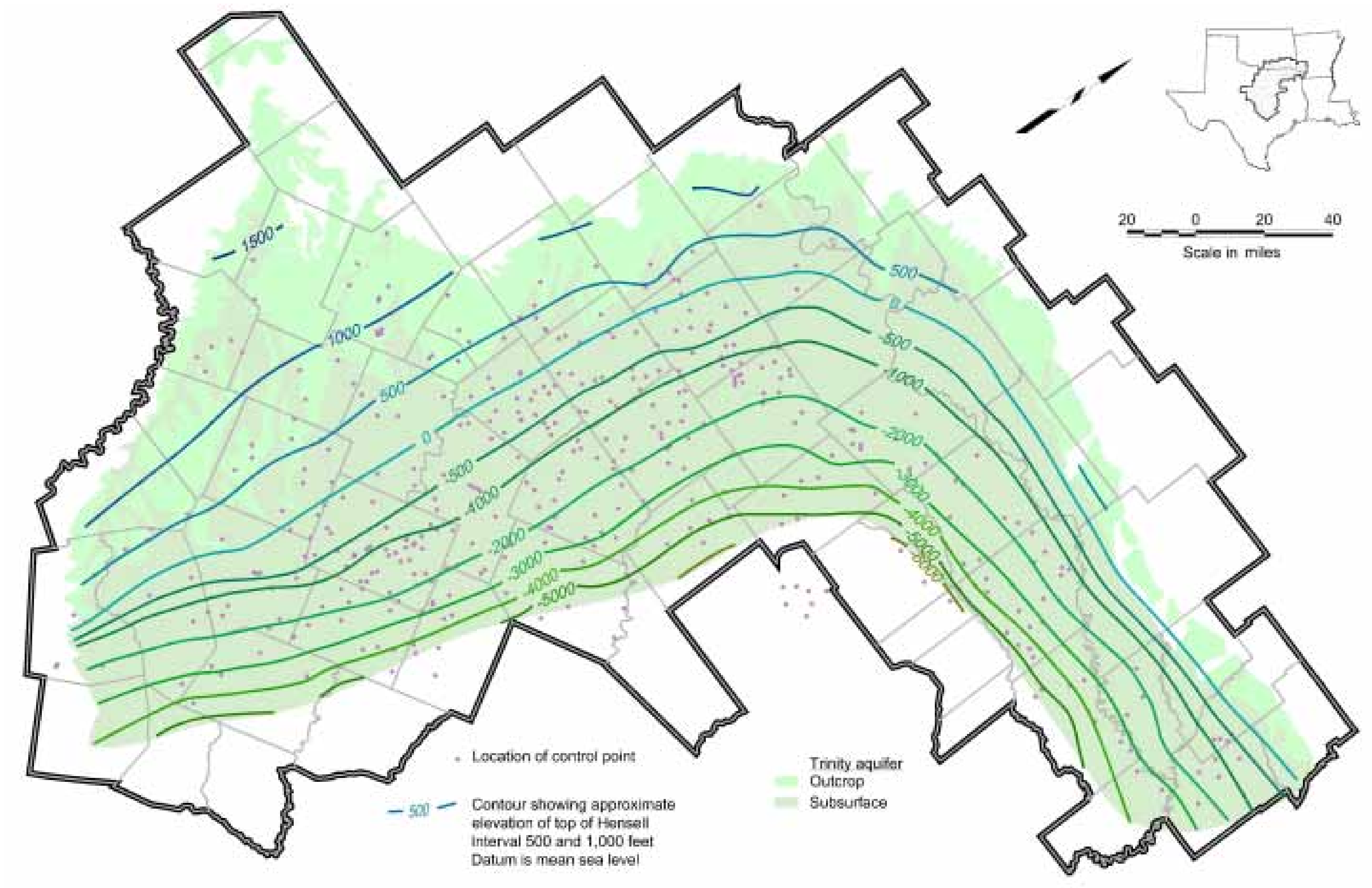



**Figure 4.10 Elevation of the Top of the Hensell**

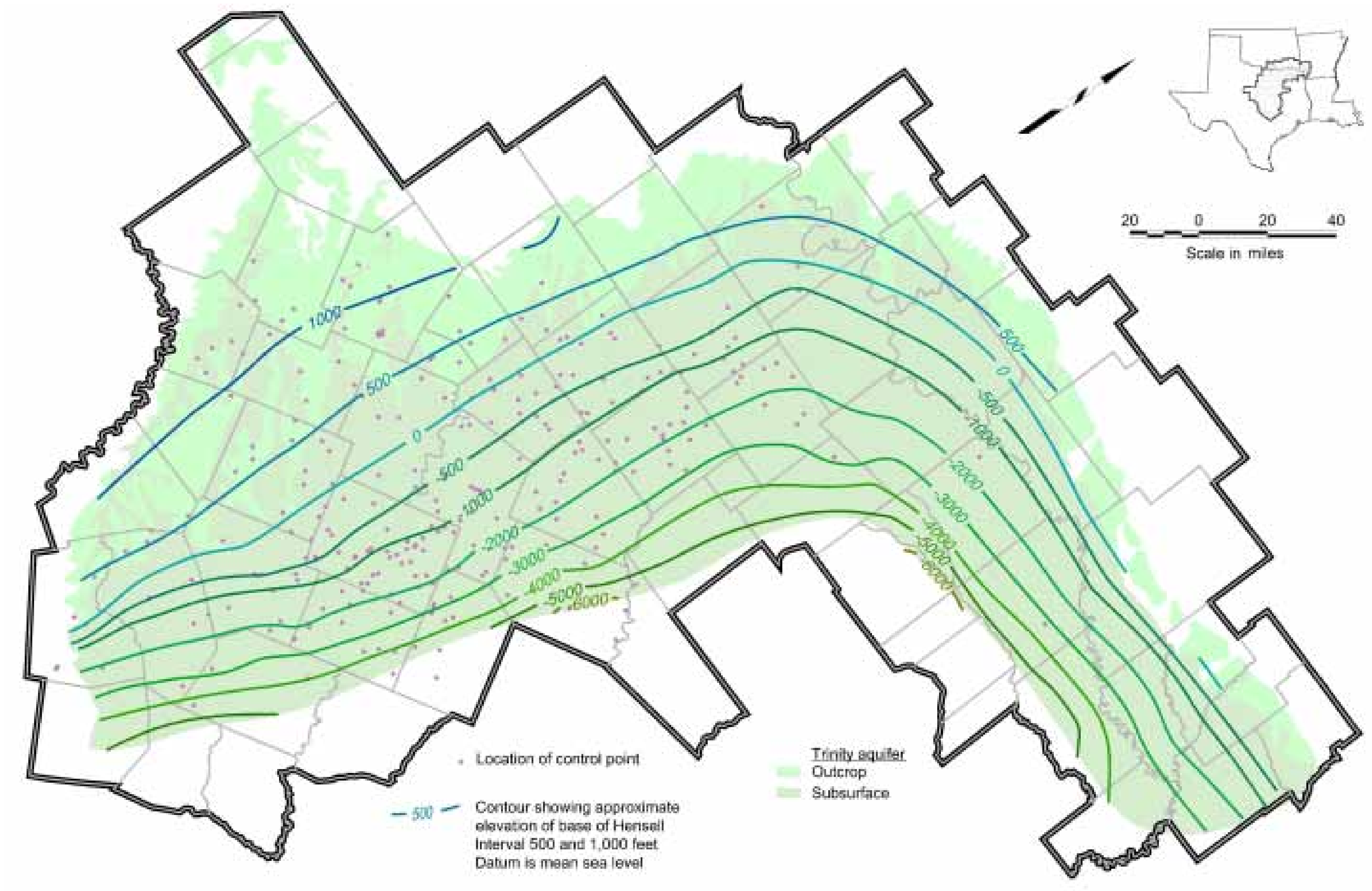



**Figure 4.11 Elevation of the Base of the Hensell**

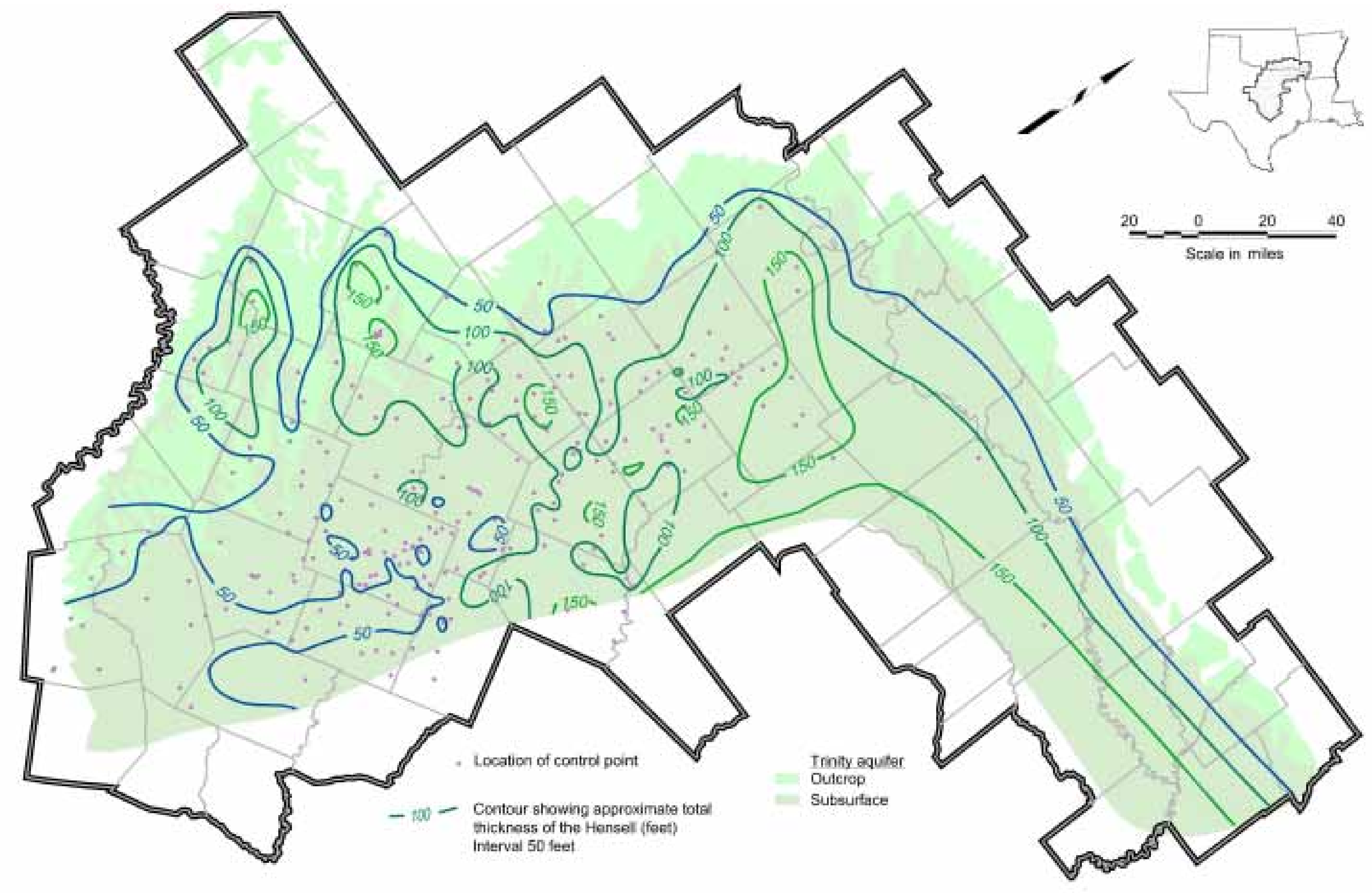



**Figure 4.12 Total Thickness of the Hensell**

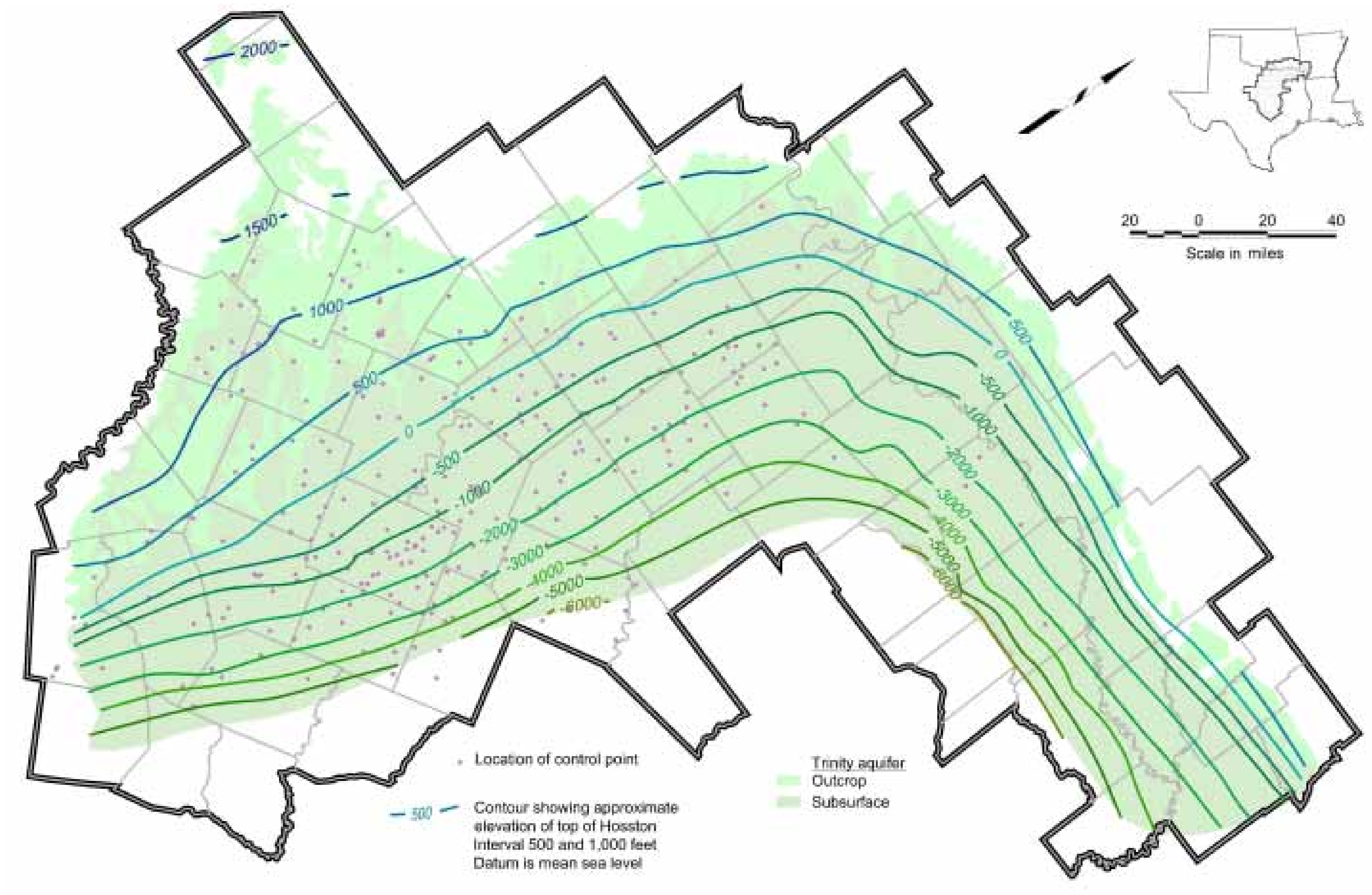



**Figure 4.13 Elevation of the Top of the Hosston**

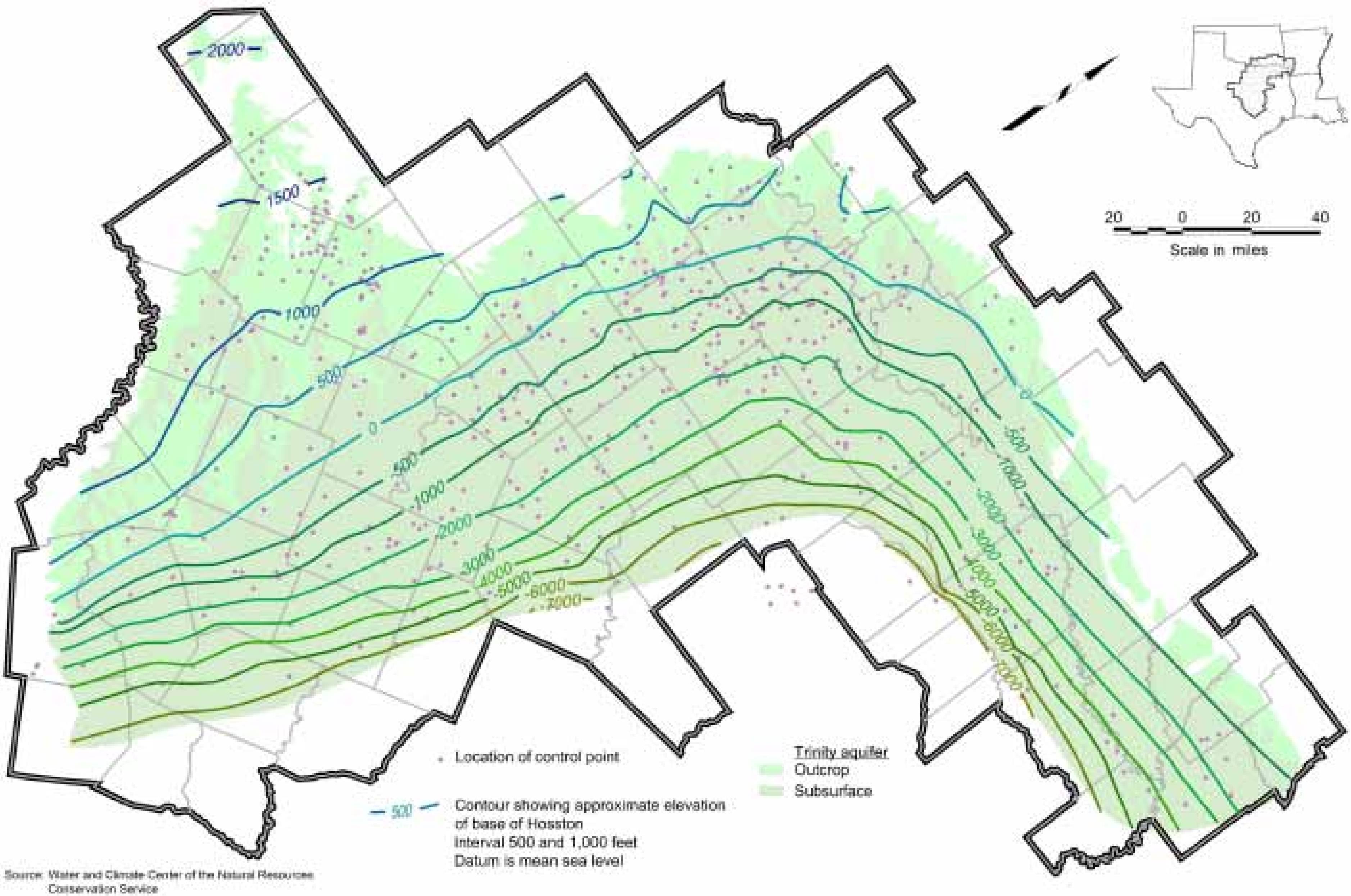



**Figure 4.14 Elevation of the Base of the Hosston**

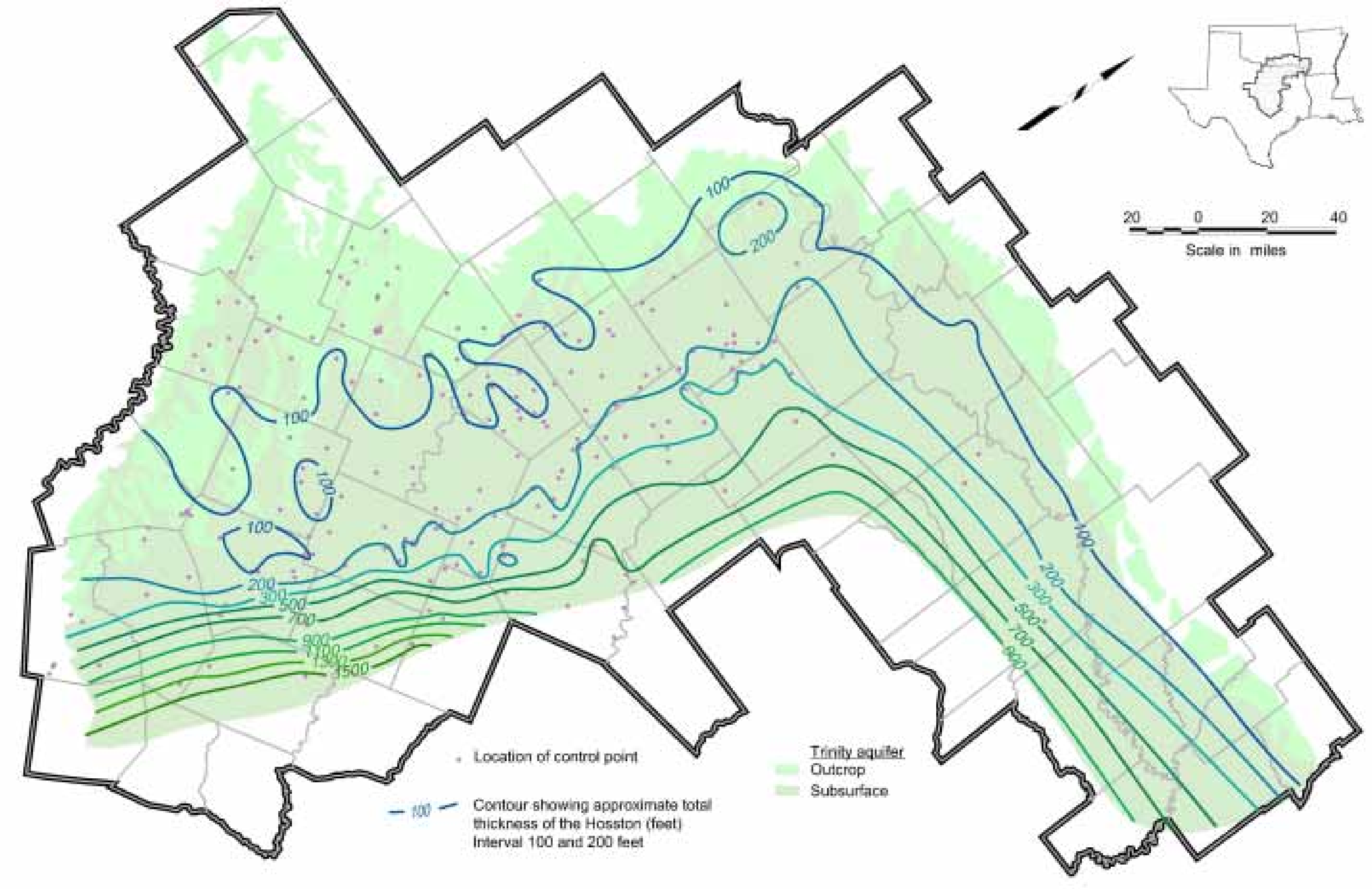



**Figure 4.15 Total Thickness of the Hosston**

## 4.3 Water Quality

The quality of groundwater in the Trinity/Woodbine aquifers was evaluated to aid in the determination of the boundaries of the model, and to help potential users of the model assess groundwater availability. A detailed evaluation of the water quality in the Woodbine Aquifer has previously been published (Hopkins, 1996). The water quality in all of the aquifers in the study area is briefly reviewed and summarized in numerous county-wide and regional reports (Baker, 1960; Baker et. al., 1990; Bayha, 1967; Beynon, 1991; Brune and Duffin, 1983; Duffin and Musick, 1991; Klemt et. al, 1975; Langley, 1999; Leggat, 1957; Nordstrom, 1982, 1987; Price et. al, 1983; D. Thompson, 1967; G.L. Thompson, 1967, 1969, 1972). Most of these reports do not go into great detail on the chemistry of the groundwater, but some potential concerns were noted in some of these reports including high TDS, chloride, sulfate, nitrate, iron, manganese, and boron, as well as high sodium adsorption ratio and a variety of anthropogenic water quality problems.

Water-quality data pertaining to the portion of the study area updip of the Luling-Mexia-Talco Fault Zone (which includes all of the model area) were compiled from the TWDB groundwater database and the Texas Commission on Environmental Quality (TCEQ) public water-supply well databases. In addition to these sources, data compiled during a recently completed analysis of Trinity/Woodbine groundwater quality (LBG-Guyton, 2003) were incorporated into this evaluation. For the assessment of gross groundwater quality in areas downdip of the Luling-Mexia-Talco Fault Zone, salinity contour maps published within TWDB Report No. 157 (Core, 1972) were utilized.

Following a review of the sources listed above, multiple analyses for individual wells were removed. The factors for selecting a single analysis for a well included: 1) completeness of the analysis; some parameters were occasionally not included in an individual analysis, and complete analyses were chosen over incomplete ones; 2) obvious anomalies; analyses that reported constituent concentrations very different from other analyses performed on the same well were not selected; 3) type of analysis; laboratory analyses were preferred over parameters measured in the field; and 4) date; if all else was equal (considering the factors described above), the most recent analysis was selected.

The term Total Dissolved Solids (TDS) refers to the sum of the concentrations of all of the dissolved ions in groundwater, which are chiefly comprised of sodium, calcium, magnesium, potassium, chloride, sulfate, and bicarbonate ions. The TWDB has defined gross aquifer water quality in terms of TDS concentrations expressed in milligrams per liter (mg/l), and has classified water into four broad categories:

- fresh (less than 1,000 mg/l);
- slightly saline (1,000 - 3,000 mg/l);
- moderately saline (3,000 - 10,000 mg/l); and
- very saline (10,000 - 35,000 mg/l).

Because of its usefulness as an indicator of general groundwater quality, TDS served as the primary parameter of interest for this evaluation; however, several other parameters may be of interest from an availability aspect. The following is a summary of the common water quality characteristics of the Trinity/Woodbine aquifers.

### 4.3.1 Selected Water Quality Standards

Water quality standards for both drinking water supplies and irrigation supplies were used for comparisons to water quality data from the Trinity and Woodbine aquifers. Drinking water standards are based on maximum contaminant levels (MCLs) and secondary constituent levels ("secondary standards") established in the Texas Administrative Code (30 TAC, Chapter 290, Subchapter F). Primary MCLs are legally enforceable standards that apply to public drinking water supplies in order to protect human health from contaminants in drinking water. Secondary standards are non-enforceable guidelines based on aesthetic effects that these constituents may cause (eg. taste, color, odor, etc.). In addition to primary MCLs and secondary standards, two constituents, lead and copper, have action levels specified. These action levels apply to community and nontransient noncommunity water systems, and to new water systems when notified by the TCEQ Executive Director.

Irrigation screening levels are based on "Irrigation Water Quality Standards and Salinity Management Strategies" produced by the Texas Cooperative Extension (Fipps, 2003). These screening levels are intended for guidance purposes only, and they are not absolute, legally established levels. Irrigation screening level parameters include TDS, salinity hazard, sodium hazard, boron, copper, fluoride, selenium, and zinc. Chloride values were not included as a screening level because the maximum chloride concentrations without loss in crop yield varies widely depending on the type of crop, from 350 mg/l for several types of vegetables to 2,800 mg/l for barley (Fipps, 2003).

Salinity hazard and the sodium hazard are based on a classification developed by the U.S. Salinity Laboratory (1954), and reviewed in Fipps (2003). Salinity hazard is based on the TDS and/or specific conductivity of the water being applied to plants or crops. The sodium hazard is described in terms of the sodium adsorption ratio (SAR), which is a quantitative evaluation of the sodium hazard to soils or plants. Waters with an SAR of 18 to 26 are considered to represent a high sodium hazard, and waters with an SAR of greater than 26 are considered to represent a very high sodium hazard. Individiual constituents, including boron, copper, fluoride, selenium, and zinc, may cause problems to plants depending on whether they are applied over a short or long time period. Therefore, each of these parameters has a different screening level for short-term and long-term use.

***Woodbine Aquifer*** - A total of 776 wells were included in the analysis of groundwater quality in the Woodbine aquifer. The occurrence of selected drinking water parameters for the Woodbine compared to screening levels is shown in Table 4.1. The occurrence of irrigation parameters for the Woodbine compared to screening levels is shown in Table 4.2.

Figure 4.16 shows the distribution of fresh, slightly saline, moderately saline, and very saline water in the Woodbine. As indicated in this figure, water quality deteriorates (TDS increases) with depth throughout the Woodbine, which contains extensive sections of slightly to moderately saline groundwater in the downdip portions of the aquifer. Some shallow zones in and near the outcrop also contain slightly to moderately saline groundwater, although this is uncommon. Fresh groundwater is found farther downdip in the northern portion of the aquifer, in particular in Grayson, Collin, and Fannin Counties, but groundwater in the southern portion of the aquifer quickly becomes saline in the downdip sections of the aquifer, as was noted in Hopkins (1996).

As shown in Table 4.1, only nitrate (3%) and fluoride (7%) exceeded primary MCLs. Several parameters, including TDS, sulfate, fluoride, iron, and manganese, are above the secondary drinking water standards in approximately one-third of the wells, primarily in the downdip portions of the aquifer. Chloride exceeded the secondary standard in 10% of the wells, also in the downdip portions of the aquifer. The action level for lead was exceeded in 10% of the wells.

**Table 4.1 Occurrence and Levels of Selected Public Drinking Water Supply Parameters in the Woodbine Aquifer**

| | Number of Wells with Analyses | Screening Level (mg/l) | Type of Standard | Percent of Wells Exceeding Screening Level |
|---|---|---|---|---|
| Nitrate-N | 720 | 10 | MCL | 3% |
| Fluoride | 710 | 4 | MCL | 7% |
| Barium | 97 | 2 | MCL | 0% |
| Chromium | 44 | 0.1 | MCL | 0% |
| Selenium | 5 | 0.05 | MCL | 0% |
| Arsenic | 10 | 0.05 | MCL | 0% |
| Lead | 10 | 0.015 | Action Level | 10% |
| Copper | 86 | 1.3 | Action Level | 0% |
| TDS | 730 | 1,000 | SS | 37% |
| Chloride | 776 | 300 | SS | 10% |
| Sulfate | 770 | 300 | SS | 34% |
| Fluoride | 710 | 2 | SS | 28% |
| Iron | 90 | 0.3 | SS | 32% |
| Manganese | 101 | 0.05 | SS | 35% |
| Aluminum | 51 | 0.2 | SS | 12% |
| Zinc | 67 | 5 | SS | 0% |
| Copper | 86 | 1 | SS | 0% |

MCL- Primary drinking water standard (maximum contaminant level) from 30 TAC Chapter 290 Subchapter F

Action Level- Copper and Lead have action levels as defined by 30 TAC 290.117

SS- Secondary drinking water standard from 30 TAC Chapter 290 Subchapter F

As shown in Table 4.2, the salinity and sodium hazards in groundwater from the Woodbine are high in a large percentage of the wells. TDS and salinity hazards are "permissible" in approximately half of the wells, meaning the groundwater may be used with some treatment (leaching). An additional 25% of the wells produce groundwater that is "doubtful" or "unsuitable" for irrigation purposes. In addition, the sodium hazard in groundwater from the Woodbine is high to very high in a majority of wells, with 62% of the wells producing groundwater with a "very high" sodium hazard, and an additional 7% with a "high" sodium hazard. Boron and fluoride are also found in more than half of the wells at levels that are higher than recommended for long-term use for irrigation purposes.

**Table 4.2 Occurrence and Levels of Selected Irrigation Water Quality Parameters in the Woodbine Aquifer**

| | Number of Wells with Analyses | Screening Level (mg/l unless otherwise noted) | Percent of Wells Exceeding Screening Level |
|---|---|---|---|
| Total Dissolved Solids | 730 | Permissible (TDS = 525-1400) | 48% |
| | | Doubtful (TDS = 1400-2100) | 17% |
| | | Unsuitable (TDS >2100) | 7% |
| Salinity Hazard | 700 | Permissible (Spec. Cond. = 750-2000 μmhos/cm) | 50% |
| | | Doubtful (Spec. Cond. = 2000-3000 μmhos/cm) | 18% |
| | | Unsuitable (Spec. Cond. > 3000 μmhos/cm) | 11% |
| Sodium Hazard | 703 | Very High (SAR >26) | 62% |
| | | High (SAR = 18-26) | 7% |
| Boron | 128 | 2 (short-term use) | 29% |
| | | 0.75 (long-term use) | 62% |
| Copper | 86 | 5 (short-term use) | 0% |
| | | 0.2 (long-term use) | 0% |
| Fluoride | 710 | 15 (short-term use) | 0% |
| | | 1 (long-term use) | 53% |
| Selenium | 5 | 0.02 (long and short-term use) | 0% |
| Zinc | 67 | 10 (short-term use) | 0% |
| | | 2 (long-term use) | 0% |

Source: Fipps, 2003.

***Paluxy Aquifer***- A total of 806 wells were included in the analysis of groundwater quality in the Paluxy. The occurrence of selected drinking water parameters for the Paluxy compared to screening levels is shown in Table 4.3. The occurrence of irrigation parameters for the Paluxy compared to screening levels is shown in Table 4.4.

Figure 4.17 shows the distribution of fresh, slightly saline, moderately saline, and very saline water analyses. As indicated in this figure, most of the data available for the Paluxy were obtained from wells producing fresh water. A few analyses exhibiting slightly saline water are observed scattered throughout the aquifer, mostly in the downdip portions of the aquifer.

As shown in Table 4.3, only two parameters exceeded primary MCLs in Paluxy groundwater, nitrate (8%) and fluoride (3%). Several parameters exceeded secondary standards, including TDS, fluoride, iron, and manganese. However, these levels were only exceeded in approximately one-tenth of the wells. Chloride and sulfate exceeded secondary standards in less than 5% of the wells.

**Table 4.3 Occurrence and Levels of Selected Public Drinking Water Supply Parameters in the Paluxy Aquifer**

| | Number of Wells | Screening Level (mg/l) | Type of Level | Percent of Wells Exceeding Screening Level |
|---|---|---|---|---|
| Nitrate-N | 753 | 10 | MCL | 8% |
| Fluoride | 688 | 4 | MCL | 3% |
| Barium | 45 | 2 | MCL | 0% |
| Chromium | 25 | 0.1 | MCL | 0% |
| Selenium | 3 | 0.05 | MCL | 0% |
| Arsenic | 2 | 0.05 | MCL | 0% |
| Lead | 6 | 0.015 | Action Level | 0% |
| Copper | 20 | 1.3 | Action Level | 0% |
| TDS | 755 | 1,000 | SS | 7% |
| Chloride | 805 | 300 | SS | 2% |
| Sulfate | 805 | 300 | SS | 3% |
| Fluoride | 688 | 2 | SS | 10% |
| Iron | 19 | 0.3 | SS | 11% |
| Manganese | 24 | 0.05 | SS | 13% |
| Aluminum | 25 | 0.2 | SS | 0% |
| Zinc | 17 | 5 | SS | 0% |
| Copper | 20 | 1 | SS | 0% |

MCL- Primary drinking water standard (maximum contaminant level) from 30 TAC Chapter 290 Subchapter F

Action Level- Copper and Lead have action levels as defined by 30 TAC 290.117

SS- Secondary drinking water standard from 30 TAC Chapter 290 Subchapter F

As shown in Table 4.4, the salinity and sodium hazards in groundwater from the Paluxy are high in a large percentage of the wells. TDS and salinity hazards are "permissible" in approximately half of the wells, meaning the groundwater may be used with some treatment (leaching). However, less than 5% of the Paluxy wells produce groundwater that is considered "doubtful" or "unsuitable" for irrigation purposes. In addition, the sodium hazard in groundwater from the Paluxy is high to very high in a majority of Paluxy wells, with 48% of the wells producing groundwater with a "very high" sodium hazard, and an additional 8% with a "high" sodium hazard. Boron and fluoride are also found in approximately one-third of the wells at levels that are higher than recommended for long-term use for irrigation purposes.

**Table 4.4 Occurrence and Levels of Selected Irrigation Water Quality Parameters in the Paluxy Aquifer**

| | Number of Wells | Screening Level (mg/l unless otherwise noted) | Percent of Wells Exceeding Screening Level |
|---|---|---|---|
| Total Dissolved Solids | 755 | Permissible (TDS = 525-1400) | 45% |
| | | Doubtful (TDS = 1400-2100) | 2% |
| | | Unsuitable (TDS >2100) | 1% |
| Salinity Hazard | 735 | Permissible (Spec. Cond. = 750-2000 μmhos/cm) | 63% |
| | | Doubtful (Spec. Cond. = 2000-3000 μmhos/cm) | 2% |
| | | Unsuitable (Spec. Cond. > 3000 μmhos/cm) | 2% |
| Sodium Hazard | 733 | Very High (SAR >26) | 49% |
| | | High (SAR = 18-26) | 8% |
| Boron | 60 | 2 (short-term use) | 7% |
| | | 0.75 (long-term use) | 35% |
| Copper | 20 | 5 (short-term use) | 0% |
| | | 0.2 (long-term use) | 0% |
| Fluoride | 688 | 15 (short-term use) | 0% |
| | | 1 (long-term use) | 30% |
| Selenium | 3 | 0.02 (long and short-term use) | 0% |
| Zinc | 17 | 10 (short-term use) | 0% |
| | | 2 (long-term use) | 0% |

Source: Fipps, 2003.

***Hensell Aquifer***- A total of 234 wells were included in the analysis of groundwater quality in the Hensell. The occurrence of selected drinking water parameters for the Hensell compared to screening levels is shown in Table 4.5. The occurrence of irrigation parameters for the Hensell compared to screening levels is shown in Table 4.6.

Figure 4.18 shows the distribution of fresh, slightly saline, moderately saline, and very saline water in the Hensell. As indicated in this figure, most of the data available for the Hensell were acquired from wells producing fresh water, with less than 25% of the wells producing groundwater with greater than 1,000 mg/l TDS. Although TDS concentrations are expected to generally increase in downdip areas, the data shown in Figure 4.18 indicate that the location of groundwater with TDS greater than 1,000 mg/l is scattered throughout the aquifer.

As shown in Table 4.5, both nitrate and fluoride exceeded primary MCLs in 6% of the Hensell wells. Several parameters exceeded secondary standards in approximately one-fifth of the wells, including TDS, sulfate, fluoride, and iron. In addition to these, chloride and manganese exceeded secondary standards 4% and 7% of the wells, respectively.

**Table 4.5 Occurrence and Levels of Selected Public Drinking Water Supply Parameters in the Hensell Aquifer**

| | Number of Wells | Screening Level | Type of Level | Percent of Wells Exceeding Screening Level |
|---|---|---|---|---|
| Nitrate-N | 231 | 10 | MCL | 6% |
| Fluoride | 225 | 4 | MCL | 6% |
| Barium | 25 | 2 | MCL | 0% |
| Chromium | 14 | 0.1 | MCL | 0% |
| Mercury | 2 | 0.002 | MCL | 50% |
| Lead | 1 | 0.015 | Action Level | 0% |
| Copper | 12 | 1.3 | Action Level | 0% |
| TDS | 231 | 1,000 | SS | 22% |
| Chloride | 234 | 300 | SS | 4% |
| Sulfate | 234 | 300 | SS | 19% |
| Fluoride | 225 | 2 | SS | 24% |
| Iron | 16 | 0.3 | SS | 19% |
| Manganese | 15 | 0.05 | SS | 7% |
| Aluminum | 5 | 0.2 | SS | 0% |
| Zinc | 18 | 5 | SS | 0% |
| Copper | 12 | 1 | SS | 0% |

MCL- Primary drinking water standard (maximum contaminant level) from 30 TAC Chapter 290 Subchapter F
Action Level- Copper and Lead have action levels as defined by 30 TAC 290.117
SS- Secondary drinking water standard from 30 TAC Chapter 290 Subchapter F

As shown in Table 4.6, the salinity and sodium hazards in groundwater from the Hensell are high in a large percentage of the wells. TDS and salinity hazards are "permissible" in approximately two-thirds of the wells, meaning the groundwater may be used with some treatment (leaching). An additional 10-20% of the wells produce groundwater that is "doubtful" or "unsuitable" for irrigation purposes. In addition, the sodium hazard in groundwater from the Hensell is high to very high in nearly half of the Hensell wells, with 23% of the wells producing groundwater with a "very high" sodium hazard, and an additional 26% with a "high" sodium hazard. Boron and fluoride are also found in one-third to one-half half of the wells at levels that are higher than recommended for long-term use for irrigation purposes, and boron is higher than the short-term level in 3% of the wells.

**Table 4.6 Occurrence and Levels of Selected Irrigation Water Quality Parameters in the Hensell Aquifer**

| | Number of Wells | Screening Level (mg/l unless otherwise noted) | Percent of Wells Exceeding Screening Level |
|---|---|---|---|
| Total Dissolved Solids | 231 | Permissible (TDS = 525-1400) | 58% |
| | | Doubtful (TDS = 1400-2100) | 6% |
| | | Unsuitable (TDS >2100) | 4% |
| Salinity Hazard | 215 | Permissible (Spec. Cond. = 750-2000 μmhos/cm) | 68% |
| | | Doubtful (Spec. Cond. = 2000-3000 μmhos/cm) | 12% |
| | | Unsuitable (Spec. Cond. > 3000 μmhos/cm) | 6% |
| Sodium Hazard | 228 | Very High (SAR >26) | 23% |
| | | High (SAR = 18-26) | 26% |
| Boron | 29 | 2 (short-term use) | 3% |
| | | 0.75 (long-term use) | 34% |
| Copper | 12 | 5 (short-term use) | 0% |
| | | 0.2 (long-term use) | 0% |
| Fluoride | 225 | 15 (short-term use) | 0% |
| | | 1 (long-term use) | 55% |
| Zinc | 18 | 10 (short-term use) | 0% |
| | | 2 (long-term use) | 0% |

Source: Fipps, 2003.

***Hosston Aquifer***- As described in Section 2.2, the individual members of the Travis Peak Formation are not always distinguishable in geophysical logs. Stratigraphic complications also occur in areas where the Glen Rose carbonates pinch out, allowing contact (nomenclaturally) between the Paluxy and the Lower Trinity aquifers. In these areas, screened aquifers are often reported as one of three composite formations: 1) Travis Peak, 2) Twin Mountains, or 3) Antlers Sand. Analysis of the available data suggests that the chemical quality of water from the Hosston most closely matches the quality of water reported for wells completed in these composite formations. Because of this, the quality data associated with the composite formations were combined with Hosston data in an effort to depict the regional groundwater quality of the Trinity aquifer(s).

Using this approach, 2,648 water quality analyses wells were included in this evaluation. The occurrence of selected drinking water parameters for the Hosston compared to screening levels is shown in Table 4.7. The occurrence of irrigation parameters for the Hosston compared to screening levels is shown in Table 4.8.

Figure 4.19 shows the distribution of fresh, slightly saline, moderately saline, and very saline water in the Hosston/Trinity. As shown in this figure, most of the groundwater in the Hosston/Trinity is fresh, with less than 20% of the total analyses containing TDS in excess of 1,000 mg/l. Several portions of the outcrop area contain groundwater with elevated TDS concentrations, especially in Brown, Callahan, and Eastland Counties. These elevated TDS concentrations may be associated with improper disposal of waste brine water from oil and gas production. In downdip areas, many elevated TDS concentrations are reported; however, available analyses also indicate some fresh water may also be found in the deeper portions of the aquifer. Higher TDS groundwater is also found in the higher pumping centers, in particular the Dallas-Fort Worth, where poorer quality water is being drawn into the high pumpage regions from non-production aquifers.

As shown in Table 4.7, only three parameters exceeded primary MCLs in Hosston groundwater, nitrate (22%), selenium (3%), and fluoride (1%). Several parameters exceeded secondary standards, including TDS (18%), iron (13%), chloride (12%), fluoride (11%), sulfate (8%), manganese (4%) and aluminum (4%).

**Table 4.7 Occurrence and Levels of Selected Public Drinking Water Supply Parameters in the Hosston Aquifer Layer (Antlers, Twin Mountains, Travis Peak, and Hosston Aquifers)**

| | Number of Wells | Screening Level | Type of Level | Percent of Wells Exceeding Screening Level |
|---|---|---|---|---|
| Nitrate-N | 2,441 | 10 | MCL | 22% |
| Fluoride | 2,370 | 4 | MCL | 1% |
| Barium | 317 | 2 | MCL | 0% |
| Chromium | 152 | 0.1 | MCL | 0% |
| Selenium | 59 | 0.05 | MCL | 3% |
| Arsenic | 33 | 0.05 | MCL | 0% |
| Mercury | 5 | 0.002 | MCL | 0% |
| Lead | 28 | 0.015 | Action Level | 0% |
| Copper | 148 | 1.3 | Action Level | 0% |
| TDS | 2,537 | 1,000 | SS | 18% |
| Chloride | 2,644 | 300 | SS | 12% |
| Sulfate | 2,637 | 300 | SS | 8% |
| Fluoride | 2,370 | 2 | SS | 11% |
| Iron | 173 | 0.3 | SS | 13% |
| Manganese | 183 | 0.05 | SS | 4% |
| Aluminum | 83 | 0.2 | SS | 4% |
| Zinc | 170 | 5 | SS | 0% |
| Copper | 148 | 1 | SS | 0% |

MCL- Primary drinking water standard (maximum contaminant level) from 30 TAC Chapter 290 Subchapter F
Action Level- Copper and Lead have action levels as defined by 30 TAC 290.117
SS- Secondary drinking water standard from 30 TAC Chapter 290 Subchapter F

As shown in Table 4.8, the salinity and sodium hazards in groundwater from the Hosston are high in a large percentage of the wells. TDS and salinity hazards are "permissible" in approximately two-thirds of the wells, meaning the groundwater may be used with some treatment (leaching). An additional 7-14% of the wells produce groundwater that is "doubtful" or "unsuitable" for irrigation purposes. In addition, the sodium hazard in groundwater from the Hosston is high to very high in nearly 40% of the wells, with 33% of the wells producing groundwater with a "very high" sodium hazard, and an additional 6% with a "high" sodium hazard. Boron (17%) and fluoride (31%) are also found at levels that are higher than recommended for long-term use for irrigation purposes in some wells, and 3% of the wells have boron above the recommended concentration for short-term use. Selenium is found above the level recommended for both short and long-term use in 8% of the wells in the Hosston.

**Table 4.8 Occurrence and Levels of Selected Irrigation Water Quality Parameters in the Hosston Aquifer Layer (Antlers, Twin Mountains, Travis Peak, and Hosston Aquifers)**

| | Number of Wells | Screening Level (mg/l unless otherwise noted) | Percent of Wells Exceeding Screening Level |
|---|---|---|---|
| Total Dissolved Solids | 2,537 | Permissible (TDS = 525-1400) | 57% |
| | | Doubtful (TDS = 1400-2100) | 4% |
| | | Unsuitable (TDS >2100) | 3% |
| Salinity Hazard | 2,382 | Permissible (Spec. Cond. = 750-2000 μmhos/cm) | 66% |
| | | Doubtful (Spec. Cond. = 2000-3000 μmhos/cm) | 9% |
| | | Unsuitable (Spec. Cond. > 3000 μmhos/cm) | 5% |
| Sodium Hazard | 2,476 | Very High (SAR >26) | 33% |
| | | High (SAR = 18-26) | 6% |
| Boron | 643 | 2 (short-term use) | 3% |
| | | 0.75 (long-term use) | 17% |
| Copper | 148 | 5 (short-term use) | 0% |
| | | 0.2 (long-term use) | 0% |
| Fluoride | 2,370 | 15 (short-term use) | 0% |
| | | 1 (long-term use) | 31% |
| Selenium | 59 | 0.02 (long and short-term use) | 8% |
| Zinc | 170 | 10 (short-term use) | 0% |
| | | 2 (long-term use) | 0% |

Source: Fipps, 2003.

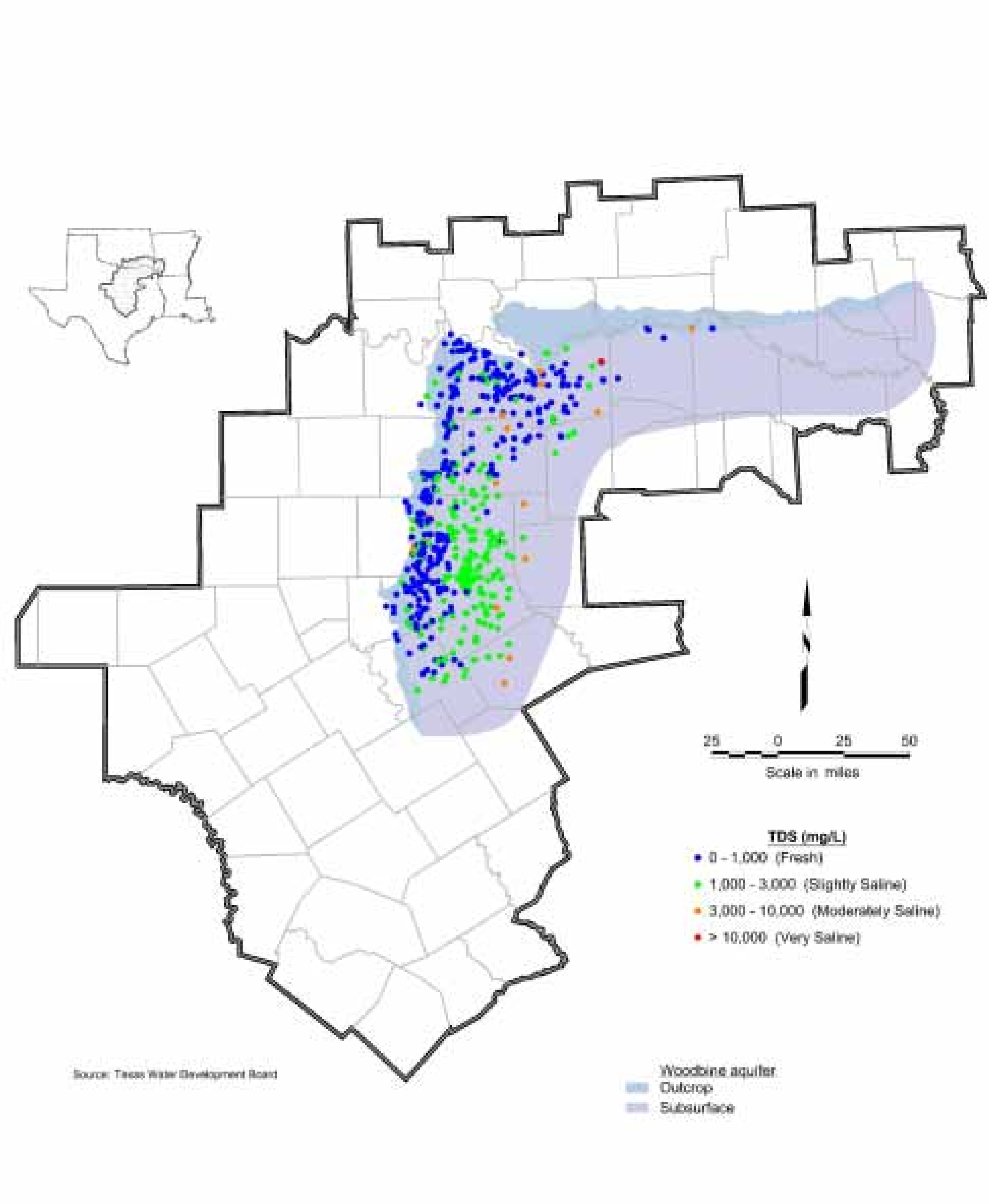



**Figure 4.16 Woodbine Water Quality**

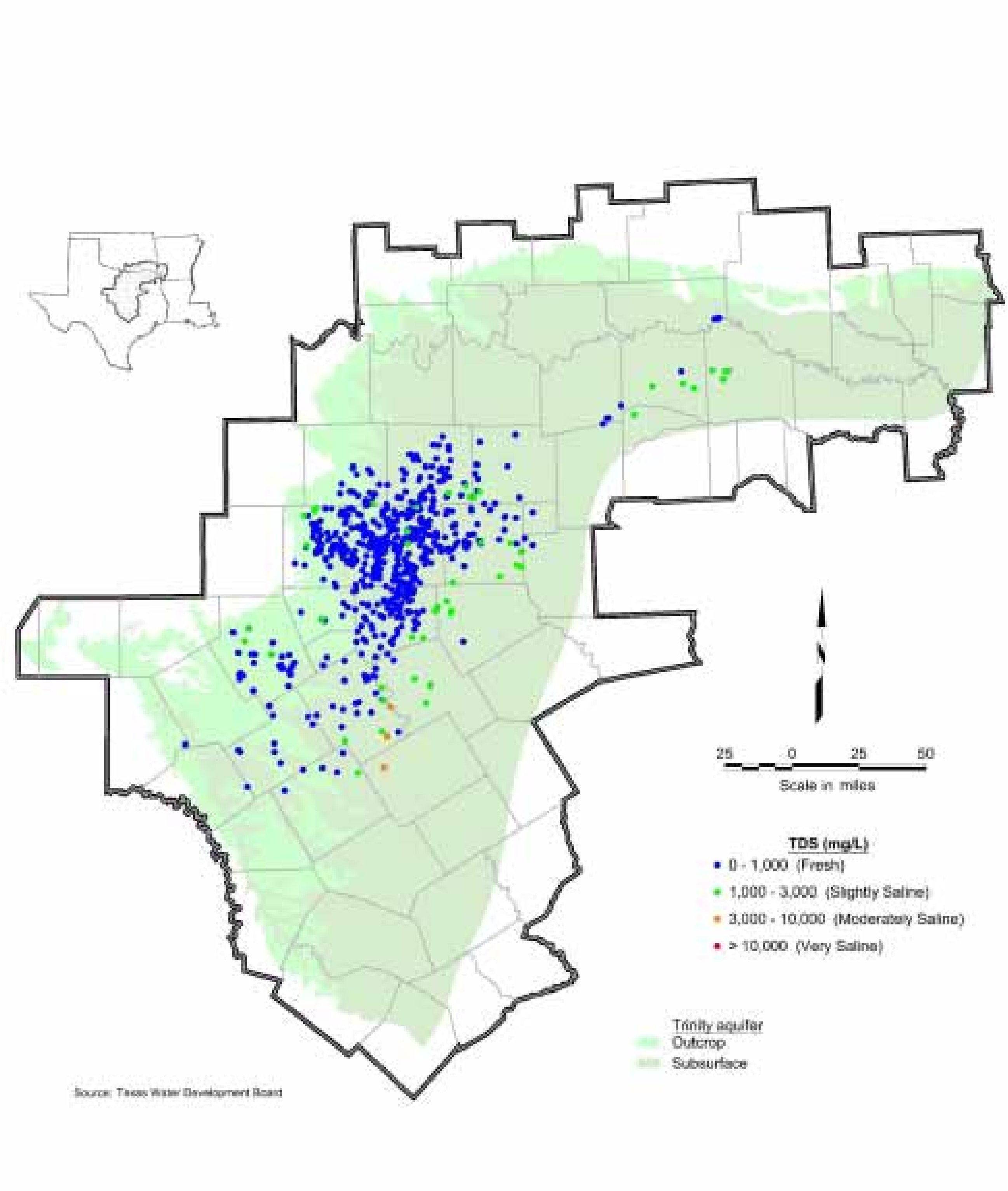



**Figure 4.17 Paluxy Water Quality**

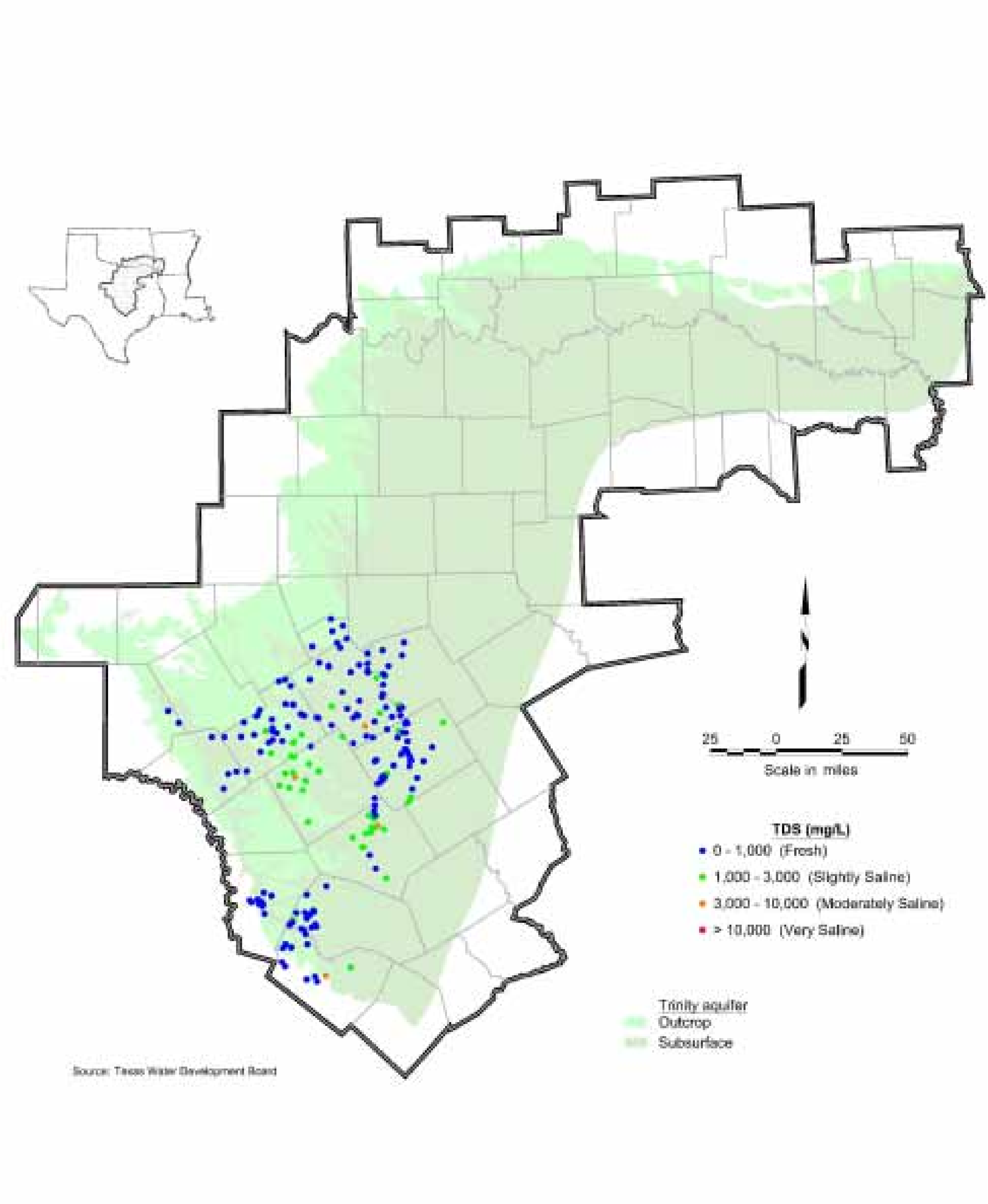



**Figure 4.18 Hensell Water Quality**

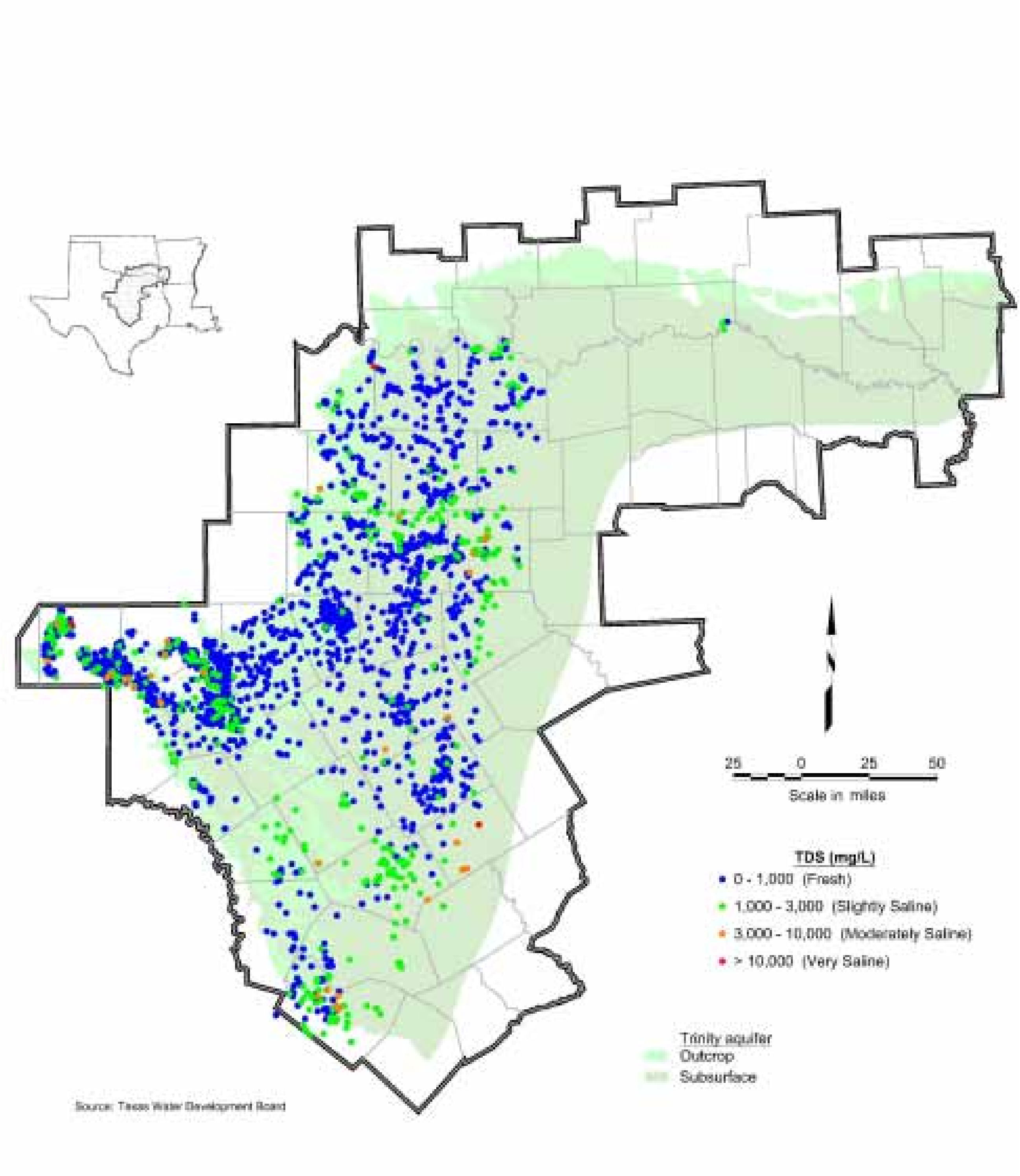



**Figure 4.19 Hosston/Trinity Water Quality**

## 4.4 Water Levels and Regional Groundwater Flow

Settlers in North-Central Texas had drilled numerous Trinity/Woodbine wells by the late 1800's. At that time, the artesian pressure in some areas of the aquifer was sufficient to drive the water up the well bore and onto the land surface without the installation of pumping equipment. Wells that discharge water without the use of pumps are known as flowing or artesian wells and these were common in the Fort Worth and Waco areas at the end of the 19th century. Because these wells reduced the artesian pressure of the Trinity/Woodbine aquifers before accurate water level measurements were made, a precise description of the true "predevelopment" water levels is not possible. By 1914, the extensive development of the Trinity/Woodbine caused the artesian pressure in most areas to drop below ground level, and previously flowing wells required the installation of pumps in order to continue to produce groundwater. The reduction in the number of flowing wells created a corresponding decline in groundwater production from the Trinity and Woodbine sands during the early 1900's.

As described above, a significant amount of development in both the Trinity and Woodbine aquifer occurred prior to 1900. Mace and others (1994) indicate that a cone of depression was already evident in their 1900 water level map of the Woodbine aquifer. Similarly, estimates of late 19$^{th}$ Century Trinity water levels suggest that there may have been some influence from groundwater production in the Fort Worth area. Data from Hill (1901) document the number of wells present in these units in 1900. More than 150 wells were producing from the Woodbine, including 43 in Dallas County, more than 33 in Ellis County, and 25 in Grayson County. There were also in excess of 160 wells producing from the Paluxy aquifer, including 46 in Tarrant County, 45 in Denton County, and 37 in Cooke County. There were more than 600 wells, including nearly 300 in Somervell County, 67 in Bosque County, and more than 20 wells in Bell, Coryell, Erath, Hamilton, Hood, McLennan, Parker, and Williamson Counties producing from the Trinity aquifer (consisting of both the Hensell and Hosston hydrostratigraphic units).

Since the late 1800's, groundwater withdrawal has dramatically increased in the Dallas-Fort Worth region and other high-demand areas. In the first half of the 20$^{th}$ century, artesian pressure dropped several hundred feet in some areas, at rates as high as 20 feet per year. However, since the development of surface water resources in some areas, Trinity production has decreased, and groundwater levels have risen or stabilized in response to this pumpage reduction (Kaiser, 2002).

### 4.4.1 Data and Methods

Water level data developed during the last century were compiled from the TWDB groundwater database. These data were evaluated and used to create hydrographs and water level maps for each of the aquifer units in the model area. Only "publishable" and "good measurement" data (as defined by the appropriate database code) were selected for use in the hydrographs and water level maps.

Hydrographs were constructed for any well producing from one of the aquifer units being modeled in this study. These graphs were constructed for wells that had either data spanning lengthy periods of record (greater than 10-15 years), data recorded during either the calibration or verification periods (i.e. 1980-2000), or wells with a large number of water level measurements. More than 750 hydrographs were constructed for this study. There are many subregions within the study area that contain a disproportionately large number of wells for which hydrographs were constructed, and in some cases, the hydrographs within these subregions do not correlate well with each other.

In order to construct water level maps for 1980, 1990, and 2000, data were extracted from the TWDB database for these particular years. In an effort to populate these datasets with as many measurements as possible, water levels for two years on either side of the target year were selected (e.g. 1978 to 1982 data were used to create the 1980 data set). To minimize the possible effects from pumping, only water levels for November, December, January, February, and March were selected. Because data could be selected from five different months over a five-year span for each of the three target years, most wells contained several water level values in the resulting data set. Following the initial selection process, the datasets were evaluated and redundant values were removed, so that only one representative water level per well remained in the data set for each target year. While selecting the representative water level, the data values were evaluated to determine which was likely the most characteristic of the aquifer water level during that period. When clearly defined, the water level closest to the target year (i.e. 1980, 1990, and 2000) was selected. When the water levels for a particular well varied significantly, the data were evaluated to determine which water level to select. Data that displayed coherent trends were included in the data set, while water level data that exhibited excessive variation or random trends were excluded.

As described above, very few (if any) predevelopment water level measurements were available due to the production from these aquifers before 1900. Predevelopment water level maps were generated based on the analysis of data collated from four sources:

- Available data from Hill (1901) and Fiedler (1934);

- Maps from Hill (1901) showing locations of flowing artesian wells and other wells for the Woodbine, Paluxy, and Trinity aquifers. These maps also indicate areas where flowing artesian wells would be expected;

- Hydrographs for wells throughout the study area. For example, reverse extrapolation of more recent historical water level measurement may suggest predevelopment conditions in some areas;

- Maps constructed by Mace et al. (1994). However, as described above, these 1900 water level maps indicated some influence of late-1800's groundwater production from these aquifers.

Once a representative data set was constructed for a particular aquifer in a particular year, the data were posted and contoured. Representative water level contours were drawn for each map; however, it is important to note that due to the scale of these maps, and the high degree of variability in the data, not all data points were honored when creating the water level contours.

### 4.4.2 Predevelopment Distribution of Hydraulic Head

The earliest available water level measurements for the Woodbine, Paluxy, and Hosston/Trinity aquifers are shown in Figures 4.20, 4.21, and 4.22, respectively. Older sources of water level measurements do not typically differentiate between the Hensell and Hosston, simply describing these units as the Trinity aquifer. For this reason, the combined term Hosston/Trinity is used herein to describe the water levels associated with the Lower Cretaceous aquifers in the study area.

In all cases, water levels tend to follow the topography in outcrop areas, and then flatten out in the downdip, artesian portions of the aquifer. Gradients of approximately 5 to 10 feet per mile were estimated in the artesian portions of the Woodbine and Paluxy, while a gradient of about 4 to 7 feet per mile is inferred for the Hosston/Trinity. Flow within the Trinity/Woodbine was in a downdip direction away from the outcrop areas and towards the Luling-Mexia-Talco Fault Zone. A comparison of the predevelopment water levels for the Woodbine, Paluxy, and Hosston/Trinity shows progressive increases in the elevation of the potentiometric surface in the deeper units, indicating upward flow.

It is important to note that many (if not all) of the water levels shown in Figures 4.20 through 4.22 likely do not represent true predevelopment conditions. According to Hill (1901), hundreds of wells had been drilled into Trinity/Woodbine sediments prior to the dates of most measurements. Many of these wells were flowing artesian wells, which continually discharge groundwater after construction. Because these wells depressed the potentiometric surface associated with the

Trinity/Woodbine aquifers, the recorded water level elevations are lower than the true predevelopment water level elevations. The amount of predevelopment water level depression experienced undoubtedly varied with location; the magnitude and extent of the cones of depression associated with early wells were affected by the hydraulic properties of the aquifer, boundary conditions, and the rate of discharge from the wells. Near the Waco well field, it is estimated (based on pumpage records and the average pump test transmissivity for the area) that more than 200 feet of artesian pressure decline likely occurred prior to the earliest water level measurements.

### 4.4.3 Postdevelopment Changes in Hydraulic Head

Beginning in the late 1800's, development of the Trinity/Woodbine resulted in changes in the potentiometric surfaces in many regions of the study area. This development, coupled with the relatively low transmissivities of these aquifers, produced comparatively large artesian pressure declines near population centers in Central and North-Central Texas. For example, in the Dallas-Fort Worth area, declines of over 1,000 feet in the artesian pressure surface associated with Trinity groundwater occurred during the 20th Century. Conversely, historical water level measurements suggest that no significant regional declines have occurred in Trinity/Woodbine water table levels. As illustrated by Figures 4.23 and 4.24, outcrop water levels have exhibited both minor increases and minor declines (typically much less than 10 feet) during the past 50 years.

Seasonal water level fluctuations were evident in many of the wells included in the evaluation. The most pronounced annual variations were recorded in wells completed the artesian portions of the Trinity/Woodbine, and are presumably due to seasonal changes in pumping rates from the aquifers. Annual fluctuations of as much as 60 feet were evident in wells in the middle of major urban pumping centers such as the Cities of Dallas, Fort Worth, and Waco. In smaller municipalities, fluctuations were also evident. The City of Gatesville (Coryell County/Hosston aquifer) had somewhat irregular 10 to 20 foot declines between 1993 and 2000. Wells in the City of Stephenville area (Erath County/Twin Mountains aquifer) exhibited consistent 10 to 20 foot summer water level declines. The City of Hurst (Tarrant County/Paluxy aquifer) showed 5 to 10 foot declines every year from 1973-98.

Conversely, many wells showed very small or zero declines in water level during the summer months. Many of these wells were located in rural areas, although some are located in and around larger municipalities, such as the Cities of Temple, Coryell City, and Waxahachie.

Representative hydrographs for the Woodbine, Paluxy, Hensell, and Hosston aquifers are shown in Figures 4.25 through 4.28. Of the more than 750 hydrographs that were constructed for this project, 24 are presented in these figures as representative of these hydrostratigraphic units.

Figure 4.25 shows six hydrographs of water levels in wells completed in the Woodbine aquifer. Because significant production from this aquifer and declines in water levels occurred prior to the water level measurement dates shown in this figure, much of the declines that have occurred are not reflected in these hydrographs. As illustrated, decreases in water levels of over 200 feet have been observed since 1964 in the downdip portions of the Woodbine aquifer. Water level trends in the outcrop areas vary, maintaining relatively constant values in some regions, while exhibiting declines in other areas. However, declines in the outcrop areas may not be entirely due to regional declines in water levels, but may instead be a response to local pumping conditions in that part of the outcrop area and also partially reflective of artesian pressure decline in adjacent, lower strata.

Figure 4.26 shows six representative hydrographs for the Paluxy aquifer. As with the Woodbine, significant groundwater production occurred in the Paluxy prior to 1949, and declines due to this early pumpage are not reflected in these hydrographs. As shown, declines of over 100 feet have occurred over less than a 20-year period in some downdip areas of the Paluxy. Although reductions in outcrop water table elevations resulting from localized pumpage have been observed in some areas, water levels in the outcrop portions of the aquifer generally do not indicate long-term, regional declines.

Figure 4.27 shows six representative hydrographs for the Hensell aquifer. As with the Woodbine and Paluxy aquifers, production from the Hensell occurred prior to 1955, and reduction in water levels due to this production are not reflected in these hydrographs. Production from the Hensell is generally not as great as from the lower Hosston Formation, and some of the declines observed in the Hensell may be due to the downward leakage of water in response to pumpage from the Hosston. Most production from the Hensell has occurred in the southern portion of the study area, with artesian pressure declines of over 350 feet reported near Waco. Well No. 40-30-603 in McLennan County is a typical hydrograph for a Hensell well in the Waco area, with significant reductions still occurring into the 1990's. Some declines have been observed in the outcrop portions of the aquifer; however, as described above, this may be a response to localized pumping in the outcrop area or partially reflective of artesian pressure decline in lower, adjacent strata.

As described in Section 2.2, the individual members of the Travis Peak Formation are not always distinguishable in geophysical logs. Stratigraphic complications also occur in areas where the Glen Rose carbonates pinch out, allowing contact (nomenclaturally) between the Paluxy and the Lower Trinity aquifers. In these areas, screened aquifers are often reported as one of three composite formations: 1) Travis Peak, 2) Twin Mountains, or 3) Antlers Sand. Analysis of the available data suggests that the potentiometric surface of the Hosston most closely matches the water levels reported for wells completed in these composite formations. Because of this, the water level data associated with the composite formations were combined with Hosston data in an effort to depict the regional potentiometric surface of the Hosston/Trinity aquifer(s).

Figure 4.28 shows six hydrographs for wells completed in the Hosston, Twin Mountains, Travis Peak, and Antlers aquifers. As with the Woodbine, Paluxy, and Hensell aquifers, a significant amount of production occurred in the Hosston/Trinity prior to 1945, and declines due to this production are not reflected in these hydrographs. As shown, reductions in artesian pressure of over 600 feet have been recorded since 1945. Historical water levels in Well 40-31-802 in McLennan County decline from 1945 until the present, which is typical for the Waco area. Well 58-29-603 in Williamson County shows about 200 feet of decline in the interval between 1950 and 2000. Water levels in the outcrop portions of the Hosston/Trinity also show small declines in some areas (per previous stated reasons), but regional declines were not observed. Potentiometric surface maps for each of these aquifers were also developed for 1980, 1990, and 2000. A brief description of each is given below.

Woodbine water level maps for 1980, 1990, and 2000 are shown in Figures 4.29, 4.30, and 4.31. As shown in Figure 4.29, artesian pressure declines of over 250 feet in some areas had occurred in this unit by 1980. Water levels have declined several hundred feet and cones of depression are evident in the Dallas and Grayson County areas. The cone of depression around Sherman, in Grayson County, continues to develop in 1990 and 2000, while water levels in Dallas remained relatively stable.

Paluxy water level maps for 1980, 1990, and 2000 are shown in Figures 4.32, 4.33, and 4.34. As seen in Figure 4.32, a cone of depression had formed in the Dallas-Fort Worth area in the Paluxy aquifer by 1980. This cone of depression may have expanded slightly by 1990, but in general, significant water level declines or an expansion of the cone of depression in the Dallas-Fort Worth area were not observed between 1980 and 2000. Most groundwater flow is towards pumping centers in the Paluxy, in particular the Dallas-Fort Worth area.

Hensell water level maps for 1980, 1990, and 2000 are shown in Figures 4.35, 4.36, and 4.37. As seen in Figure 4.35, a cone of depression had formed in the Waco area in the Hensell by 1980. Between 1980 and 2000, this cone of depression continued to expand, with water levels in the Waco area declining more than two hundred feet in some areas during this 20-year period. Gradients have increased to between 10 to 20 feet per mile, with estimated gradients in excess of 30 feet per mile near Waco. Groundwater flow in the Hensell continues to be in the downdip direction, with a major component flowing towards the major pumping centers in Waco.

Hosston/Trinity water level maps for 1980, 1990, and 2000 are shown in Figures 4.38, 4.39, and 4.40. As shown in Figure 4.38, cones of depression had formed by 1980 in the Dallas-Fort Worth, Waco, and Sherman areas. Between 1980 and 2000, continued artesian pressure decline resulted in the formation of a single cone of depression stretching from Grayson County to McLennan County. Groundwater gradients in the artesian portion of the Hosston/Trinity have increased from estimated predevelopment gradients of 4 to 7 feet per mile to between 15 and 30 feet per mile, with even larger estimated gradients near major pumpage centers.

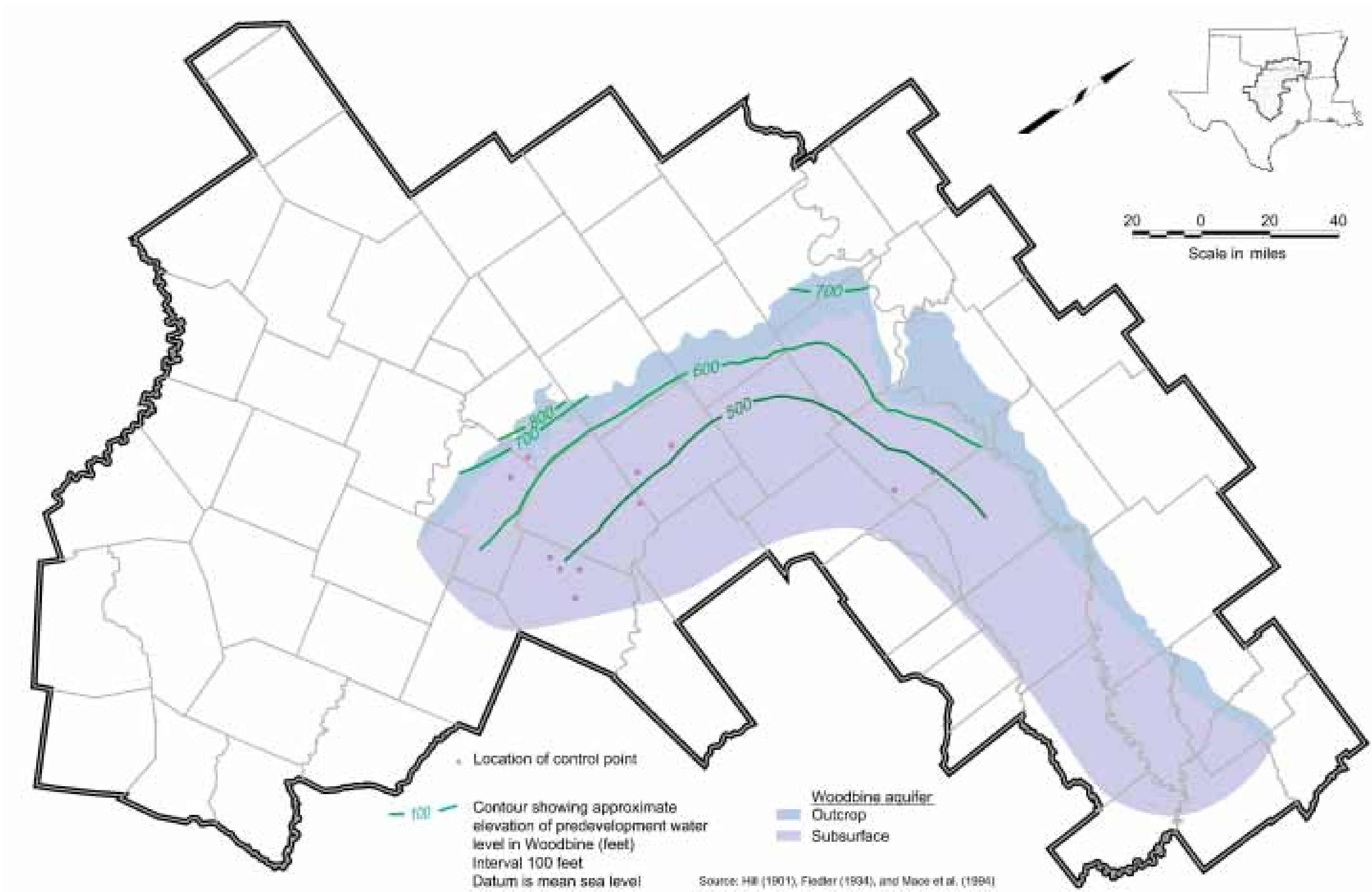



**Figure 4.20 Woodbine Water Level – Earliest Measurements**

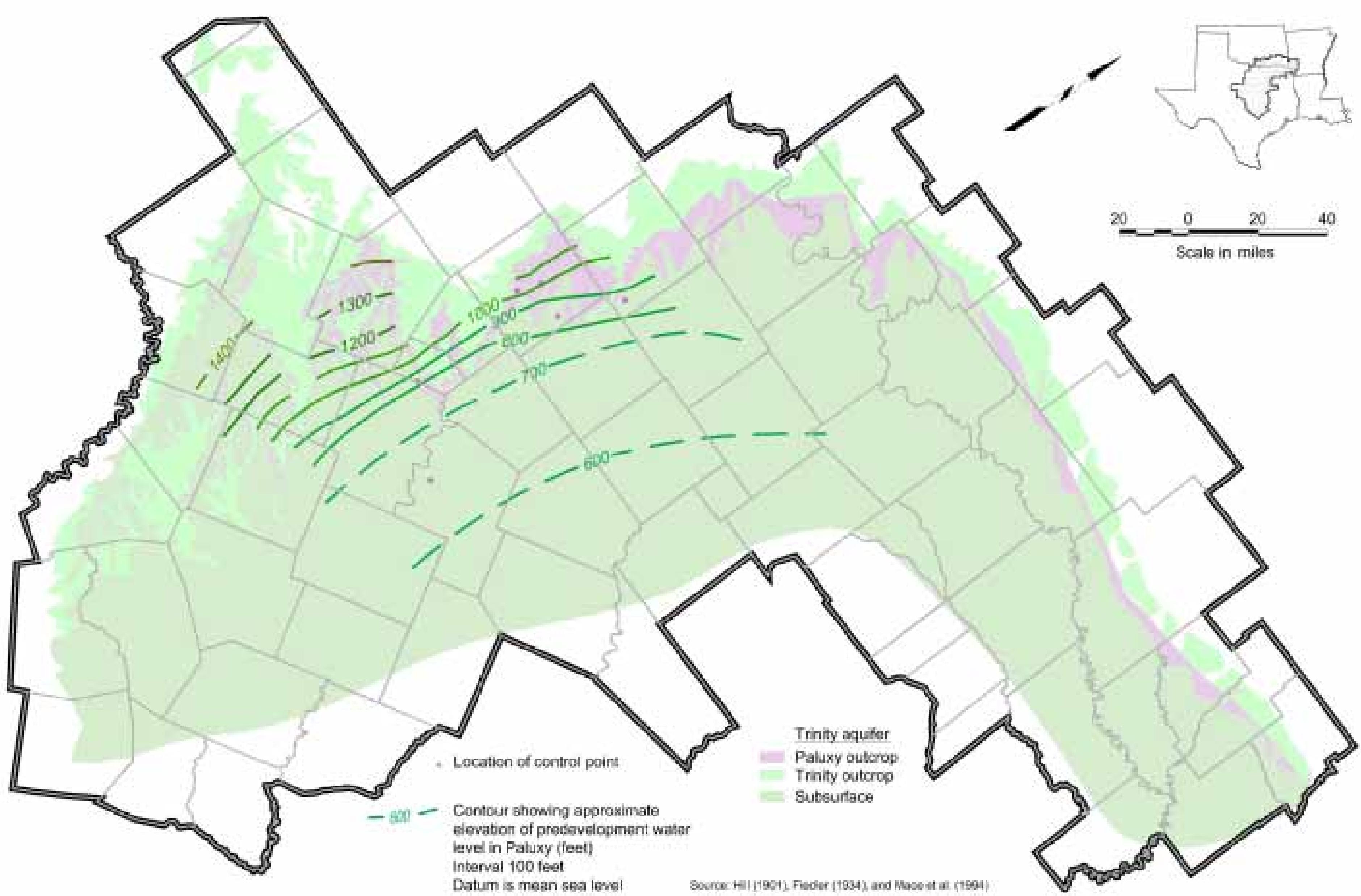



**Figure 4.21 Paluxy Water Level – Earliest Measurements**

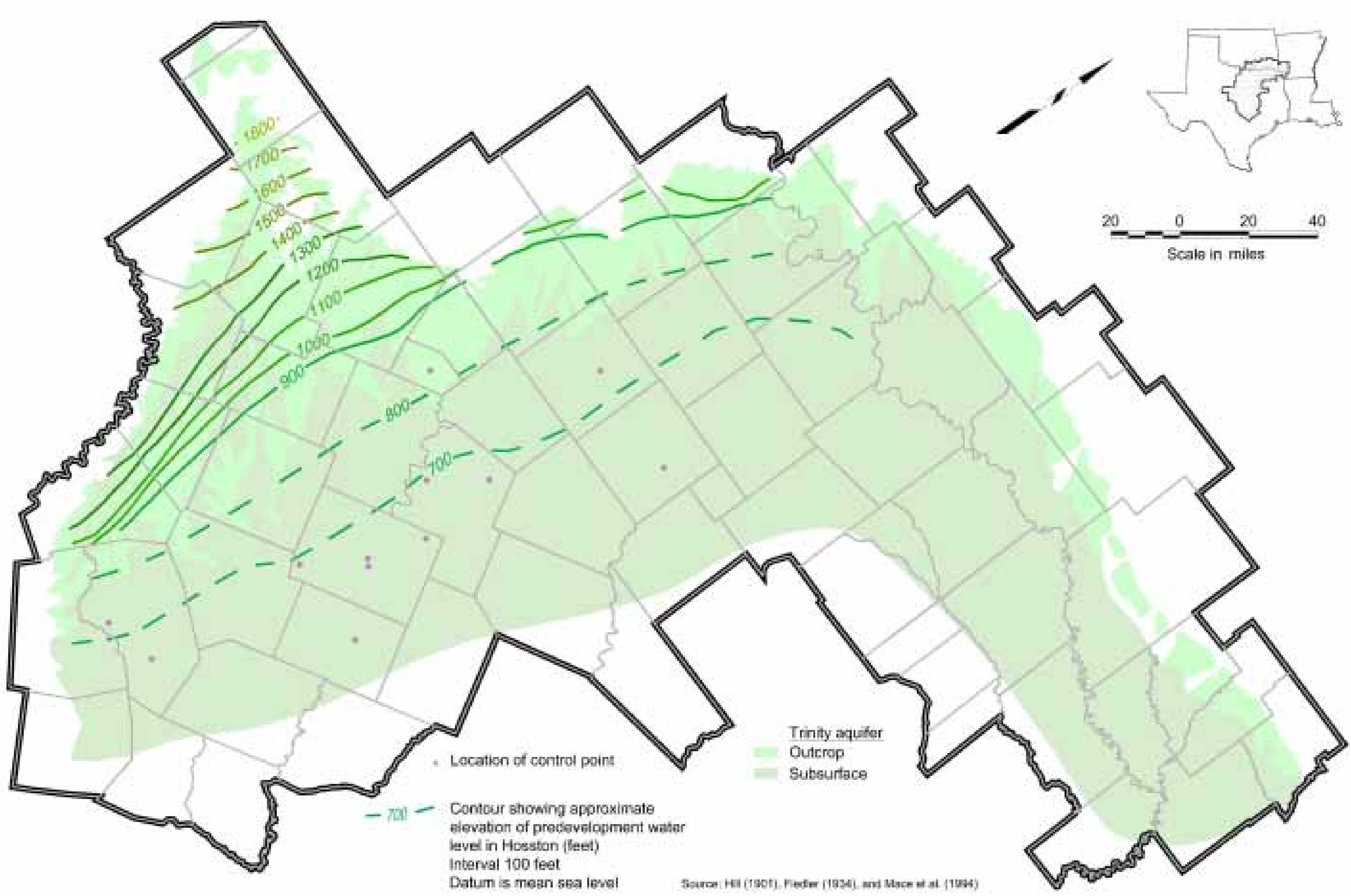



**Figure 4.22 Hosston/Trinity Water Level – Earliest Measurements**

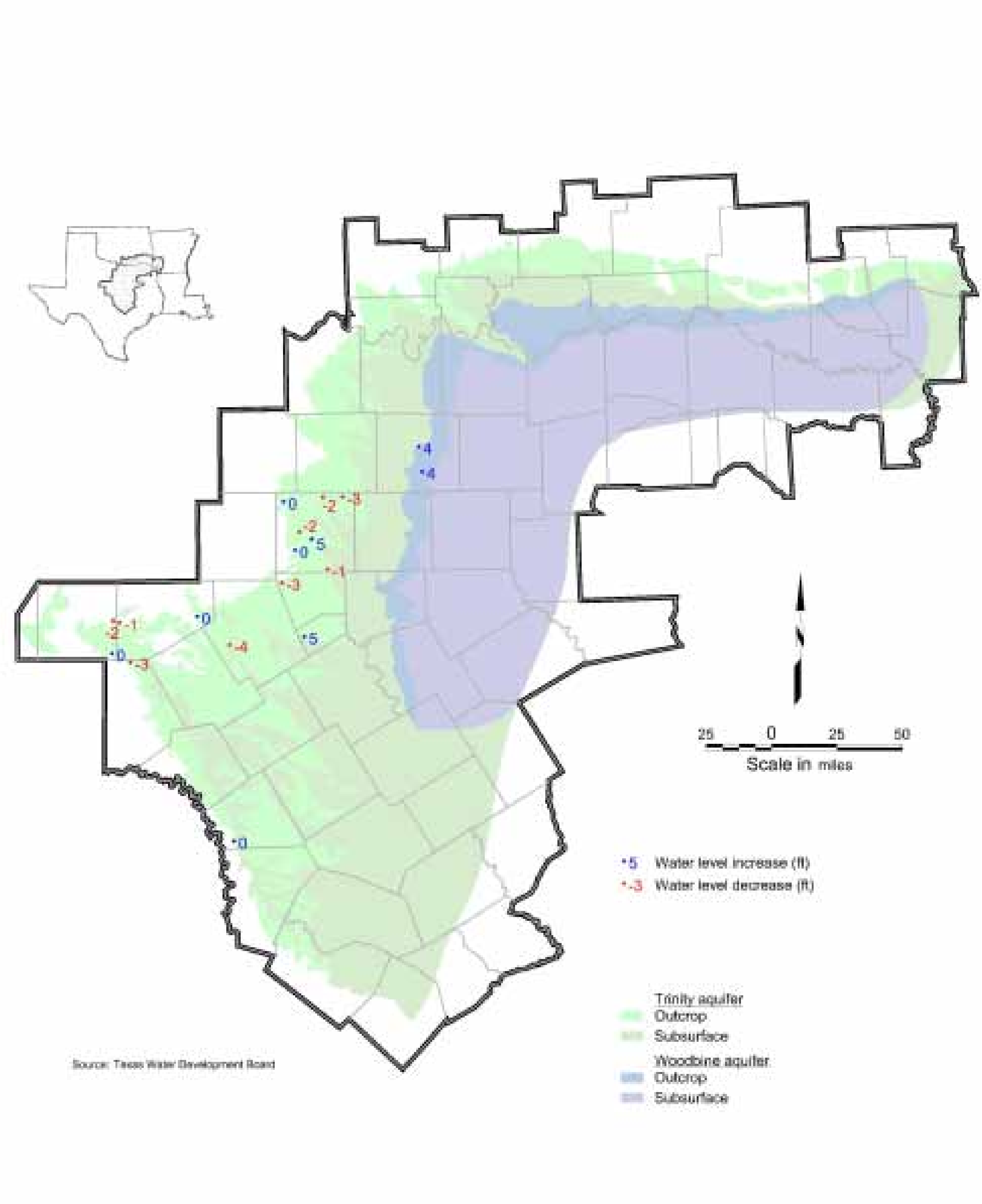



**Figure 4.23 Water Table Change in Outcrop Wells 1950 to 1980**

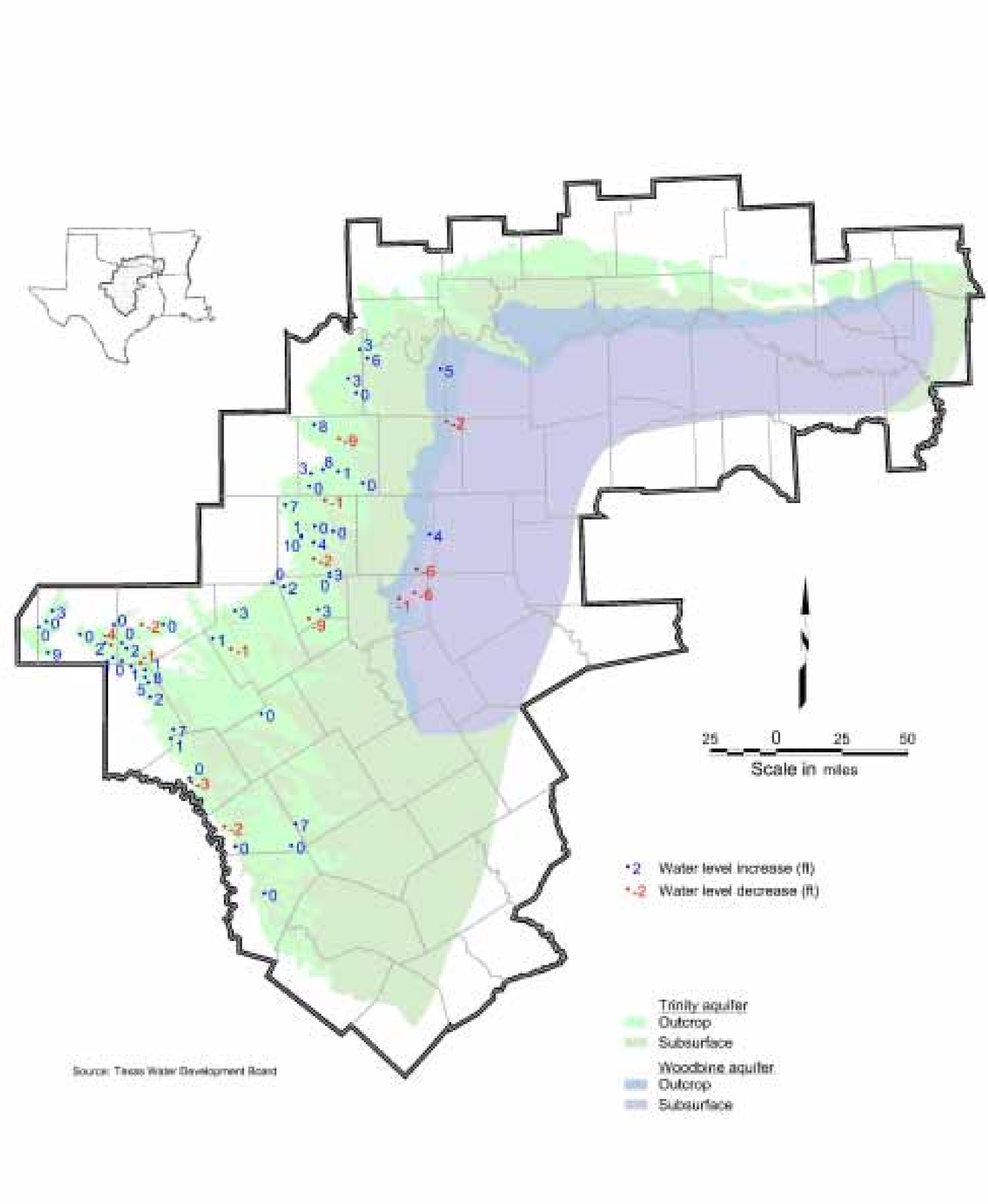
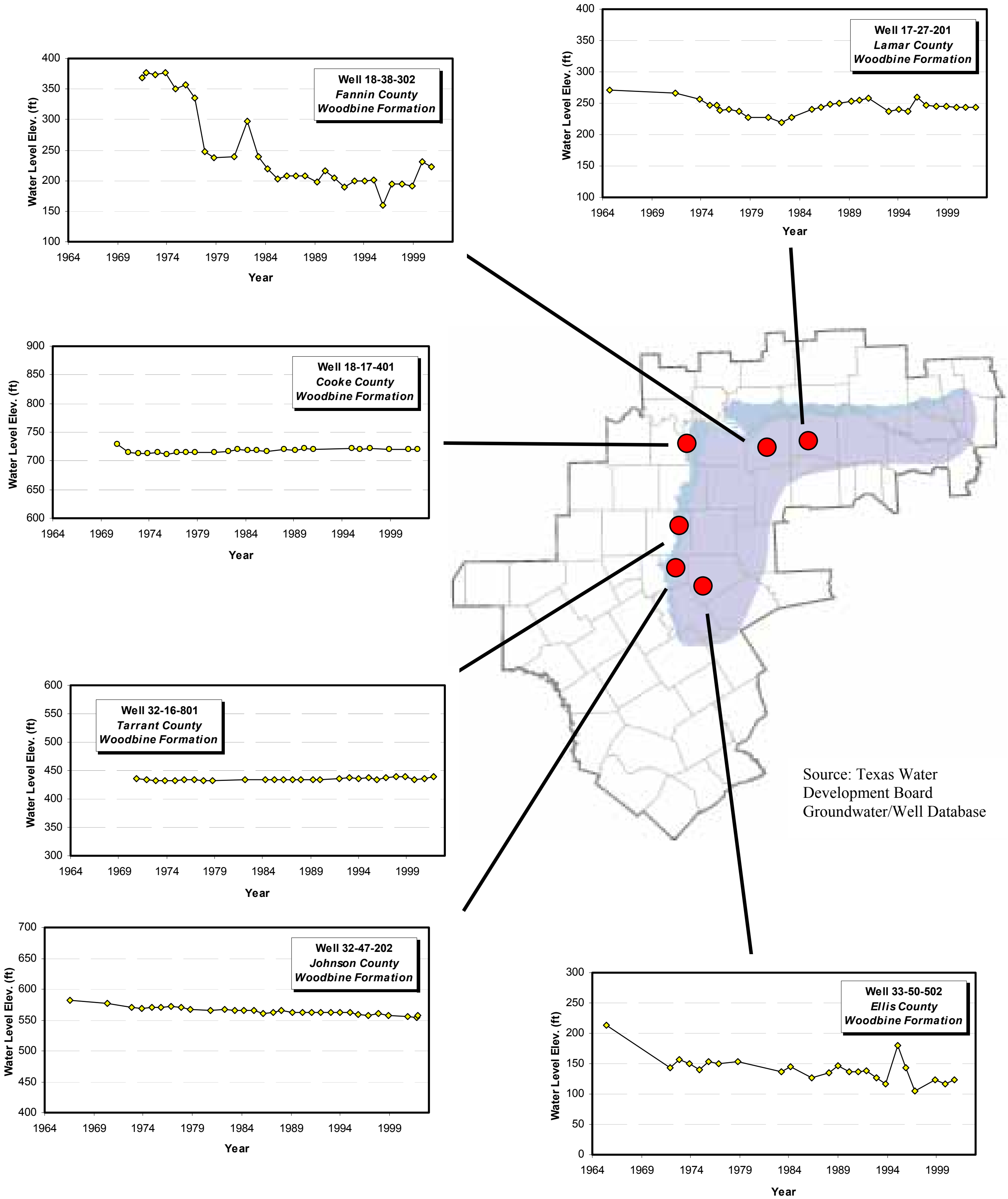
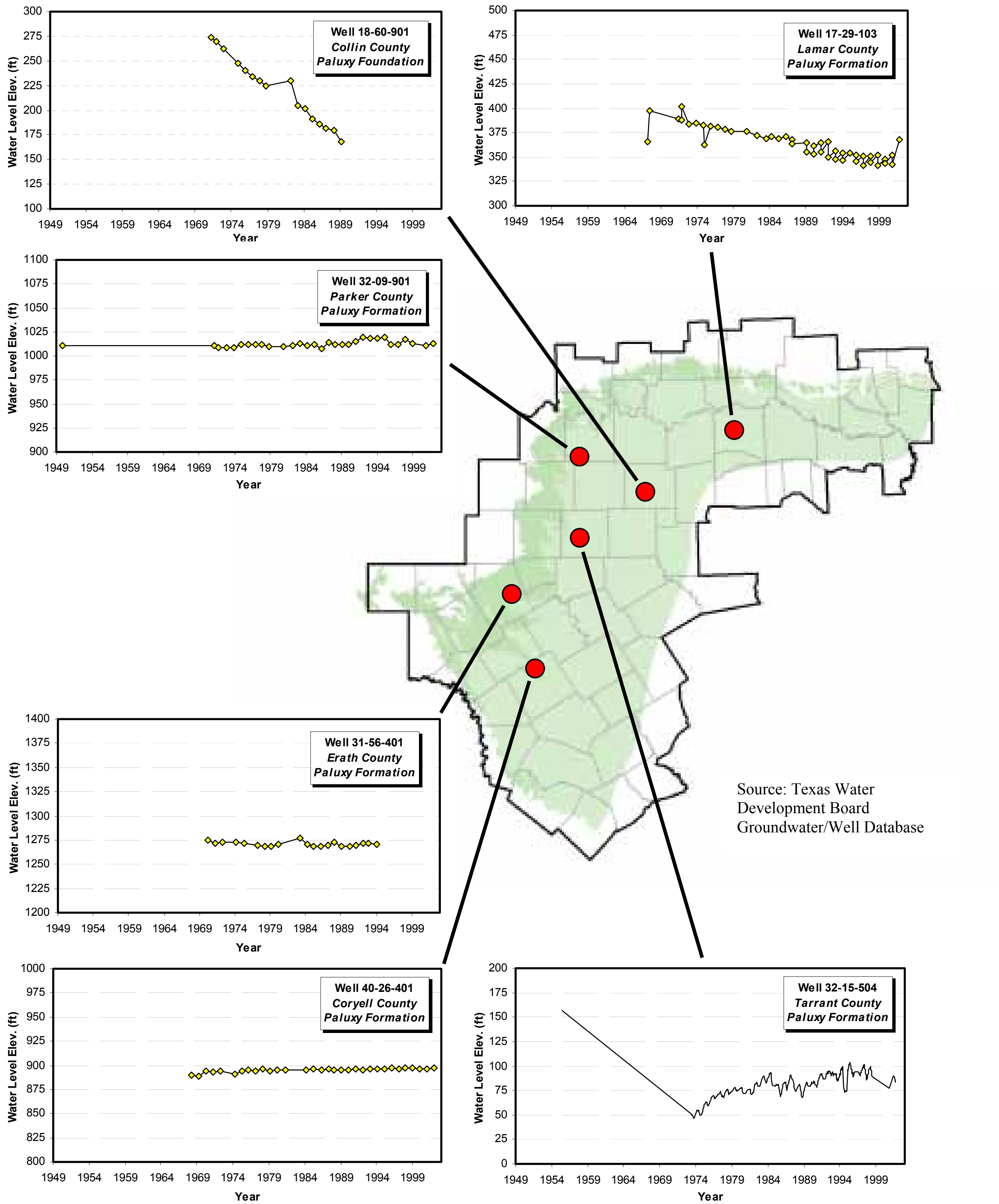



**Figure 4.24 Water Table Change in Outcrop Wells 1980 to 2000**

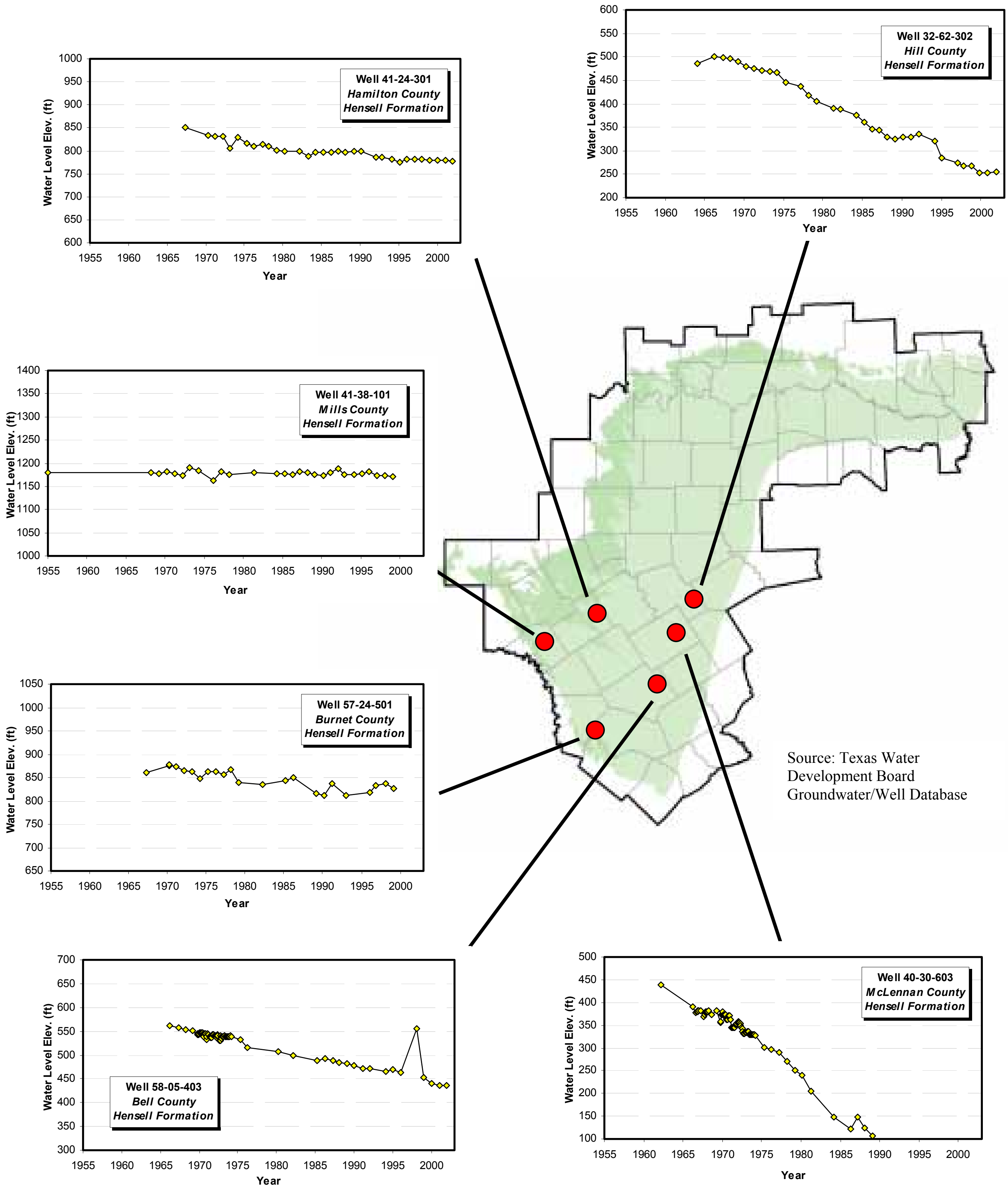
# Figure 4.25 Woodbine Historical Water Level Hydrographs



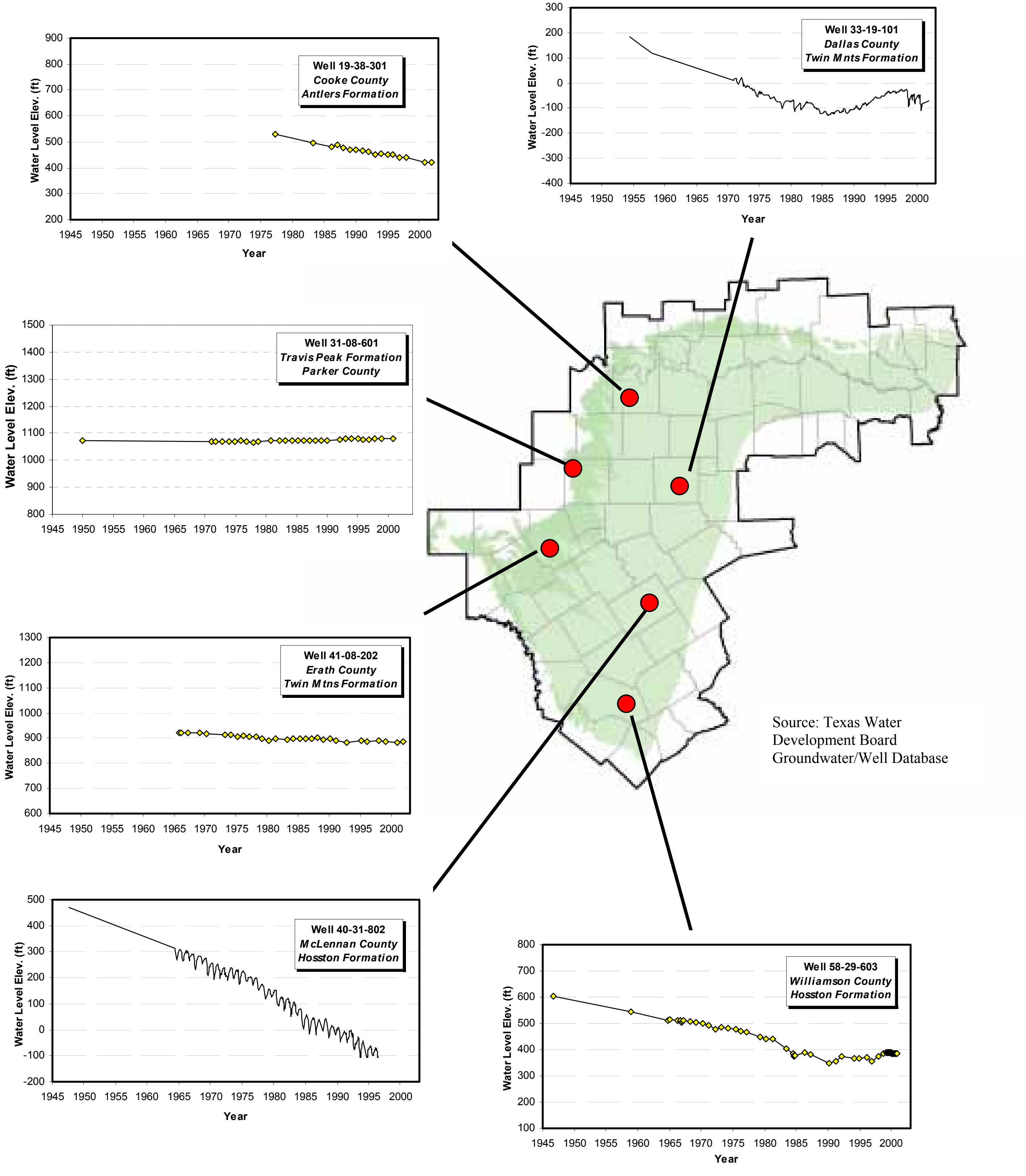
# Figure 4.26 Paluxy Historical Water Level Hydrographs



# Figure 4.27 Hensell Historical Water Level Hydrographs



# Figure 4.28 Hosston/Trinity Historical Water Level Hydrographs




Source: Texas Water Development Board Groundwater/Well Database

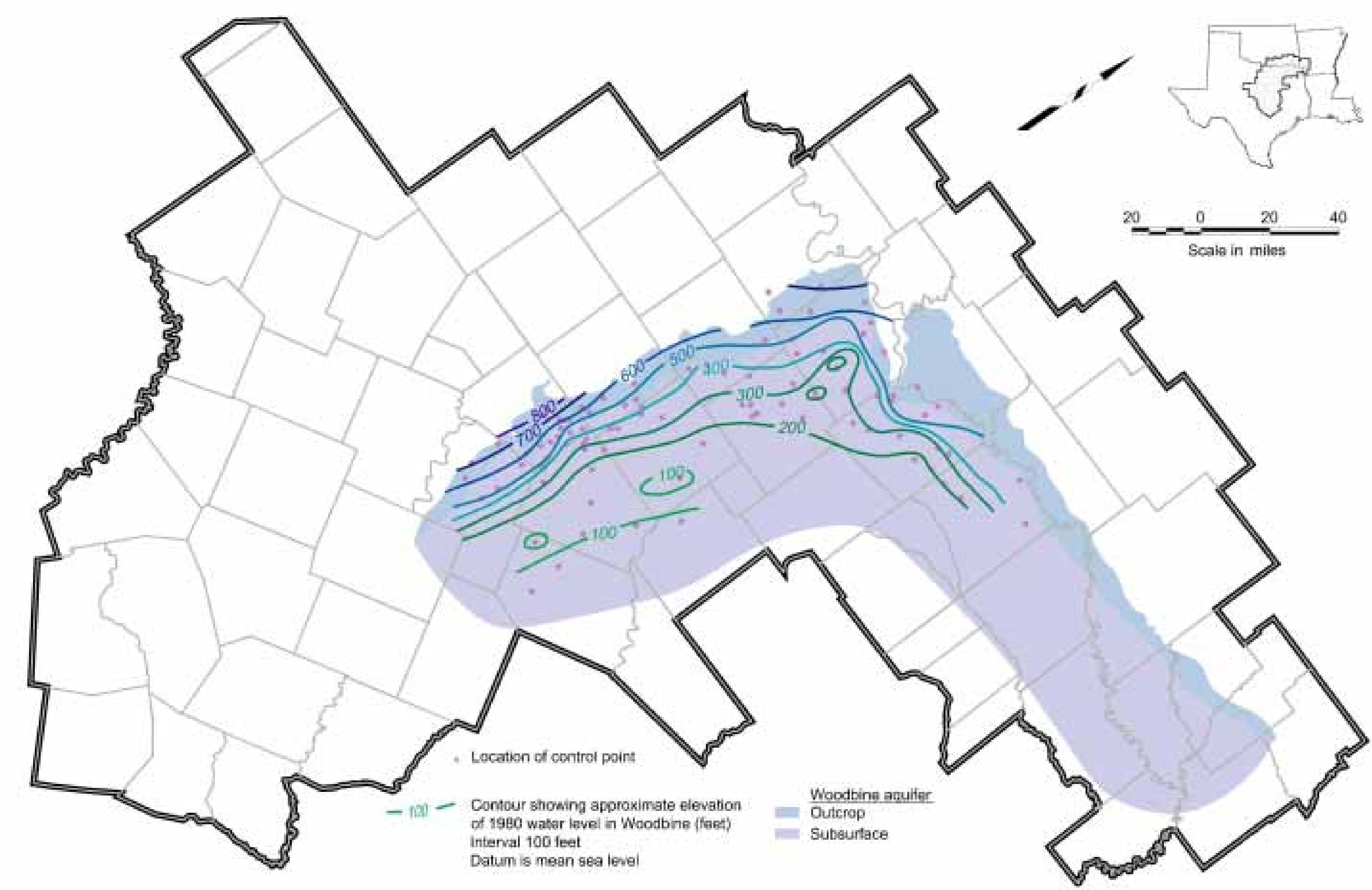



**Figure 4.29 Woodbine Water Level – 1980**

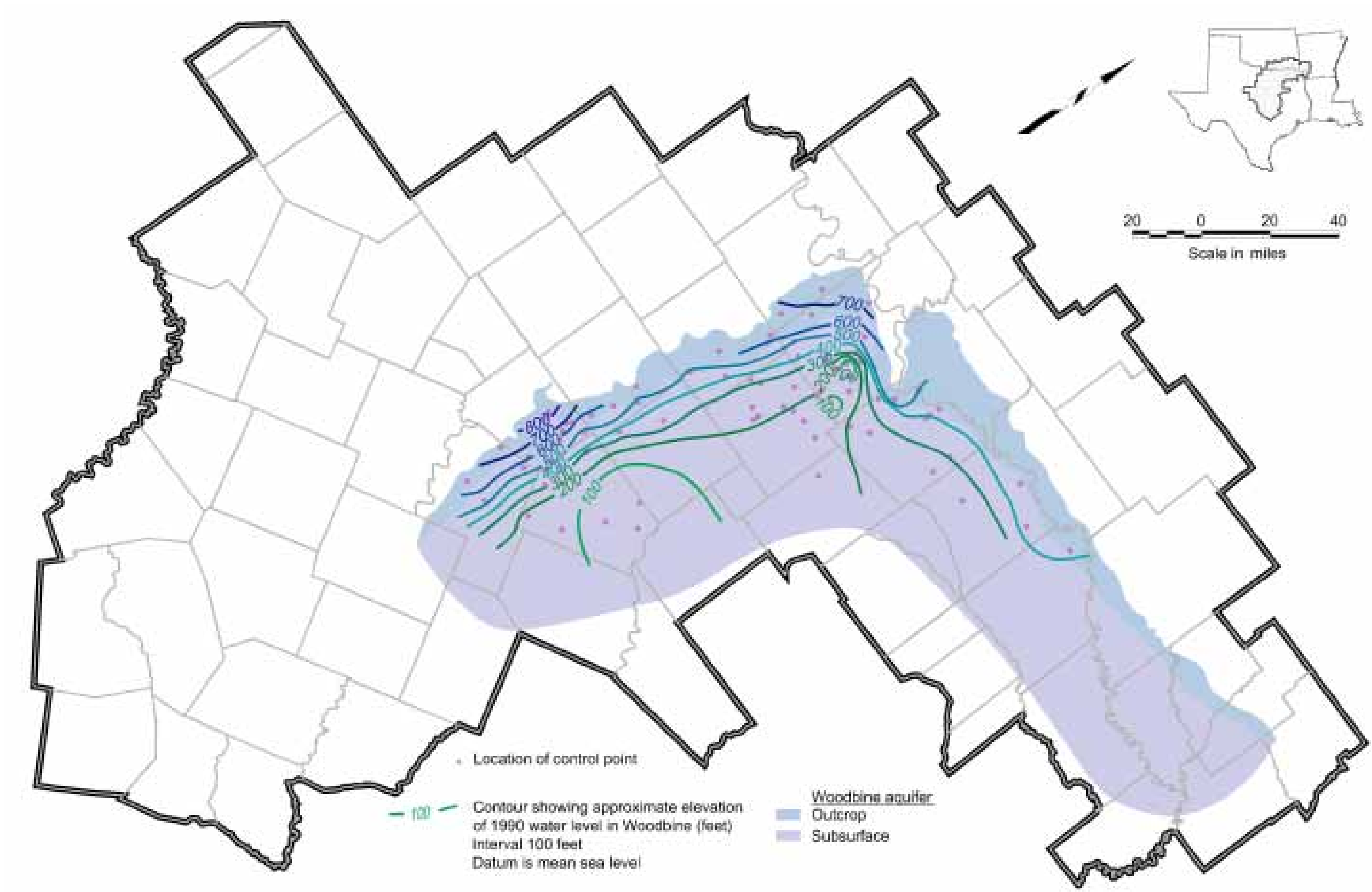



**Figure 4.30 Woodbine Water Level – 1990**

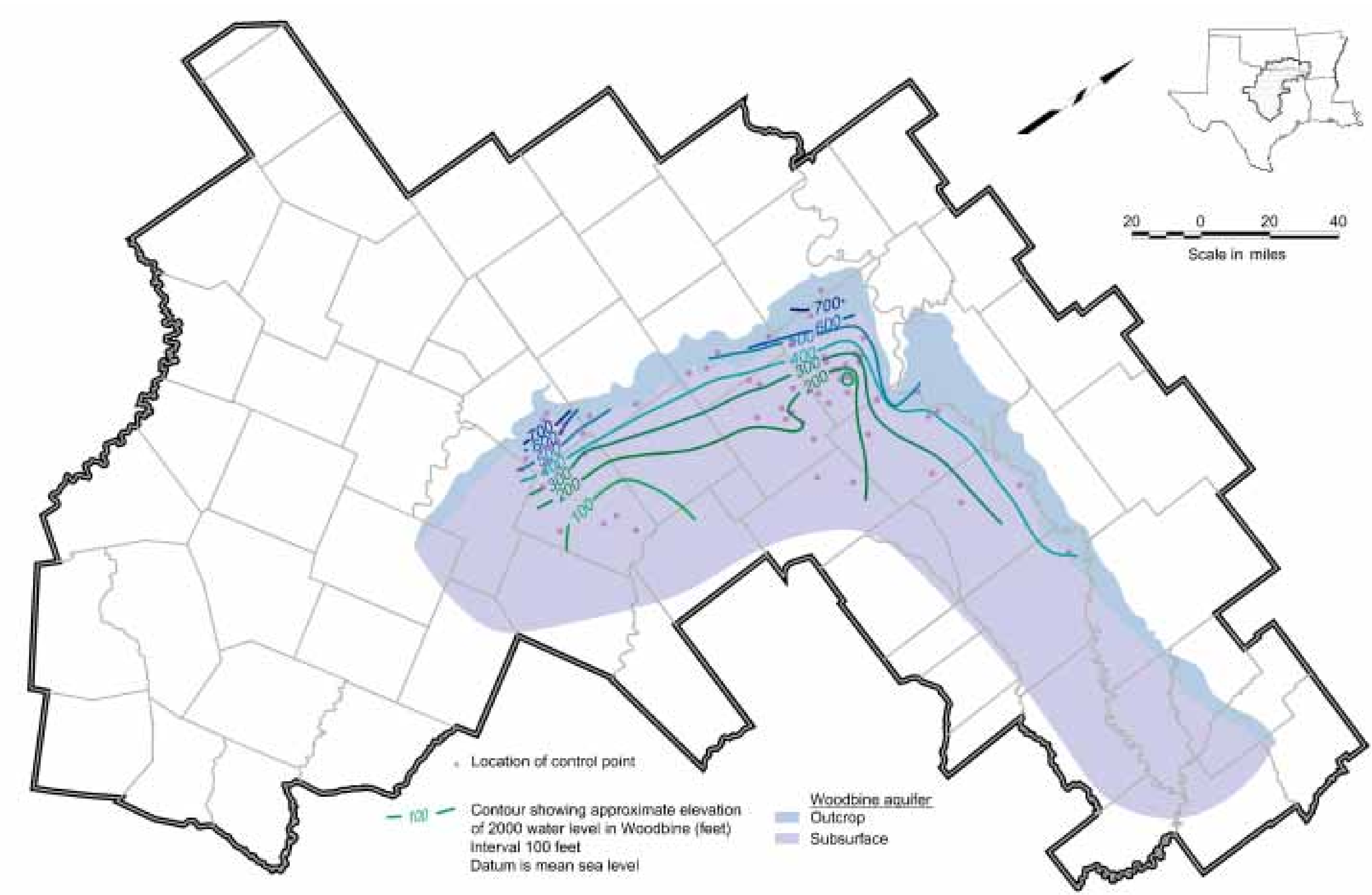



**Figure 4.31 Woodbine Water Level – 2000**

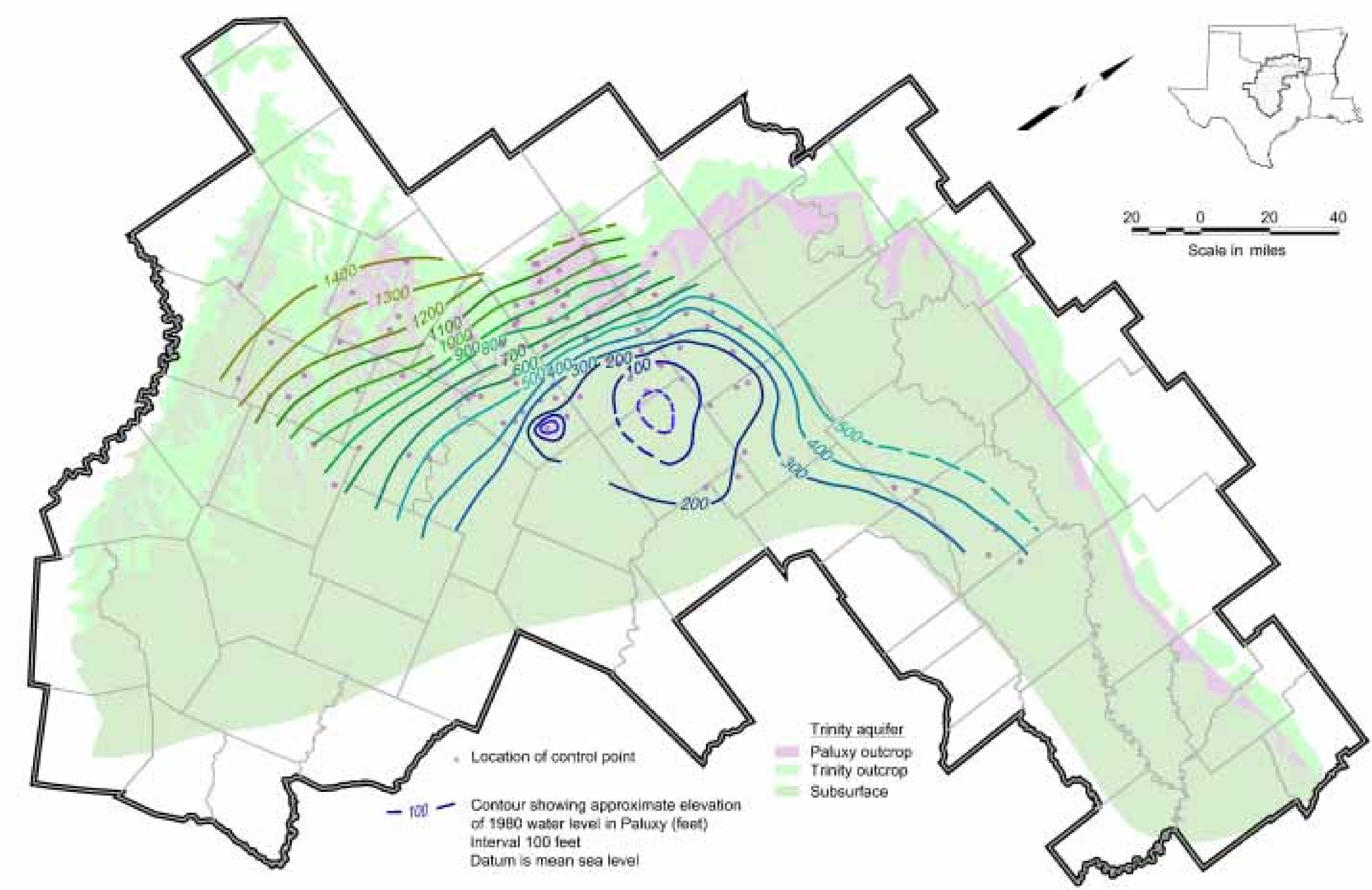



**Figure 4.32 Paluxy Water Level – 1980**

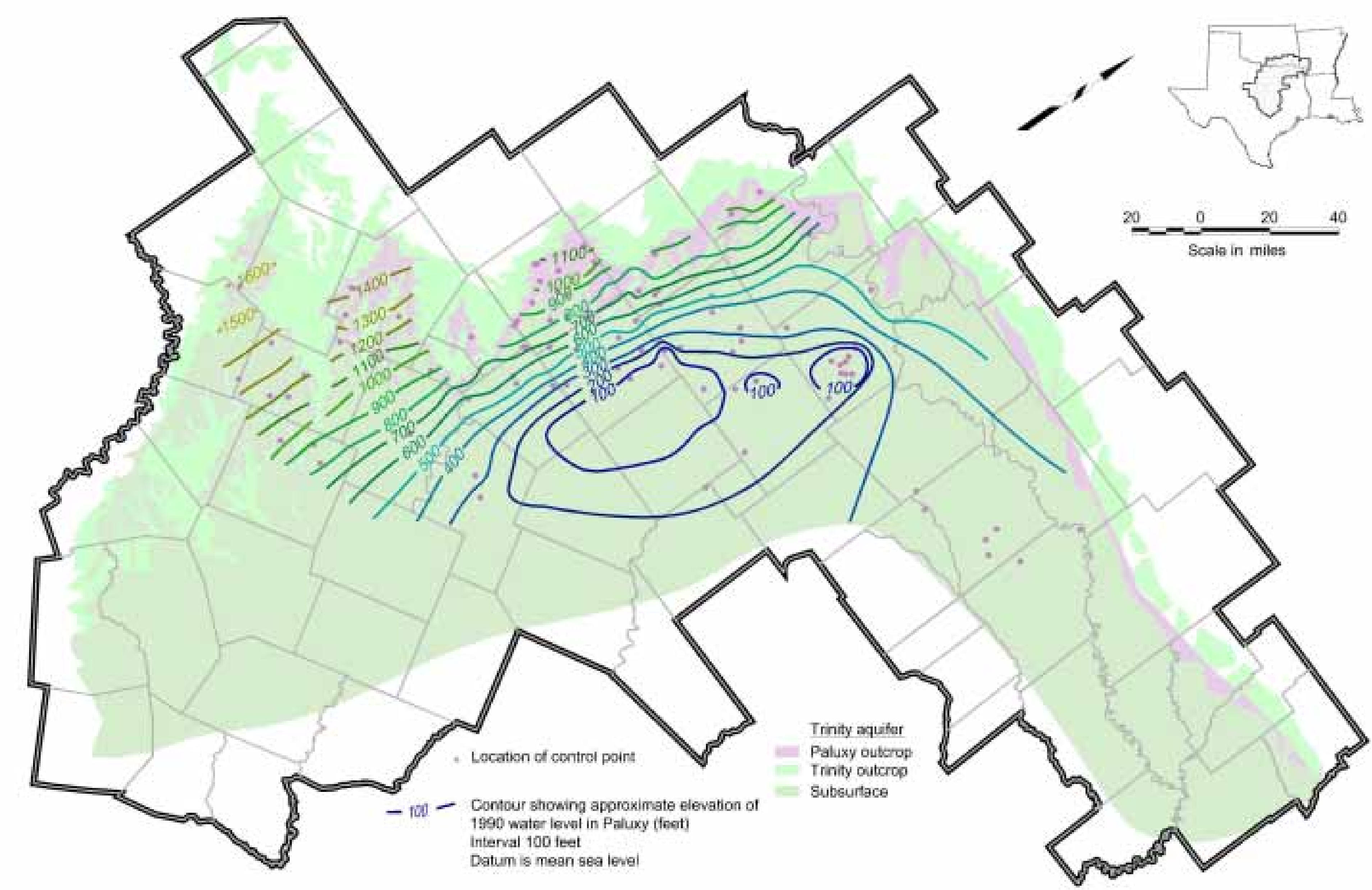



**Figure 4.33 Paluxy Water Level – 1990**

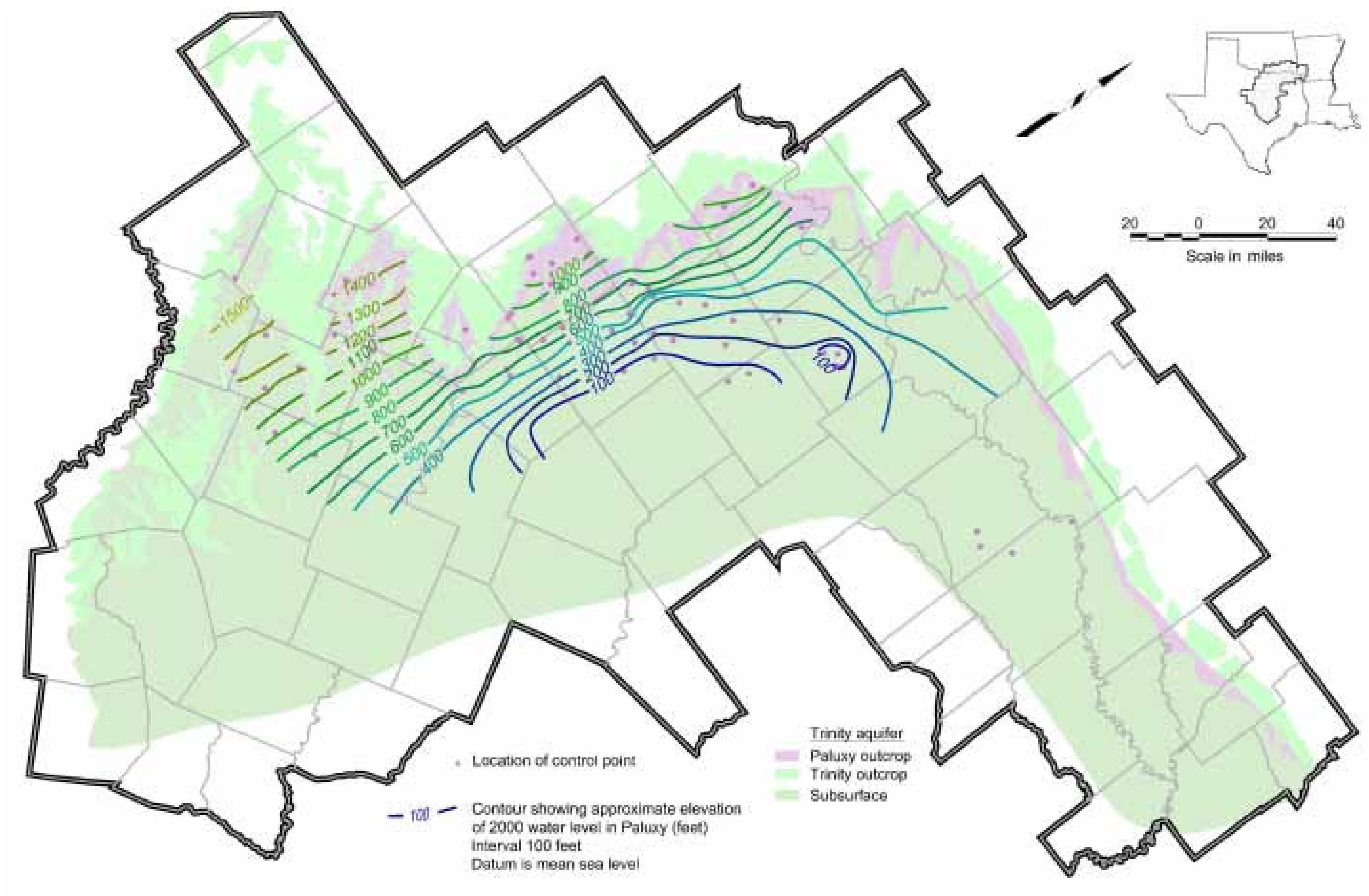



**Figure 4.34 Paluxy Water Level – 2000**

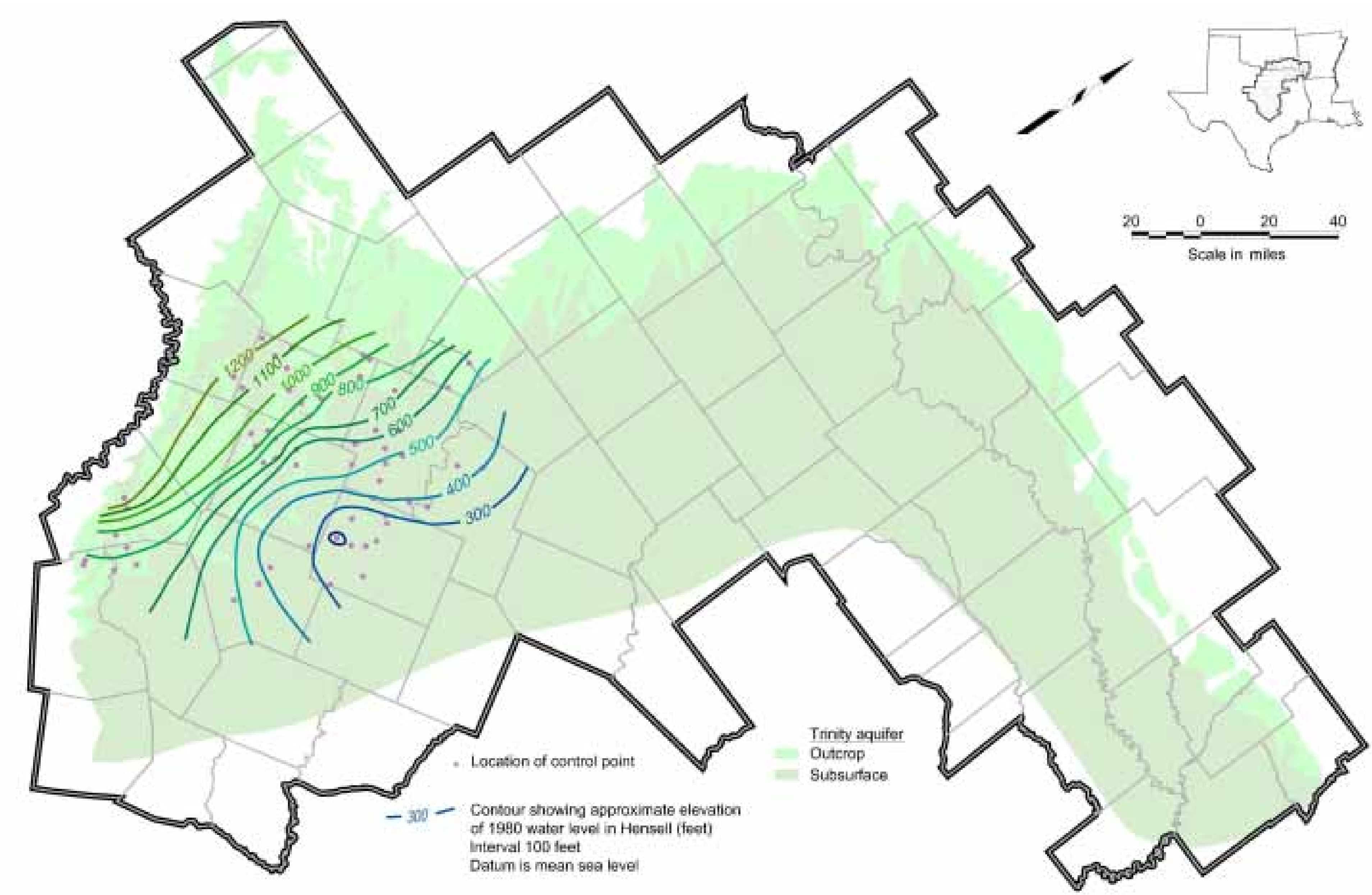



**Figure 4.35 Hensell Water Level – 1980**

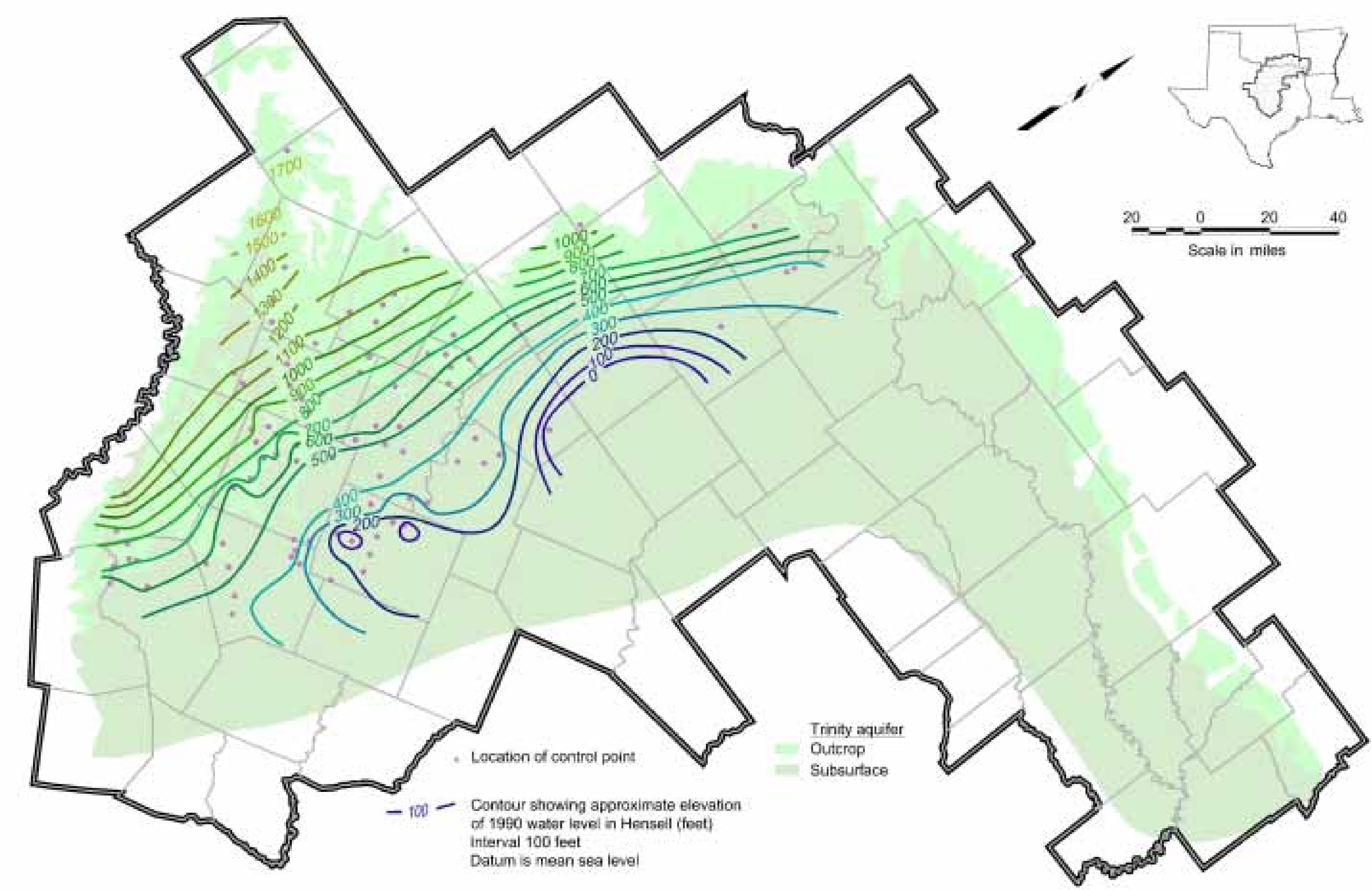



**Figure 4.36 Hensell Water Level – 1990**

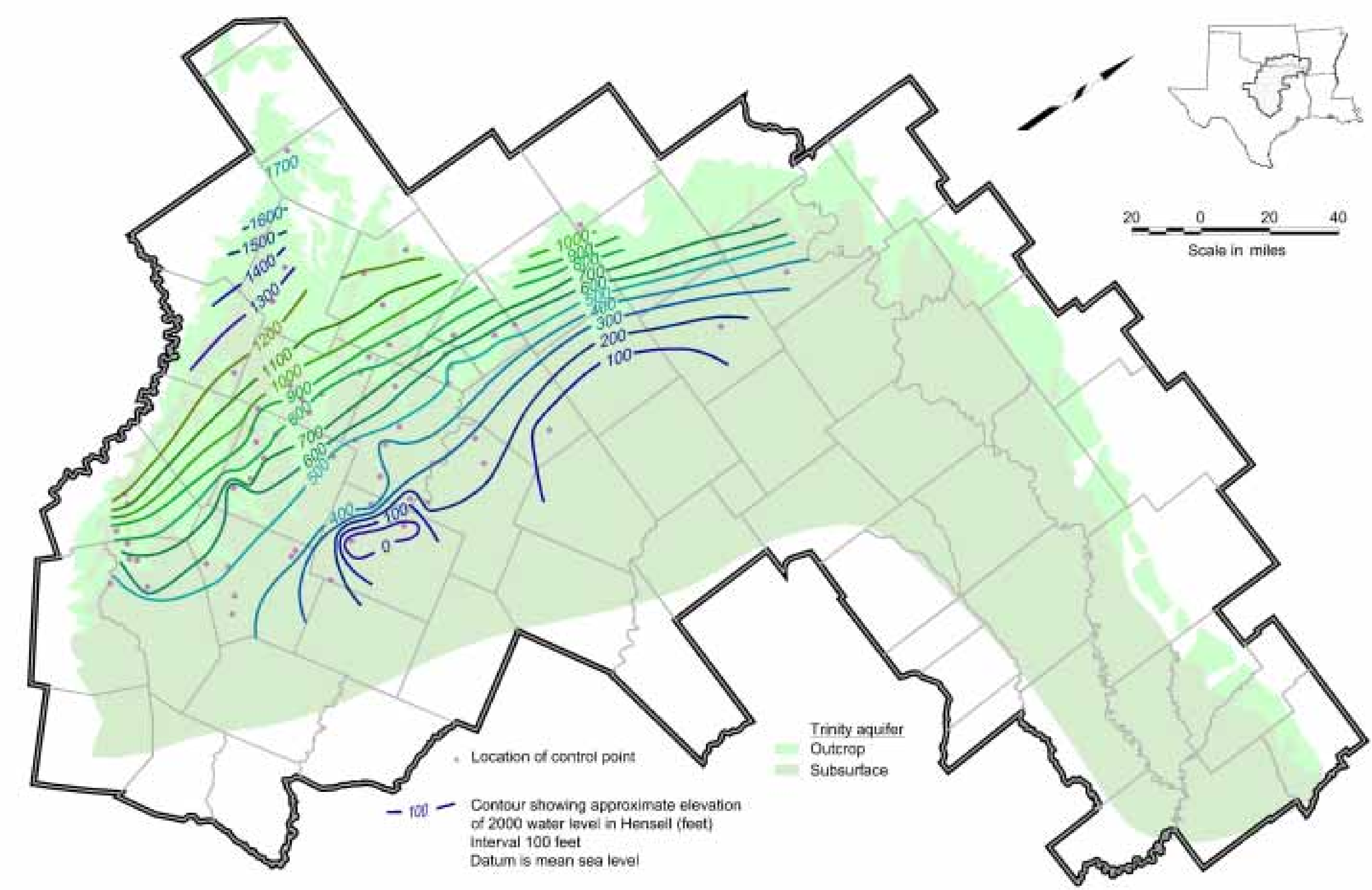



**Figure 4.37 Hensell Water Level – 2000**

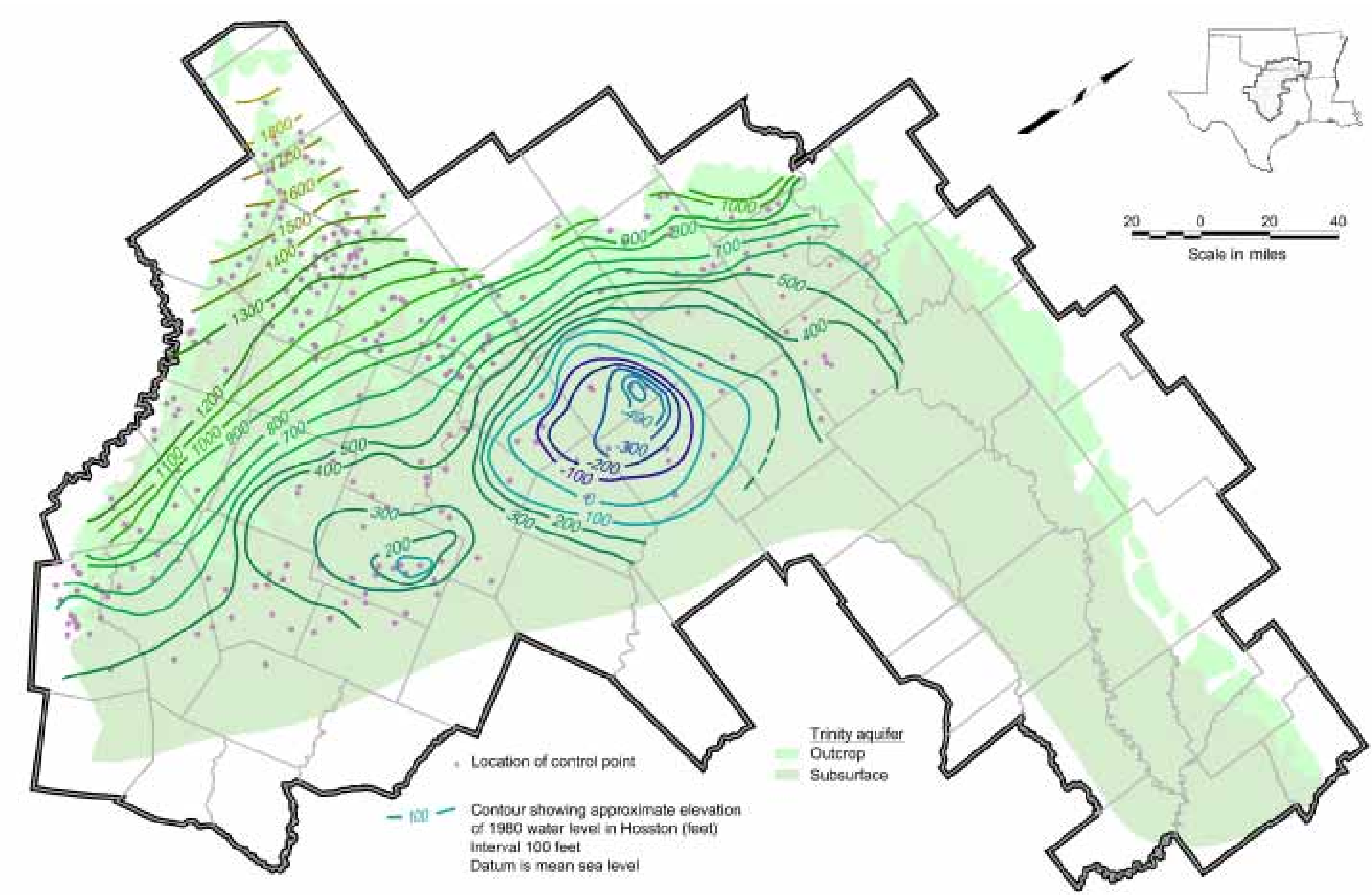



**Figure 4.38 Hosston/Trinity Water Level – 1980**

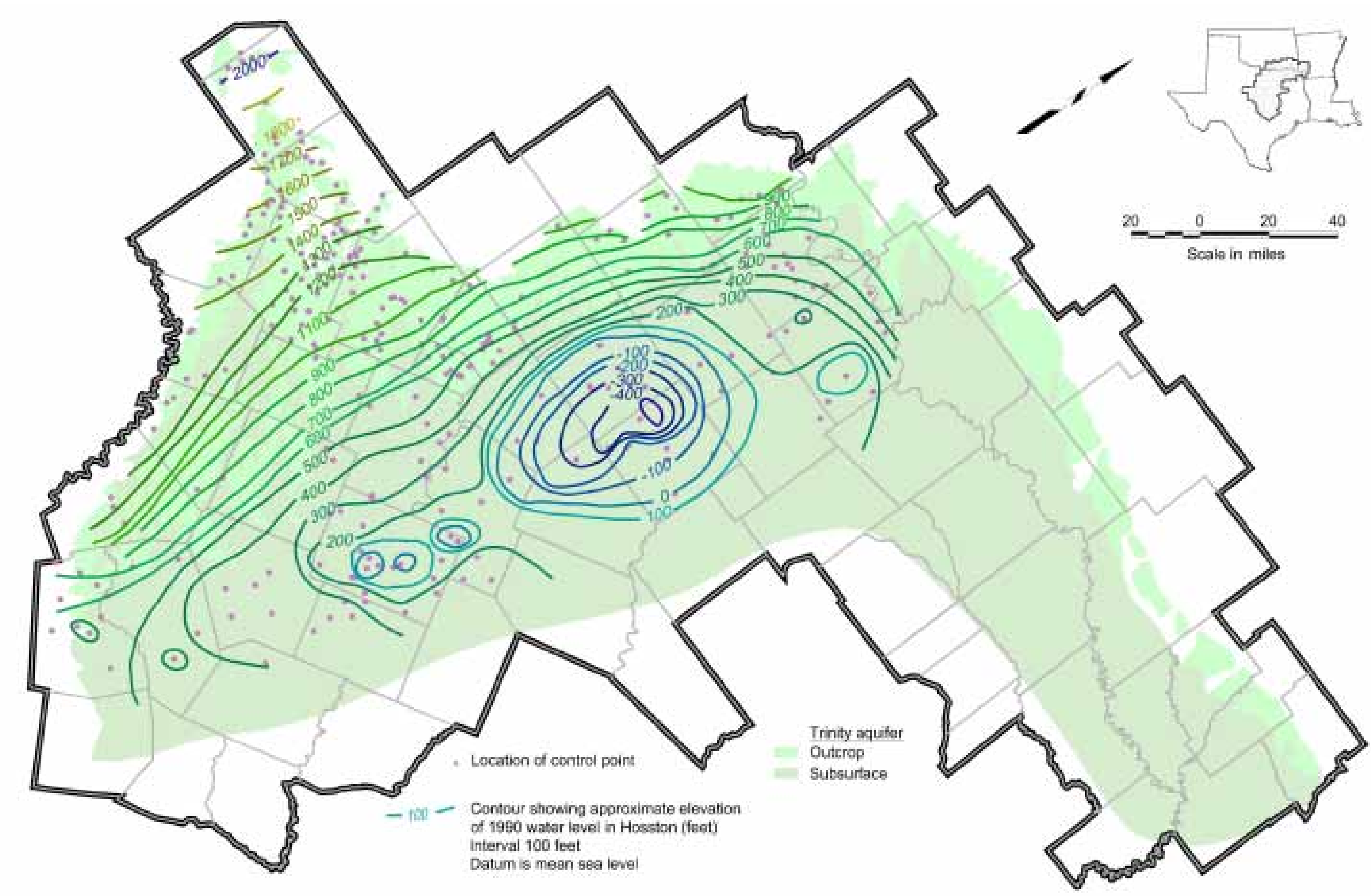



**Figure 4.39 Hosston/Trinity Water Level – 1990**

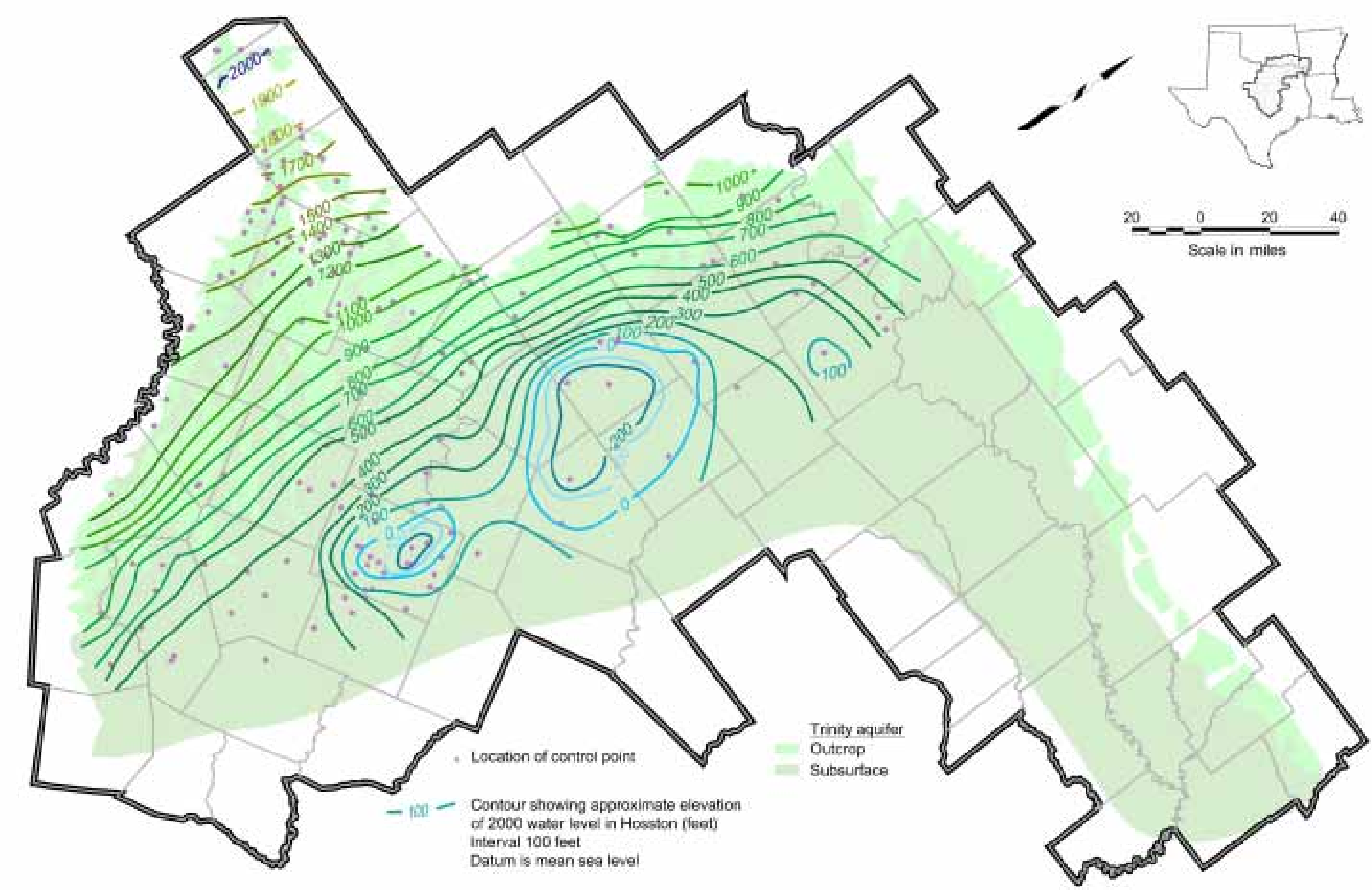



**Figure 4.40 Hosston/Trinity Water Level – 2000**

### 4.4.4 Regional Groundwater Flow

Regional groundwater flow discussions from Nordstrom (1982), Nordstrom (1987), Klemt et al. (1975) and numerous other publications were reviewed for the GAM project. In addition, potentiometric surface maps generated for this study were used to help evaluate groundwater flow patterns for the Trinity/Woodbine. Predevelopment flow patterns were difficult to define due to the lack of early water level data, and very little discussion of predevelopment water levels or groundwater flow patterns was found in the references reviewed. Conversely, the large quantity of water level data reported during the last 50 years allowed for a relatively detailed evaluation of recent groundwater flow patterns and trends.

Prior to groundwater development, water levels in the outcrop areas tended to mimic surface topography. Localized, unconfined groundwater flow occurred towards seeps, streams, rivers, and other drainages, which accounted for much of the groundwater movement and discharge in the outcrop areas. There was also a downdip, regional component of groundwater flow from the outcrop areas towards the artesian section of the aquifers. Once reaching the artesian portion of an aquifer, groundwater flow continues in a downdip direction, but with a significantly reduced hydraulic gradient. During predevelopment conditions, groundwater is believed to have migrated upwards through overlying strata. However, based on the low hydraulic gradients in the artesian portion of these aquifers and the relative impermeability of the overlying confining units, the rate of upward discharge from the artesian sections was likely small.

Groundwater flow in the study area was significantly altered by the development of these aquifers. In and near the fresh water (<1,000 mg/l TDS) portion of the aquifer, nearly all of the discharge from the artesian section of the aquifers is now to pumpage, and groundwater flow in the artesian portions of the aquifer is towards the pumping centers. As described above, hydraulic gradients in the artesian areas have increased significantly, especially near areas of more intense use. Water levels in the Woodbine and Paluxy are now higher than in the underlying Hensell and Hosston, indicating a downward direction of interformational leakage in and near the major pumping centers.

## 4.5 Recharge

Inflow to the Trinity and Woodbine aquifers occurs through the infiltration of precipitation in outcrop areas, interformational leakage, and through the interaction between surface-water bodies (streams, rivers, lakes) and the underlying aquifers. For the purposes of this GAM, recharge is defined as the infiltration of precipitation to the water table on the outcrop portions of the aquifers being modeled. The infiltration of water from surface water bodies and vertical leakage from adjacent hydrologic units are evaluated individually and described in later sections of this report.

Previous estimates of recharge rates to the Trinity aquifer were compiled by Scanlon et al. (2002), and are presented in Table 4.9. Scanlon noted that, in general, recharge to the Trinity was estimated to be between 0.1 and 2 inches per year (in/yr). However, previous estimates of recharge to the Trinity have varied widely, ranging anywhere from less than 0.1 inches per year to 6 inches per year (roughly equivalent to less than 1% to greater than 14% of annual average precipitation). This range probably reflects the uncertainty inherent in estimating recharge, the methodology used to make the estimates, and the variability in the hydraulic conductivity of the Trinity/Woodbine geologic materials. As noted in the table, a wide variety of methods was used to make these recharge estimates, with groundwater modeling as one of the more common techniques employed.

**Table 4.9 Previous Recharge Estimates for the Trinity Aquifer**

| Location | Recharge rate (in/yr) | Reference | Technique |
|---|---|---|---|
| ***Kendall*** | 1.3 | Ashworth, 1983 | Baseflow discharge |
| ***Hill Country*** | 1.5 (0.07 - 4.6) | Bluntzer, 1992 | Baseflow discharge |
| ***Northern Trinity*** | 4.4 | Dutton et al., 1996 | Groundwater modeling |
| ***Northern Trinity*** | 0.04 - 0.3 | Dutton et al., 1996 | Groundwater modeling |
| ***Northern Trinity*** | 1.2 | Klemt et al., 1975 | Assumed |
| ***Hill Country*** | 2.2 | Kuniansky and Holligan, 1994 | Groundwater modeling |
| ***Hill Country*** | 2.1 - 6.0 | Kuniansky, 1989 | Baseflow |
| ***Kendall*** | 2.2 | Mace et al., 2000 | Baseflow |
| ***Hill Country*** | 1.4 | Mace et al., 2000 | Groundwater modeling |
| ***Kendall*** | 1.5 | Reeves, 1967 | Baseflow |
| ***Kerr*** | 1 | Reeves, 1969 | Baseflow |

Source: Scanlon et al., 2002.

Previous estimates of recharge rates to the Woodbine aquifer were compiled from available references. Nordstrom (1982) estimates that less than one inch per year is recharged on the sandy portions of the Woodbine outcrop. No other original estimates of recharge for the Woodbine aquifer were identified in any of the reports reviewed.

### 4.5.1 Recharge Factors

Factors that influence the amount of precipitation that infiltrates and becomes recharge to an aquifer include:

- Precipitation
- Evapotranspiration
- Soil Type
- Soil Permeability
- Land Use
- Surface geology
- Topography

Each of these factors is evaluated and discussed below. The methodology that was ultimately used to estimate the potential recharge for input into the model is described at the end of this section.

***Precipitation*** - The rate and volume of precipitation that falls onto outcrop areas exerts a strong influence on the amount of recharge that ultimately reaches the saturated portion of an aquifer. Because the study area incorporates a relatively large portion of Texas, average annual rainfall varies significantly over the study area. In western portions of the model, precipitation averages approximately 30 inches per year, while about 50 inches per year falls in eastern portions of the study area. Figures 2.10 and 2.11 illustrate the distribution of precipitation within the study area.

***Evapotranspiration*** – The term evapotranspiration (ET) is used to describe the vaporization of soil moisture or groundwater through the combined effects of transpiration by plants and evaporation. In areas where the water table lies at depth, precipitation must infiltrate and percolate through the unsaturated zone (vadose zone) to the water table. Evapotranspiration of infiltrated water, before transfer to the saturated zone is completed, can remove a large percentage of the volume of potential recharge to Trinity/Woodbine aquifers. Evaporation rates within the study area vary considerably and are shown in Figure 2.8. In far western portions of the study area, the reported rate of gross lake evaporation is about 60 inches per year, while approximately 40 inches per year are reported in the northeastern section of the study area.

***Soil Type*** – A soil type map was constructed from the USGS STATSGO map of Texas, and is shown in Figure 4.41. The soil type, specifically the hydrologic soil group, was analyzed for the purposes of this investigation. The hydrologic soil group is a group of soils having similar runoff potential under similar storm and cover conditions. The soils in the United States have been divided up into four groups, A, B, C, and D, and three dual classes, A/D, B/D, and C/D.

Figure 4.41 shows the hydrologic groups of soils represented as A, B, C, and D. Soils classified as “Group A” generally consist of deep, well-drained sands or gravels. “Group A” soils also have a comparatively high rate of water transmission and a low runoff potential. These soils are found along rivers in the northern portion of the study area.

Soils classified as “Group B” are commonly moderate to deep, fairly well drained soils that have moderately fine to moderately coarse textures. When thoroughly wetted, these soils have a comparatively moderate infiltration rate, and a moderate rate of water transmission. These soils are located mostly within the central and western portions of the study area, but can be found throughout the entire area.

“Group C” soils generally possess a layer that hinders downward movement of water or exhibit fine to moderately fine texture. These soils have a slow infiltration rate when thoroughly wetted and have a slow rate of water transmission. “Group C” soils are found throughout the study area and comprise a large percentage of the soil overlying the Woodbine outcrop in Texas.

Soils of “Group D” consist predominantly of clay soils that have a high swelling potential, a clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow infiltration rate when thoroughly wetted, and have a very slow rate of water transmission and high runoff potential. “Group D” soils make up a large percentage of the soils overlying the Trinity outcrop.

***Soil Permeability*** – Soil permeability affects the rate of infiltration and downward percolation of water through the vadose zone. The permeabilities of the soils in the study area were estimated based on the USGS STATSGO maps of the study area, and are shown in Figure 4.42. Soils in the model area overlying the aquifer range in permeability from essentially zero to greater than 300 inches per hour (in/hr). As illustrated in Figure 4.42, much of the Trinity outcrop is overlain by soils characterized by permeabilities of 2 to 50 in/hr. The permeability of soils overlying the Woodbine outcrop is generally greater than 10 in/hr; however, some zones in the northern portion of the study area exhibit much smaller rates of infiltration.

***Land Use*** – Characterization of land use in the study area may aid in the evaluation of the recharge potential of Trinity/Woodbine outcrop areas. The land use in the study area was categorized into nine types, including:

- Herbaceous Planted
- Herbaceous Upland
- Non-natural Woody
- Forested Upland
- Shrubland
- Developed
- Barren
- Water
- Wetlands

The distribution of these land use types in the study area is shown in Figure 4.43. As illustrated, the “Herbaceous Planted”, “Forested Upland”, and “Schrubland” types constitute the majority of the categorized land uses. Land characterized as “Herbaceous Planted” comprises much of the north and northeast portions of the study area. A large percentage of the northwest and central portions of the study area are categorized as “Non-natural Woody” land use. The land use in the south is predominantly a mix between “Shrubland” and “Forested Upland”. A large amount of “Herbaceous Planted” is also observed just south of the “Forested Upland” in the south. The land use categorized as “Developed” is generally concentrated around the major urban areas in the study area, chiefly the Austin, Waco, and Dallas-Fort Worth regions.

***Surface Geology*** – The surface geology of outcrop zones may also play a role in determining the recharge capacity for a particular area. The geology of the hydrostratigraphic units included in this study is described in Section 2.2. A map of the surface geology was also included in that section (Figure 2.13). In general, sand-rich sediments in outcrop areas will transmit soil moisture to the water table at a faster rate than clay or carbonate (non-karstic) rich sediments.

***Topography*** – The topography of outcrop areas affects the ratio of precipitation to runoff, which in turn can influence groundwater recharge. As illustrated in Figure 2.7, ground level elevations range from about 2,200 feet above mean sea level in the far-western areas to approximately 300 feet above mean sea level in the eastern sections of the study area.

### 4.5.2 Recharge Estimates

The amount of recharge to an aquifer is not static through time. Rather, recharge rates vary in response to changes in the hydraulic stresses imposed by boundary conditions (e.g. surface/groundwater interaction, evapotranspiration, precipitation rates, interformational leakage etc.) or by fluctuations in the hydraulic gradient imposed on the system by pumpage. The assessment of recharge is further complicated because the rate of infiltration is highly dependent on local variations in the structure and properties of an aquifer and the overlying sediments. For these reasons, the determination of a single recharge rate that applies in all situations is not possible. Instead, a qualitative approach to the estimation of recharge was pursued during the construction of the GAM. This approach entailed the identification of parameters that likely affect recharge rates and assembling a set of factors that would reasonably distribute potential recharge throughout the model area given yearly variations in precipitation.

Recharge to the Trinity/Woodbine occurs primarily in outcrop zones through percolation of precipitation through an intermediate soil zone to the underlying aquifer sediments. Because precipitation is the source of recharge, the first step in the development of initial recharge estimates for input into the model was the compilation of maps depicting average yearly precipitation over Trinity/Woodbine outcrop.

Much of the total precipitation that falls onto outcrop areas is lost to overland flow (runoff) or is intercepted by evapotranspiration before reaching the buried aquifer sediments. The rate and amount of runoff and evapotranspiration is influenced by the properties of the intermediate soil zone. In order to incorporate estimates of these properties in the generation of recharge estimates, soil permeability and land use recharge factors were prepared for this project. Soil permeability data (STATSGO) were compiled into a coverage encompassing the Trinity/Woodbine outcrop zone. Review of the STATSGO information revealed a high degree of variability in the reported soil permeability rates, with values ranging from less than 0.1 inches per hour (in/hr) to more than 300 in/hr within the study area. These data were modified such that areas with extremely high or low permeability were reduced or increased so that their application as a recharge estimation factor did not overly skew the results in those extreme areas. This was accomplished by adding 300 (the greatest approximate permeability with comprising a significant percentage of the overall data) and taking the base-10 logarithm of the resulting surface. Once smoothed in this manner, each point in the surface was then divided by 10 times the greatest single-point value (32.2) in order to obtain the final soil permeability factors.

Land use maps created by USGS (LULC 250K) were acquired, and from these recharge factors were estimated that correspond with the various land use types. The estimates are based primarily upon hydrogeologic interpretation of the average soil conditions and plant types that are likely present in each of the general categories listed (Table 4.10).

**Table 4.10 Estimated Land Use Recharge Factors**

| LULC Description | Estimated Recharge Factor |
|---|---|
| ***Barren*** | 1 |
| ***Developed*** | 0.3 |
| ***Forested Upland*** | 0.7 |
| ***Herbaceous Planted*** | 0.6 |
| ***Herbaceous Upland*** | 0.8 |
| ***Non-natural Woody*** | 0.8 |
| ***Shrubland*** | 0.6 |
| ***Water*** | 0.4 |
| ***Wetlands*** | 0.8 |

Consideration was also given to the lithology and characteristics of the underlying aquifer sediments. In general, sandy, more permeable sediments will accept more recharge at a faster rate than less permeable carbonate (non-karstic) or clay-rich sediments. Application of this concept to the model involved assigning a layer factor of 100 percent to aquifer layers, while a layer factor of 75 percent was applied to confining layers. Figures 4.44 and 4.45 show the distribution of the assumed soil permeability and land use factors that were used to generate recharge inputs for the model.

Once the distributed recharge factors described above were compiled, model recharge inputs were generated through multiplication of precipitation data by each of the factors. The recharge inputs were calculated spatially with the following formula:

*Annual recharge rate = (land use factor)(layer factor)(permeability factor)(annual rainfall)*

Figure 4.46 shows the estimate of the rate of potential recharge across the study area. For the outcrop area within Texas and near the major users, the average recharge rate input into the model is about 1.4 inches per year with the majority of area less than 1 inch per year.

### 4.5.3 <u>Rejected Recharge</u>

In 1940, C.V. Theis discussed several observations on the nature of aquifers and the changes pumping wells impart on the system as a whole. These observations, although straightforward, are often overlooked during evaluations of groundwater availability.

C.V. Theis concluded that:

1) On average, the rate of discharge from an aquifer before the construction of wells was equal to the rate of recharge. In other words, aquifers exist in a state of "dynamic equilibrium" prior to development by man.
2) Pumpage by wells represents a new mode of discharge that is superimposed on a previously stable system.
3) The new discharge to wells must be balanced by a decrease in aquifer storage, a decrease in natural discharge, an increase in recharge, or a combination of these.

In predevelopment times, input to an aquifer equals the output from an aquifer. Prior to development, the Trinity/Woodbine was effectively confined by thick, relatively impermeable sediments, and far downdip flow was restricted by structural features. Because of this, natural discharge in artesian zones was small; therefore, downdip flow through the aquifers was small. As a result, little recharge was accepted in outcrop zones and transmitted to downdip artesian areas. Instead, much of the water recharged to the Trinity/Woodbine was discharged to surface water features and/or evapotranspiration soon after reaching the water table.

The construction of wells in the Trinity/Woodbine introduced a new avenue of discharge to the previously stable system. Conservation of mass within the system dictates that water discharged from the aquifer must be balanced by some other source. Therefore, one or more of the following must occur as the aquifer responds to this new discharge; 1) natural discharge must be reduced, 2) net recharge flux into the aquifer must be increased, or 3) the amount of water in storage in the aquifer must decline. While this is fundamentally correct, the delay in the reaction of the system to the new stress is also important. In order to create drawdown in groundwater levels in any system, the water in storage must be reduced to some degree. Head levels are immediately lowered in the area of the aquifer penetrated by a discharging well. This drop in head represents a decline in aquifer storage that becomes less pronounced with distance, creating a cone of depression in water levels centered at the well. Over time, this cone expands to intersect areas where natural flux into or out of the aquifer occurs. A decline in aquifer water levels in natural discharge areas will reduce the rate of discharge in these areas. In addition, a reduction in aquifer head in discharge areas will redirect towards wells that was previously "rejected" (discharged by other mechanisms) from the system. With a sufficient magnitude of well pumpage, and given enough time for the associated cone(s) of depression to develop, natural discharge from the system will be reduced, while available recharge to the aquifer will be captured by wells.

C.V. Theis' observations are important because they remind us that recharge available for use by wells in an aquifer is constantly changing with applied pumpage. When water levels are high throughout an aquifer system, there is little drive for new water to be accepted and retained in the aquifer, and therefore recharge available for use by wells is low. The introduction of pumpage creates water level declines (drawdown) providing additional storage space for recharge. These declines redirect aquifer discharge towards areas of pumpage, increasing the amount of water that can be produced by wells over the long term. As long as there is a reserve of available but previously uncaptured water, more recharge can be accepted, retained, and directed towards wells following the initiation of pumpage then was possible under previous development conditions.

The simulation of these processes in the model is accomplished through the implementation of the Evapotranspiration (ET), Recharge, Streamflow-Routing, and River (used to simulate lakes in this model) packages. The application of the River and Streamflow-Routing packages allows groundwater to enter or exit the model domain depending on the relationship between heads calculated during simulation, and the input stream/reservoir stage. As head levels rise near the surface in the outcrop, the ET Package will abstract an increasing amount of water from the model. Conversely, when water levels drop, groundwater lost through evapotranspiration will decrease to zero as the extinction depth is reached. In this way, recharge is rejected when head levels are near ground surface, and because maximum potential ET rates are much greater than recharge rates, outcrop cells are prohibited from achieving inappropriate artesian conditions. The actual amount of water entering the system (recharge, leakage, induced recharge) can then be calculated through analysis of the cell-by-cell flow terms output by the model.

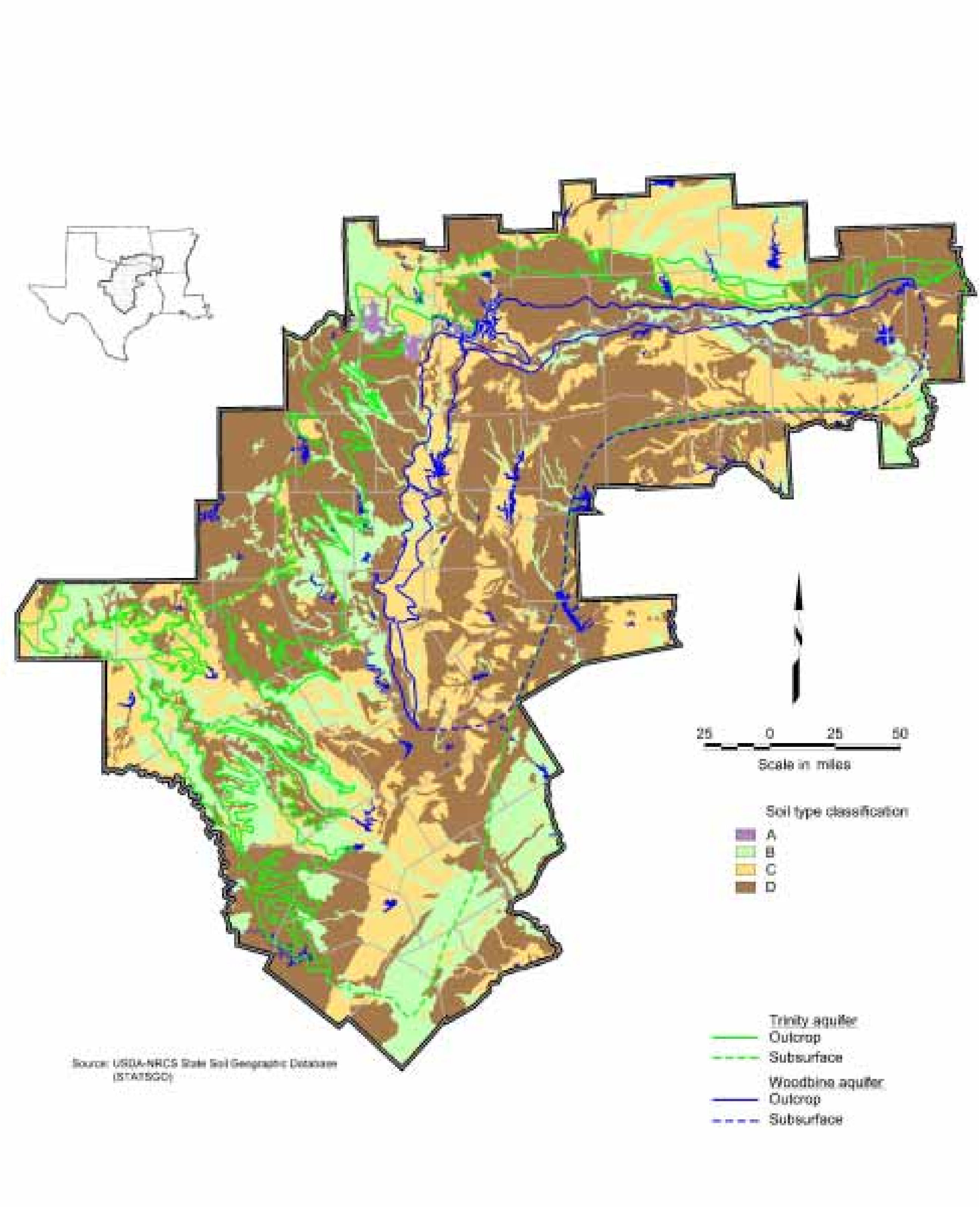



**Figure 4.41 Soil Type**

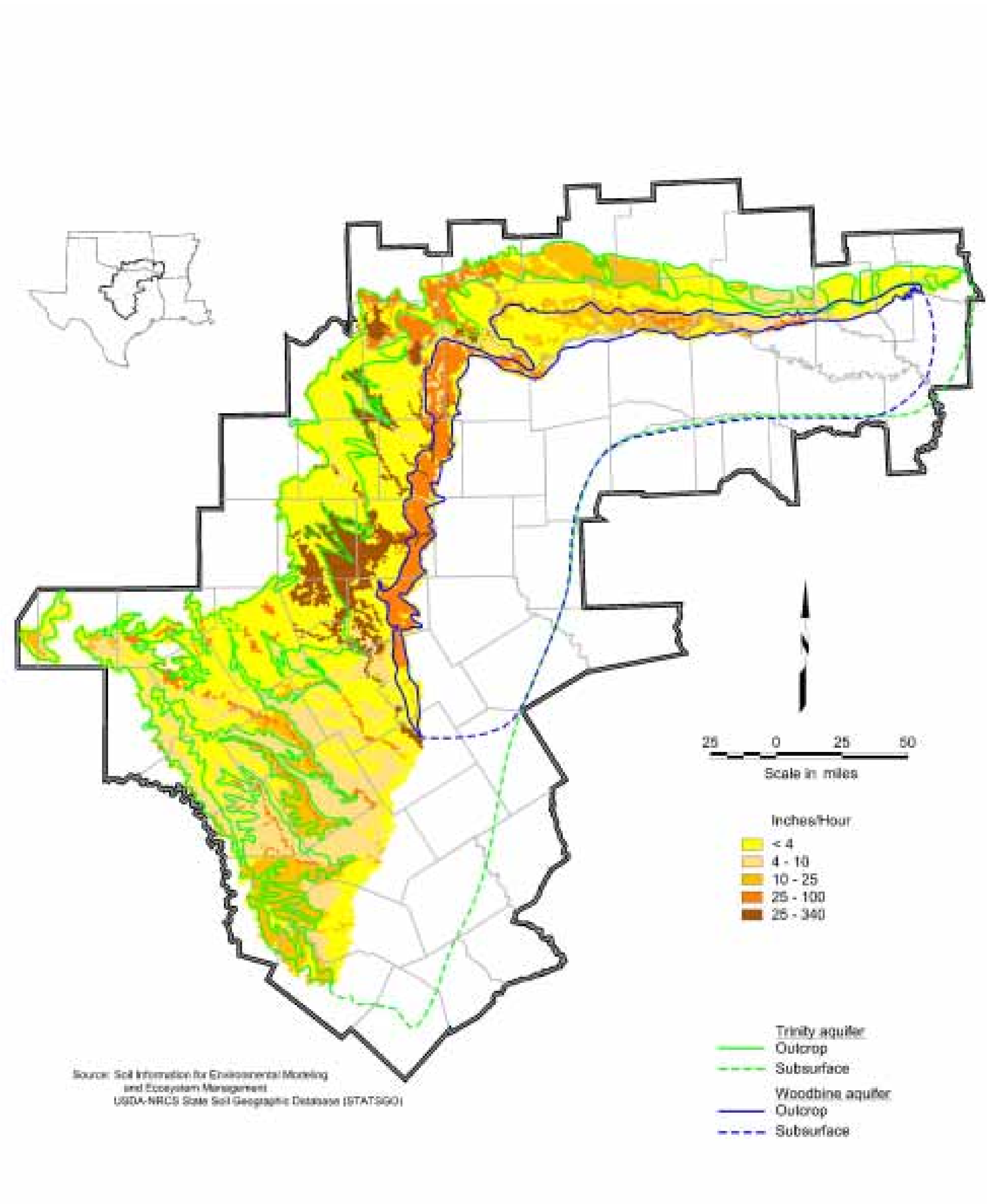



**Figure 4.42 Soil Permeability**

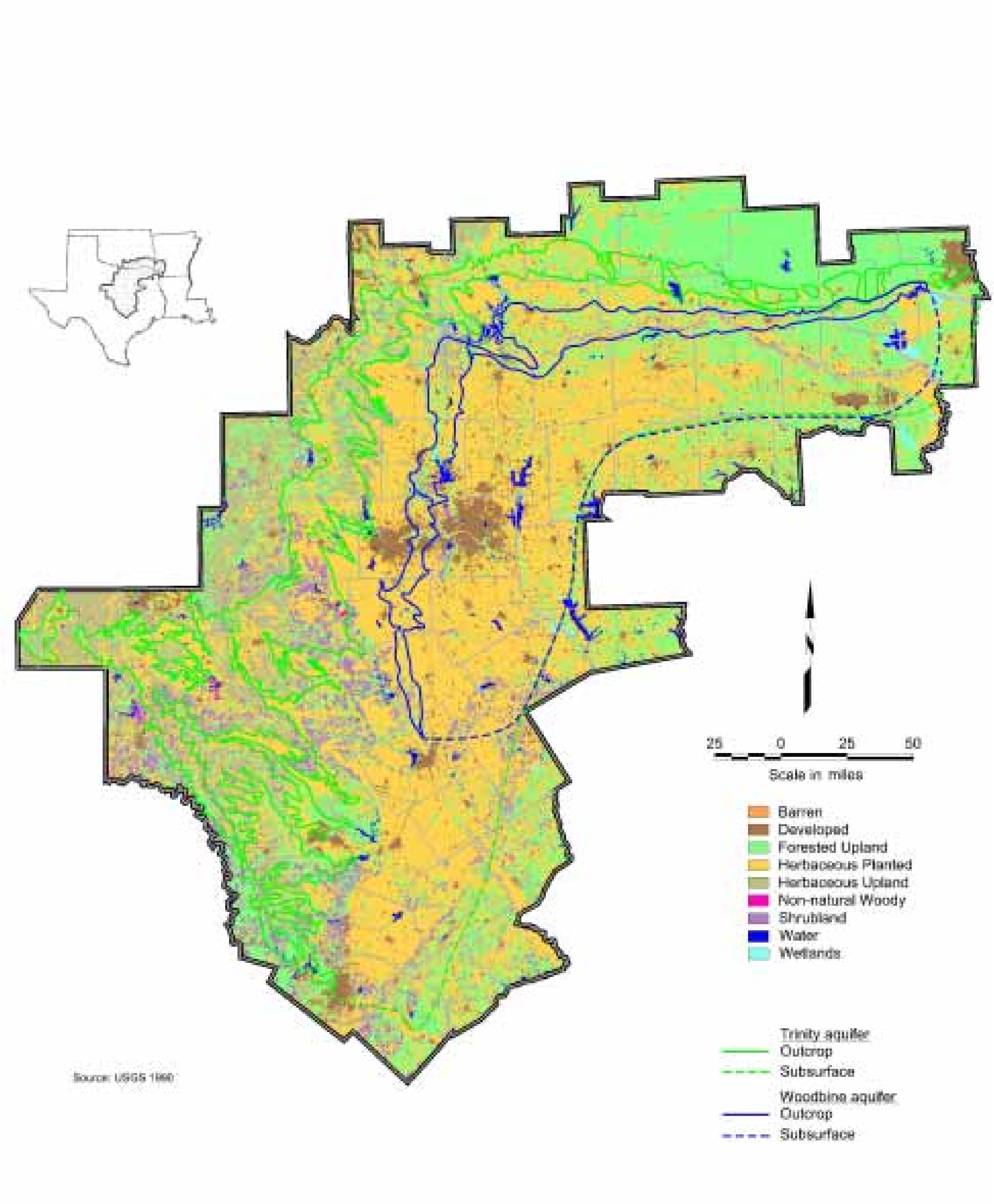



**Figure 4.43 Land Use**

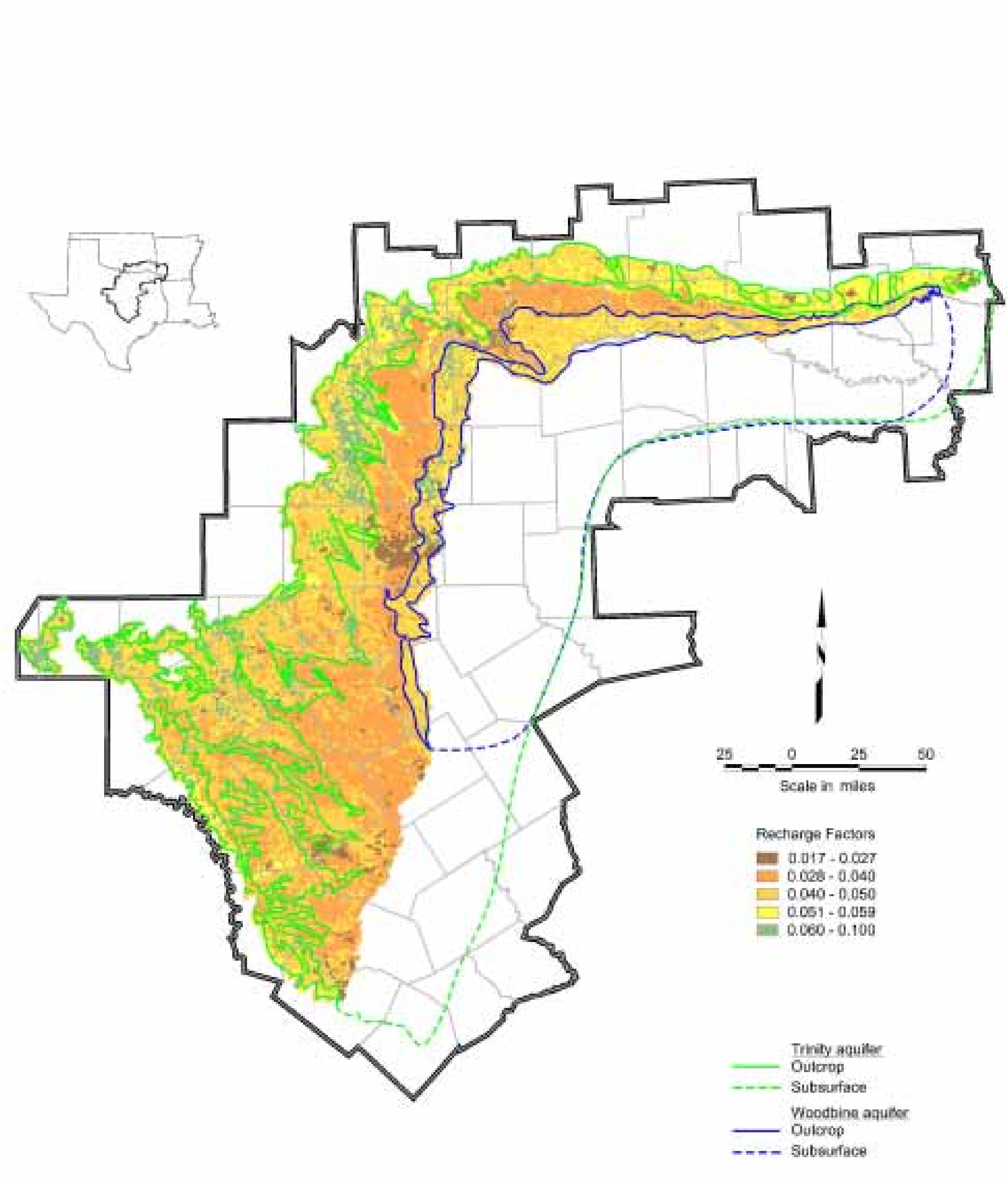



**Figure 4.44 Soil Permeability Recharge Factor**

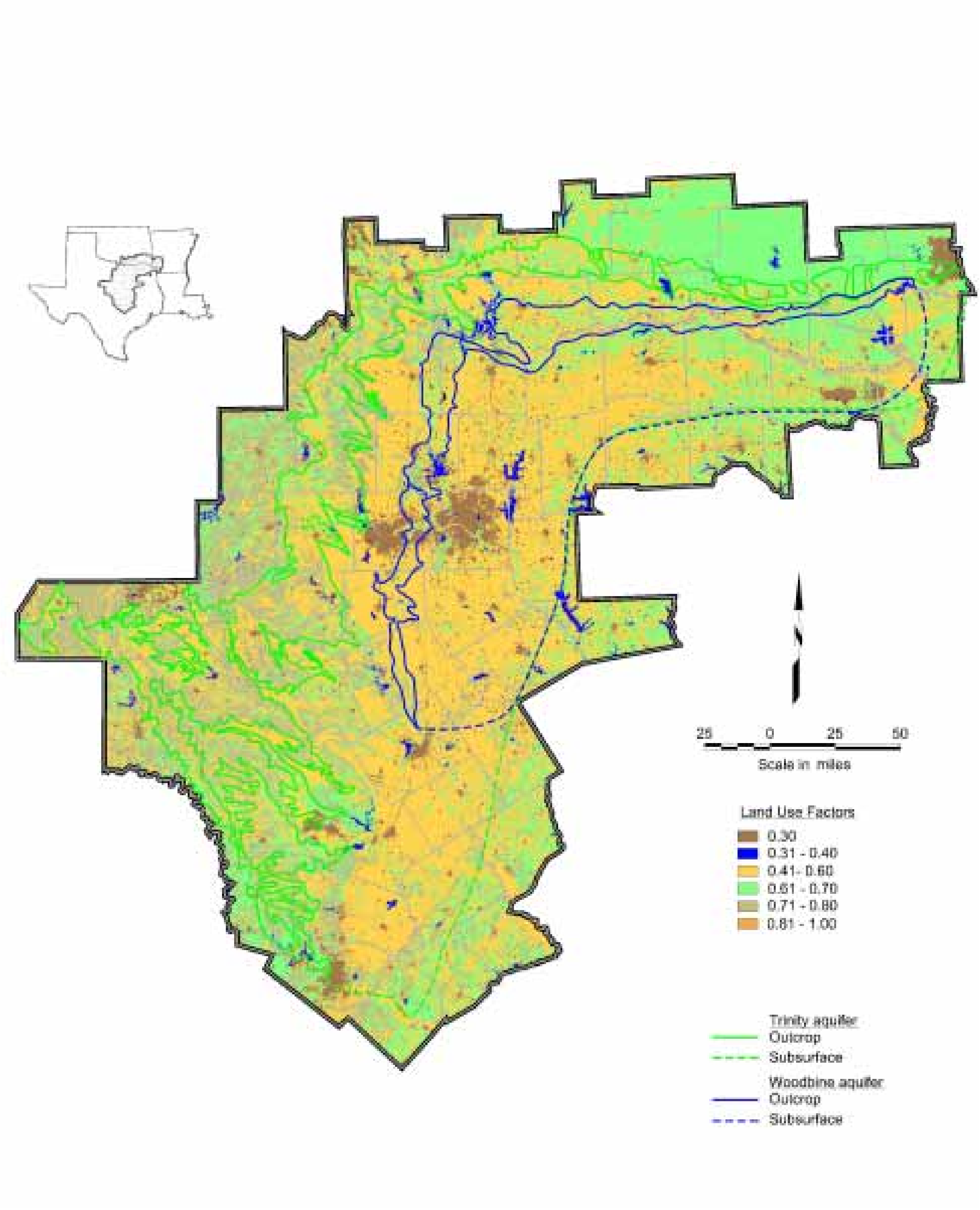



**Figure 4.45 Land Use Recharge Factor**

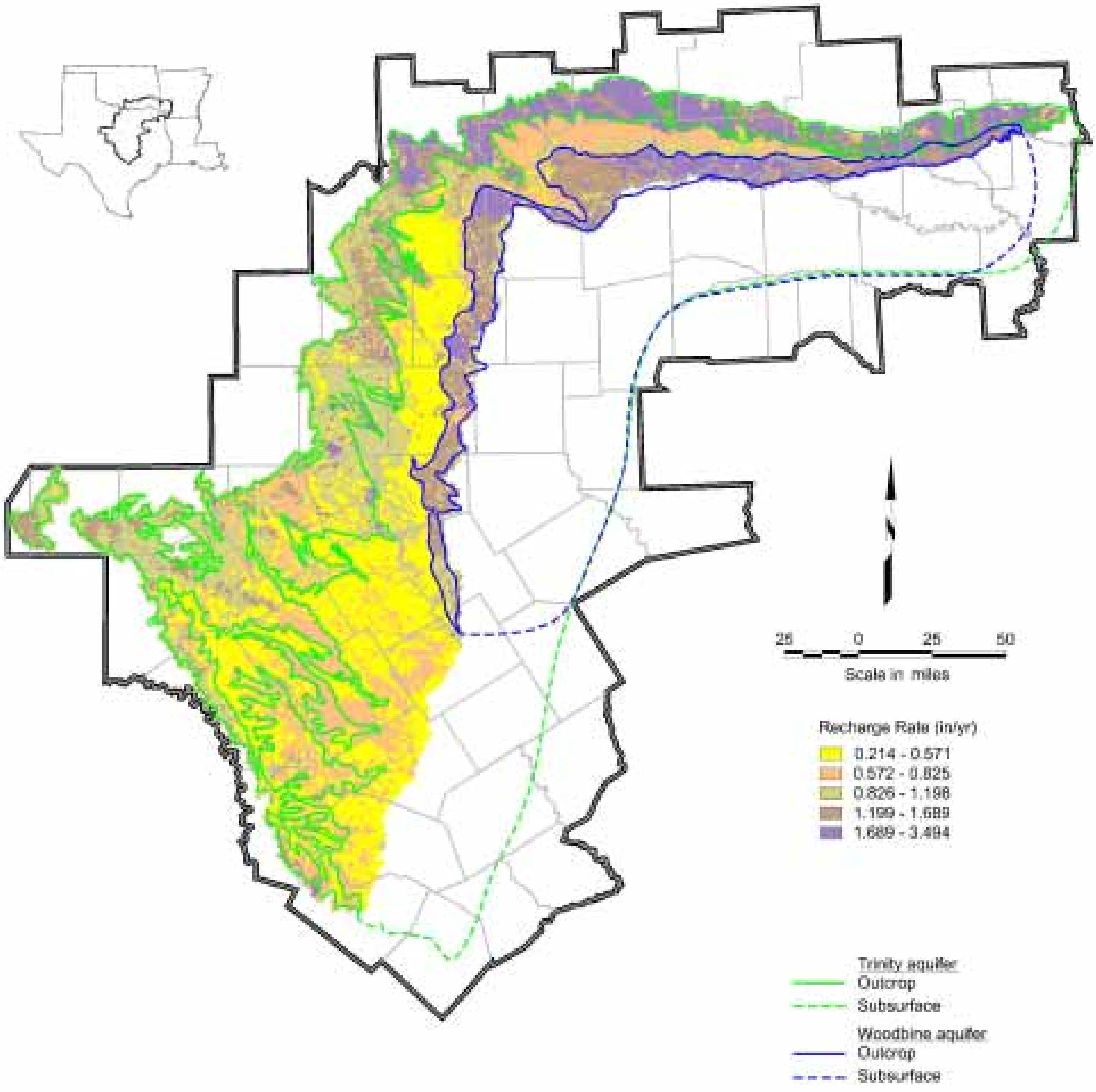



**Figure 4.46 Estimated Potential Recharge Rate**

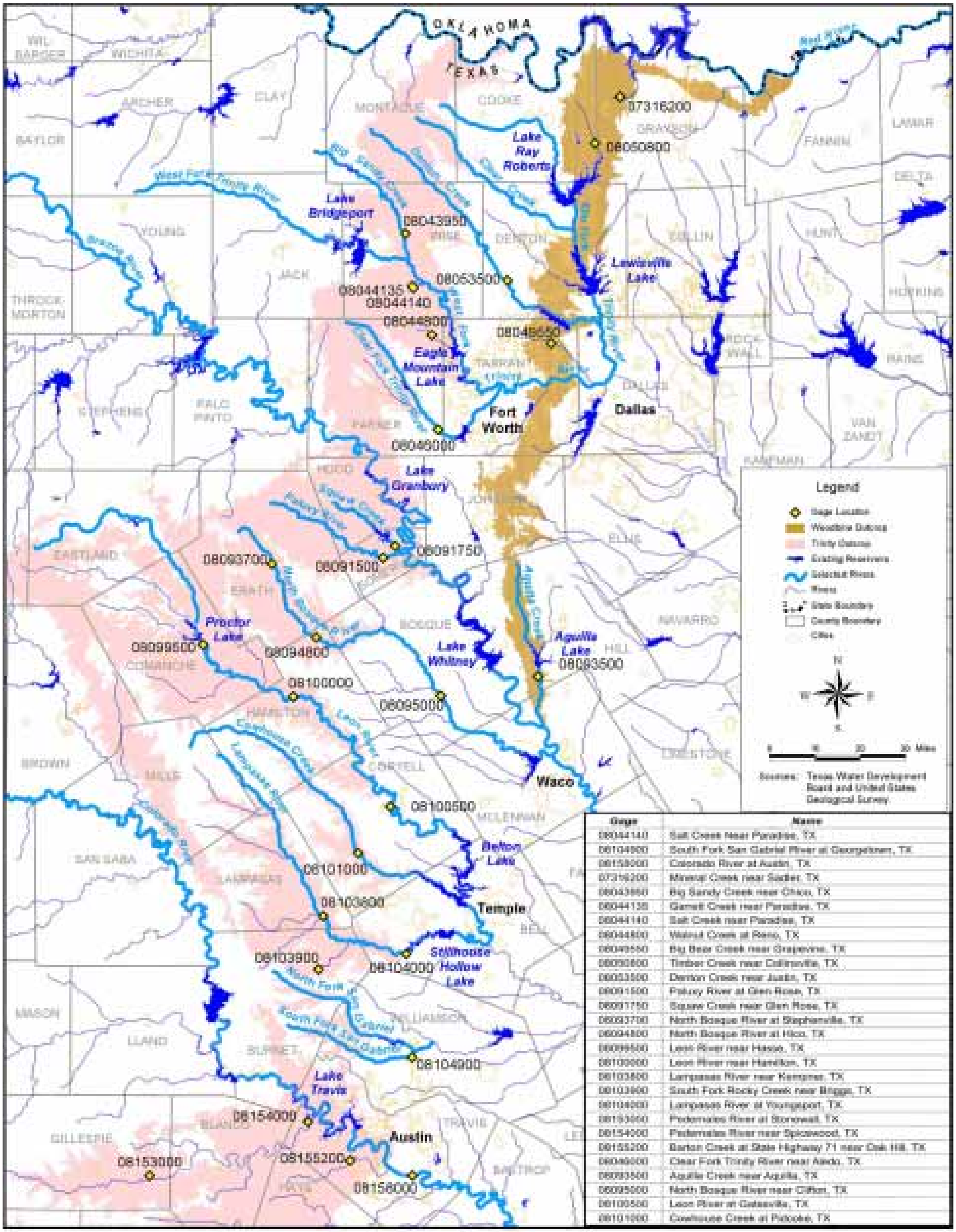
## 4.6 Interaction of Surface Water and Groundwater

Groundwater in the Trinity/Woodbine is in hydraulic communication with surface water when the water table in the outcrop meets surface water systems. Surface water/groundwater interactions represent a small but significant portion of the water budget of an aquifer system. These interactions occur primarily at springs, streams, rivers, and surface water reservoirs.

The Trinity/Woodbine can directly gain water from, or lose water to, surface water bodies in the outcrop area. When the water table is above the streambed or water surface the stream receives water from the aquifer and is called a gaining reach (i.e., it gains flow from groundwater discharge as it moves through the reach.) When the water table is below the streambed or water surface the stream is losing water to the aquifer, and is called a losing reach. These concepts will be applied and discussed below in Section 4.6.2. Table 4.11 lists the major rivers and streams that are located in the study area, which are represented in the GAM using MODFLOW's stream package. Figure 4.47 shows the location of the rivers and streams and gages within the study area.

**Table 4.11 Rivers/Streams within the Study Area**

| Major Stream | Average Flow into Trinity Outcrop Zone | Gage Number | Comment |
|---|---|---|---|
| ***Red River*** | 2,252 cfs | | Between 07315500 & 07316000 |
| ***Elm Fork Trinity*** | 0 | | |
| ***Clear Creek*** | 0 | | |
| ***Denton Creek*** | 0 | | |
| ***Big Sandy Creek*** | - | | Lake Amon Carter Upstream |
| ***West Fork Trinity*** | 153 cfs | 08043500 | |
| ***Clear Fork Trinity*** | 0 | | |
| ***Brazos River*** | 1,060 cfs | 08090800 | |
| ***Squaw Creek*** | 0 | | |
| ***Paluxy River*** | 0 | | |
| ***Bosque River*** | 0 | | |
| ***Leon River*** | 58 cfs | 08099100 | |
| ***Cowhouse Creek*** | 0 | | |
| ***Lampasas River*** | 0 | | |
| ***N/S San Gabriel*** | 0 | | |
| ***Colorado River*** | - | | Enters outcrop at Lake Travis |
| ***Aquilla Creek*** | 0 | | |




| Gage | Name |
|---|---|
| 08044140 | Salt Creek Near Paradise, TX |
| 08104900 | South Fork San Gabriel River at Georgetown, TX |
| 08158000 | Colorado River at Austin, TX |
| 07316200 | Mineral Creek near Sadler, TX |
| 08043950 | Big Sandy Creek near Chico, TX |
| 08044135 | Garrett Creek near Paradise, TX |
| 08044140 | Salt Creek near Paradise, TX |
| 08044800 | Walnut Creek at Reno, TX |
| 08049550 | Big Bear Creek near Grapevine, TX |
| 08050800 | Timber Creek near Collinsville, TX |
| 08053500 | Denton Creek near Justin, TX |
| 08091500 | Paluxy River at Glen Rose, TX |
| 08091750 | Squaw Creek near Glen Rose, TX |
| 08093700 | North Bosque River at Stephenville, TX |
| 08094800 | North Bosque River at Hico, TX |
| 08099500 | Leon River near Hasse, TX |
| 08100000 | Leon River near Hamilton, TX |
| 08103800 | Lampasas River near Kempner, TX |
| 08103900 | South Fork Rocky Creek near Briggs, TX |
| 08104000 | Lampasas River at Youngsport, TX |
| 08153500 | Pedernales River at Stonewall, TX |
| 08154000 | Pedernales River near Spicewood, TX |
| 08155200 | Barton Creek at State Highway 71 near Oak Hill, TX |
| 08046000 | Clear Fork Trinity River near Aledo, TX |
| 08093500 | Aquilla Creek near Aquilla, TX |
| 08095000 | North Bosque River near Clifton, TX |
| 08100500 | Leon River at Gatesville, TX |
| 08101000 | Cowhouse Creek at Pidcoke, TX |

**Figure 4.47 River, Reservoir, and Gage Locations**

### 4.6.1 Springs

When the water table is above land surface, usually in topographically low areas, the aquifer may discharge water through springs and seeps. The volume and rate of the discharge is dependent upon the local evapotranspiration demand and the site-specific hydraulics of the system. A literature review was performed for contributing springs from the Trinity/Woodbine aquifer system. Spring locations and flow rate data were compiled from the TWDB groundwater database, USGS records, and spring descriptions published by Brune 2002. The locations of the springs and the 25 springs with the largest flow were selected and evaluated. The flow from individual springs was relatively low, most under 10 cfs. It was judged that spring flows of this magnitude did not warrant individual representation in a regional groundwater model. Therefore, discharge to springs and seeps is conceptually lumped with evapotranspiration, and represented using the Evapotranspiration Package included with MODFLOW. Further discussion of spring/seep discharge is included in Section 4.9.

### 4.6.2 Low Flow Studies

Slade et al. (2002) compiled the results of channel gain and loss investigations of 249 Texas stream reaches. The majority of these investigations involved obtaining stream flow measurements at various locations along a stream within a short period of time, when flows were low and no significant surface runoff was occurring in the study reach. The locations of the measurement stations were verified where sufficient data existed. For other stations, the locations were inferred by field survey comments. Based on USGS gage coordinates and TWDB maps of the Trinity outcrop, the locations of gage stations with respect to the Trinity outcrop were identified.

Records were reviewed for all low-flow studies along the Trinity and Woodbine outcrops north of the Colorado River and south of the Red River. There were no low flow studies reported within the Woodbine outcrop, for the Trinity River Basin, or Trinity outcrop reaches north of the Leon River. There were 12 low-flow studies that were documented for four reaches in the study area: Lampasas, Leon, San Gabriel (North/South Fork), and Colorado River. The locations and results of these studies, all of which cross some portion of the Trinity outcrop, are presented in Figure 4.48.

Results of these low-flow studies reveal that, for most, stream flow increased in the downstream direction across the Trinity outcrop, indicating gaining conditions for the subject reaches. The most notable gains were for the North Fork San Gabriel (February 1979), South Fork San Gabriel (February 1979), and Colorado River (April 1925).

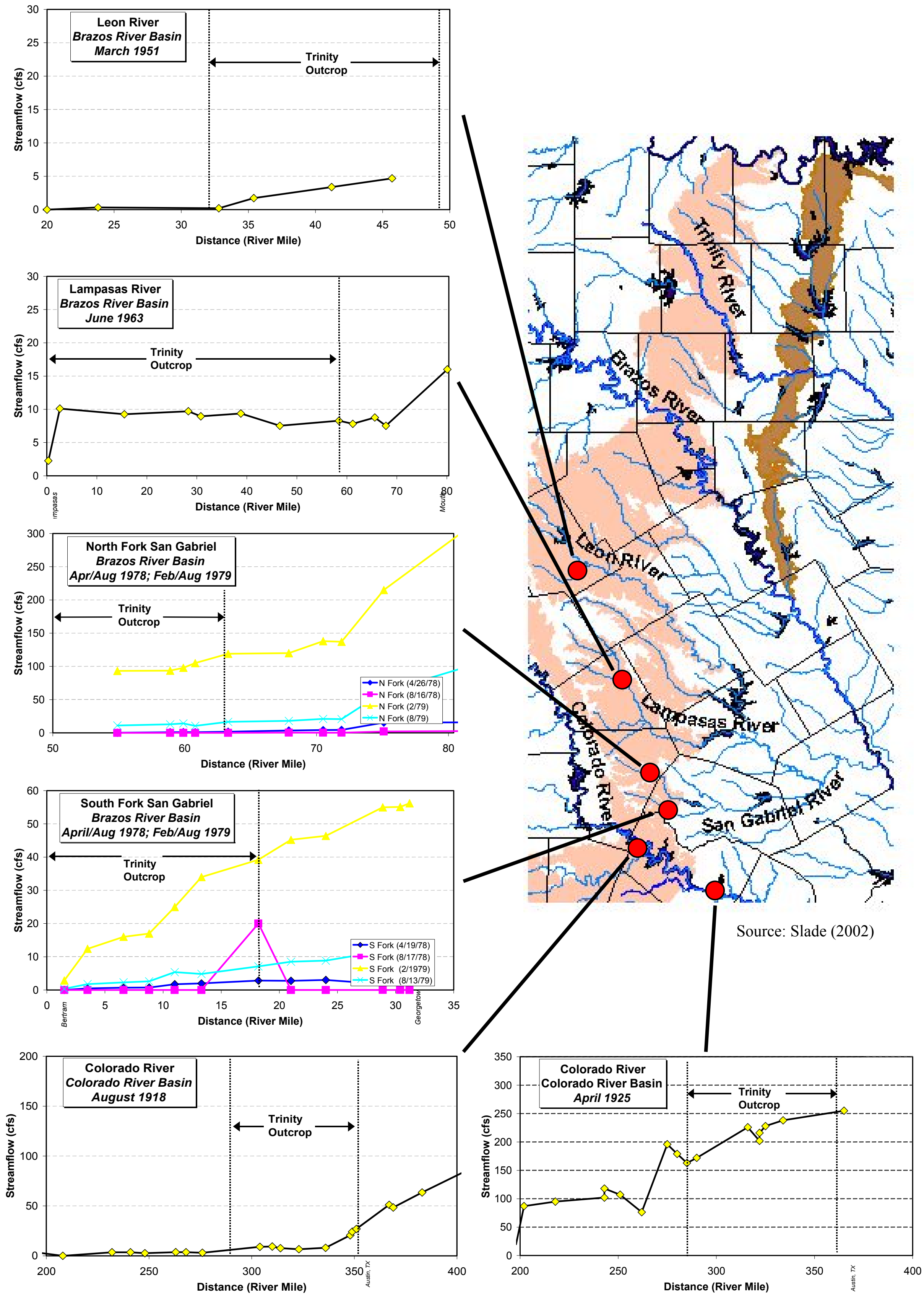
In the February 1979 North Fork San Gabriel study, the flow increased from about 93 cubic feet per second (cfs) to 119 cfs across the aquifer outcrop, an increase of 26 cfs (or 28%). The only

USGS gage with daily streamflow data on the North Fork San Gabriel is located downstream of Lake Georgetown, therefore a flow duration curve was not generated for the North Fork San Gabriel. However, upon examining the remaining three gain-loss studies conducted on the North Fork San Gabriel during low flow conditions, the data indicates that there is little change in flow across the Trinity outcrop in these studies.

For the South Fork San Gabriel studies, the flow increased 36 cfs (from 3 cfs to 39 cfs) for the February 1979 study and increased 7 cfs during the August 1979 study. Examination of a flow duration curve generated for daily flows at the South Fork San Gabriel River at Georgetown (USGS Gage No. 08104900), which is 13 miles downstream of the Trinity outcrop, indicates that these two studies spanned a wide range of flow conditions. The daily flow duration curve for the South Fork San Gabriel is presented in Figure 4.49. The location of the South Fork San Gabriel USGS gage is between the last two measurements of the gain-loss study, which reflected a value of 56 cfs during the February 1979 study and 12 cfs during the August 1979 study. When comparing the daily flow duration results to the February 1979 study, a flow of 56 cfs is exceeded 20% of the time, indicating relatively high flow conditions. By contrast, flow during the August 1979 study was 12 cfs, which is exceeded 51% of the time, indicating relatively low flow conditions. An extreme low flow condition was present (< 7 cfs) at the gage station during the April 1978 study. Because there was a slight flow increase from 0 cfs to 3 cfs across the aquifer outcrop, the South Fork San Gabriel can be considered as a gaining reach across the outcrop even during extreme low flow conditions.

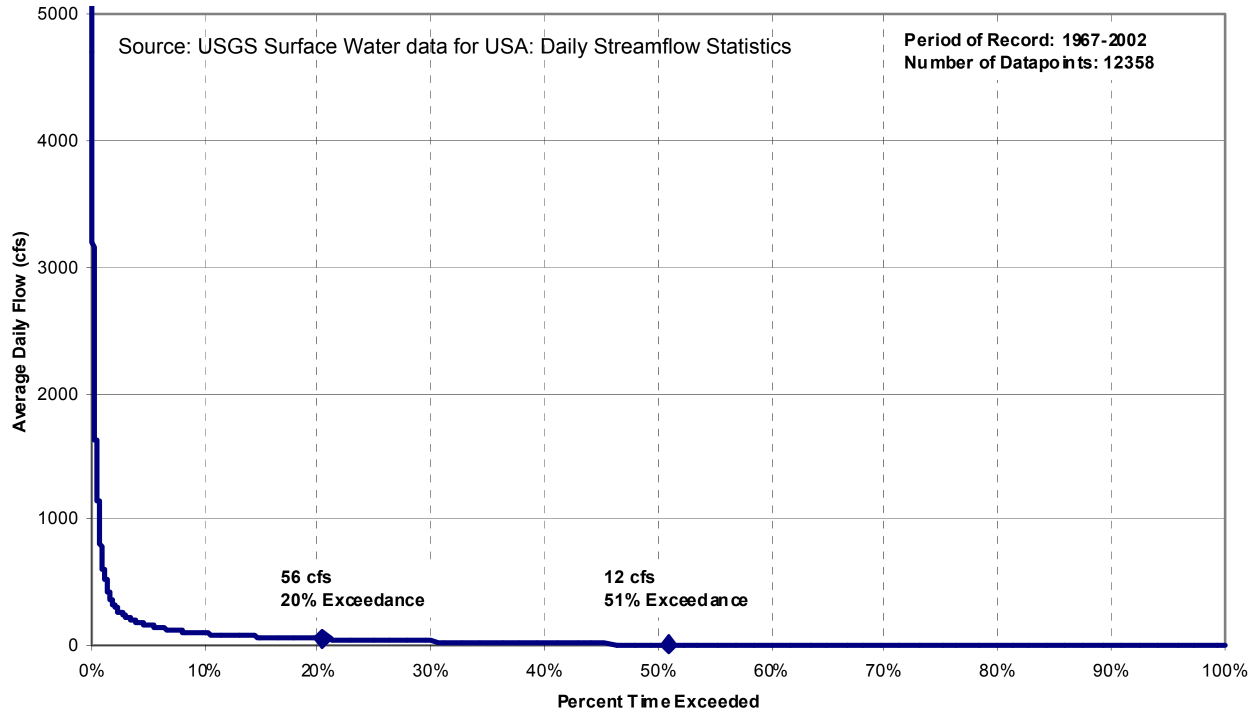
In the August 1918 Colorado River study, the flow increased from about 5 to 27 cfs across the aquifer outcrop, an increase of 22 cfs. The flow at the Colorado River at Austin (Gage No. 08158000) at the time was 40 cfs. According to the daily flow duration curve presented in Figure 4.50, a flow of 40 cfs is exceeded at the Colorado River gage 99% of the time. This indicates that during drought conditions (i.e. low flow), the Colorado River continues to be a gaining reach across the Trinity outcrop. The flow increase documented in the 1918 study may be compared to model results to estimate the minimum groundwater discharge in the Colorado River across the outcrop. In the Colorado River study conducted in April 1925, the flow increased from 163 to 250 cfs across the Trinity outcrop. The flow at the Colorado River at Austin gage at this time was 250 cfs, which is exceeded 85% of the time according to the flow duration curve. It should be noted that the flow duration curve includes only the period of record prior to construction of the first major reservoir on the Colorado River, Lake Buchanan, which began impoundment in May 1937. This was done to reduce the impact of reservoir releases on stream flow measurements. Table 4.11 reports the average annual flow at gages nearest the upstream extent of the Trinity or Woodbine outcrop. The streams that originate on the outcrops by definition have zero inflow from upstream.

# Figure 4.48 Low Flow Investigations

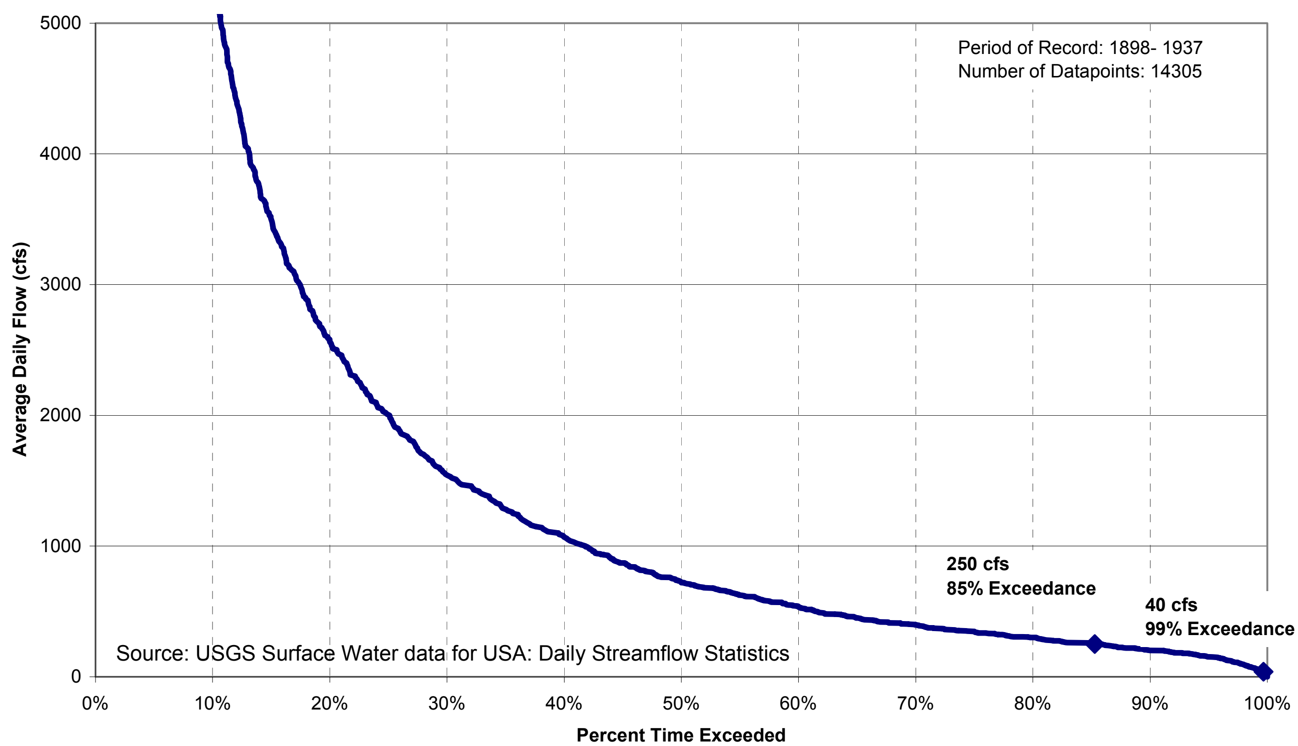



Source: Slade (2002)

## Figure 4.49 South Fork San Gabriel (Gage 08104900) Flow Duration Curve




## Figure 4.50 Colorado River (Gage 08158000) Flow Duration Curve



### 4.6.3 Baseflow Studies

A stream's baseflow is considered as the portion of its flow that is not directly influenced by runoff from storm events. In other words, baseflow partially reflects groundwater discharge from subsurface zones to a stream. Streams can have intermittent baseflow, normally associated with wet winters and dry summers. Baseflow may be estimated using graphical techniques for separation of baseflow from the total streamflow. Baseflow separation was performed on daily flow data using the Baseflow Index (BFI) program, jointly maintained by the USGS and U.S. Bureau of Reclamation (Wahl, 2001). BFI uses the Standard Hydrologic Institute Method, which identifies rises in the hydrograph typical of storm-induced runoff, and separates the total streamflow into daily time series of baseflow and storm flow for each gage. Figure 4.51 presents an example of the flow separation results for the Paluxy River. Because this baseflow method is approximate, the program may underestimate or overestimate baseflow for any given day. The long-term statistical accuracy of the BFI program is commonly accepted, but it is statistical in nature and does not consider the local hydraulics of an aquifer system. What the BFI program is incapable of doing is differentiating between individual baseflow components. Only one of these is being simulated in this groundwater model: baseflow from the regional Trinity/Woodbine aquifers. Other components not simulated include small amounts of instream detention and subsequent discharge of surface waters, alluvial aquifer recharge including bank storage/release following flood events, perched groundwater zones, or fractured zone recharge/discharge in the near subsurface. Because of these other components of baseflow, it is believed that the BFI program, while accurately estimating total baseflow, will tend to overestimate the component of groundwater discharge being modeled in this study.

Historical data for all stream gages within the study area were reviewed and analyzed to determine their applicability for determining surface/groundwater interaction for use as calibration targets in the GAM. Most of these gages were removed from consideration as "target" gages for any or all of the following reasons:

- Period of record was too short to determine long-term baseflow trends.
- Daily records were not maintained. This was the case for several gages that were installed for storm event inflow measurement during the study phase of reservoirs.
- The gage was located downstream of a significant reservoir. Reservoir operations will supplant natural flows with the artificial hydrograph of the reservoir operations, and thus baseflow analysis would not be valid at these locations.
- A significant portion of the drainage area was located outside of the study area.

- In the event of successive gages on the same stream, the periods of record may not have been overlapping.
- If gages were in densely urban areas (such as Dallas-Ft. Worth), they were removed due to the uncertainty associated with urban influences on the hydrographs.

There are potentially three types of gage arrangements, as depicted in the schematic drawings in Figure 4.52, which may be suitable to quantify baseflow for a stream reach. In a Type 1 arrangement, all of the contributing drainage area is above a single gage, as is the case for Sycamore Creek. In Type 2, two gages on the same stream may define an outcrop reach, as in the case of North Bosque River between Stephenville and Hico. Finally, in Type 3, three gages may be used if all three reaches of a stream confluence are gaged.

The study reaches that meet the previously described criteria to estimate baseflow gains and losses are presented in Table 4.12 and 4.13 according to drainage area in the Trinity or Woodbine outcrop.

Baseflow duration curves are generated from the unit, daily, baseflow values, showing the percentage of time each flow value was exceeded during the period of record. As an example, the flow duration curve for Paluxy River is presented in Figure 4.53. Basic flow statistics including maximum, minimum, median (50% exceedance), and selected percentile flows are calculated and will be presented along with the application of these values in the model development phase. However, analysis of results does not reveal any decrease in baseflows in the study reaches.

Upon completion of the streamflow data analysis, the following gages were identified as Type 1 target locations, based upon the selection criteria just described. Water budget results were examined to compare model-simulated surface/groundwater interaction at these locations with the results of the baseflow analysis.

**Table 4.12 Gage Stations used to Develop Baseflow Estimates**

| Station ID | Station Name | Period of Record | Row | Col | Lat | Long |
|---|---|---|---|---|---|---|
| 8043950 | BIG SANDY CREEK NEAR CHICO, TX | 10/1/36- 8/2001 | 163 | 80 | 33.27417 | -97.6783 |
| 8046000 | CLEAR FORK TRINITY RIVER NEAR ALEDO, TX | 8/1/47- 3/1957 | 199 | 105 | 32.64111 | -97.5642 |
| 8053500 | DENTON CREEK NR JUSTIN, TX | 10/1/49- 9/30/2001 | 162 | 105 | 33.11889 | -97.2903 |
| 8091500 | PALUXY RIVER AT GLEN ROSE, TX | 2/7/24- 8/2001 | 230 | 106 | 32.23139 | -97.7769 |
| 8093500 | AQUILLA CREEK NR AQUILLA, TX | 1/1/39- 4/1983 | 239 | 149 | 31.84444 | -97.2011 |
| 8094800 | NORTH BOSQUE RIVER AT HICO, TX | 1/1/62- 9/30/1999 | 252 | 101 | 31.97806 | -98.0344 |
| 8095000 | NORTH BOSQUE RIVER NR CLIFTON, TX | 10/1/23- 9/30/2000 | 252 | 131 | 31.78583 | -97.5678 |
| 8100500 | LEON RIVER AT GATESVILLE, TX | 10/1/50- 9/1963 | 279 | 132 | 31.43278 | -97.7617 |
| 8101000 | COWHOUSE CREEK AT PIDCOKE, TX | 10/1/50- 9/30/2000 | 291 | 130 | 31.28472 | -97.8847 |
| 8104000 | LAMPASAS RIVER AT YOUNGSPORT, TX | 4/1924- 9/30/1980 | 307 | 149 | 30.95722 | -97.7083 |

Data from Water Availability Models (WAM) prepared for the TCEQ were reviewed to identify any significant water rights or return flows located between the gages, and baseflow estimates were adjusted accordingly, but in no case was this adjustment significant compared to the total baseflow.

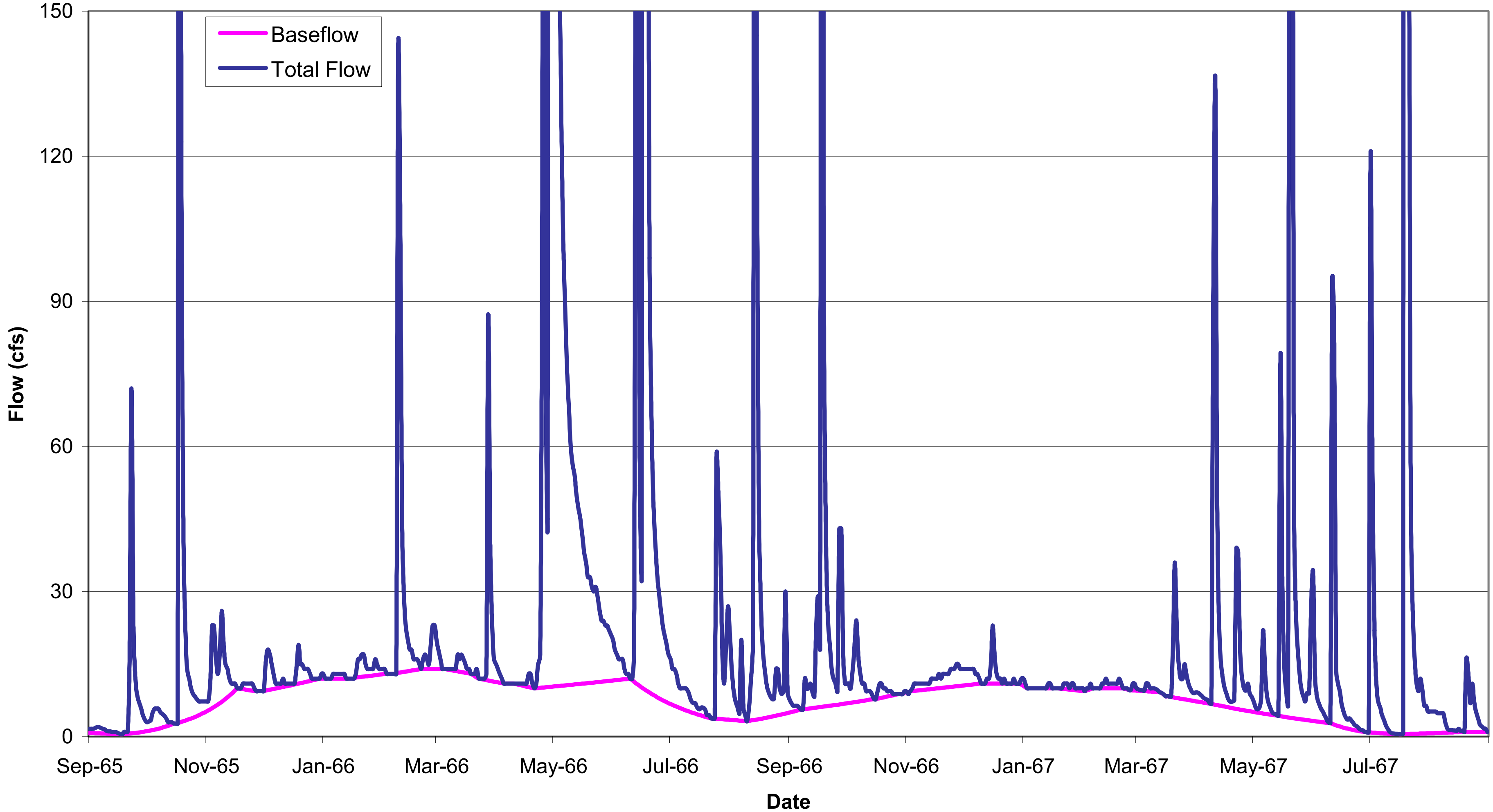
Once the quantification of baseflow change was completed for each of the ten stream reaches identified, a flow duration curve was generated from the unit daily values, showing the percentage of time that each baseflow value was exceeded during the period of record. Baseflow statistics including flows from the 10th percentile ($Q_{10}$), $Q_{25}$, $Q_{50}$ (median), and $Q_{75}$ were calculated and are presented in Table 4.13.

**Table 4.13 Streamflow Target Baseflow Duration Statistics**

| Station ID | Station Name | $Q_{10}$ (cfs) | $Q_{25}$ (cfs) | $Q_{50}$ (cfs) | $Q_{75}$ (cfs) |
|---|---|---|---|---|---|
| 8043950 | BIG SANDY CREEK NEAR CHICO, TX | 0.00 | 0.00 | 1.73* | 8.21 |
| 8046000 | CLEAR FORK TRINITY RIVER NEAR ALEDO, TX | 0.00 | 0.00 | 0.93 | 5.46 |
| 8053500 | DENTON CREEK NR JUSTIN, TX | 0.00 | 0.00 | 5.11 | 20.38 |
| 8091500 | PALUXY RIVER AT GLEN ROSE, TX | 0.28 | 3.03 | 9.40 | 21.00 |
| 8093500 | AQUILLA CREEK NR AQUILLA, TX | 0.00 | 0.15 | 1.25 | 6.24 |
| 8094800 | NORTH BOSQUE RIVER AT HICO, TX | 0.06 | 0.91 | 2.88 | 8.36 |
| 8095000 | NORTH BOSQUE RIVER NR CLIFTON, TX | 0.41 | 2.50 | 10.50 | 35.72 |
| 8100500 | LEON RIVER AT GATESVILLE, TX | 0.19 | 0.69 | 5.70 | 45.03 |
| 8101000 | COWHOUSE CREEK AT PIDCOKE, TX | 0.00 | 0.12 | 2.44 | 13.83 |
| 8104000 | LAMPASAS RIVER AT YOUNGSPORT, TX | 3.62 | 9.58 | 25.00 | 75.94 |

*Includes data after Lake Amon Carter was impounded, 1956.

**Figure 4.51 Stream Hydrograph and Base Flow Separation- Paluxy River**




Source: USGS Surface Water data for USA: Daily Streamflow Statistics

**Figure 4.52 Schematic Stream Gage Configurations for Estimating Baseflow**

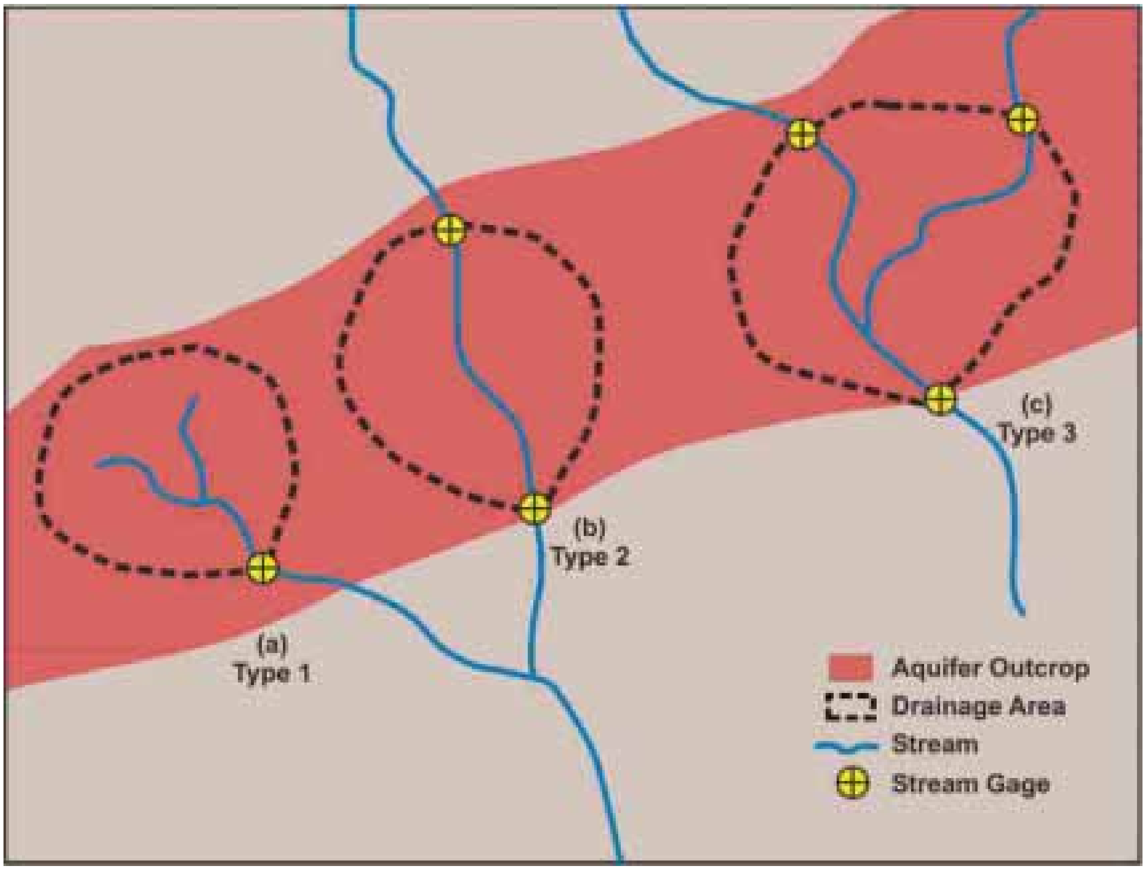
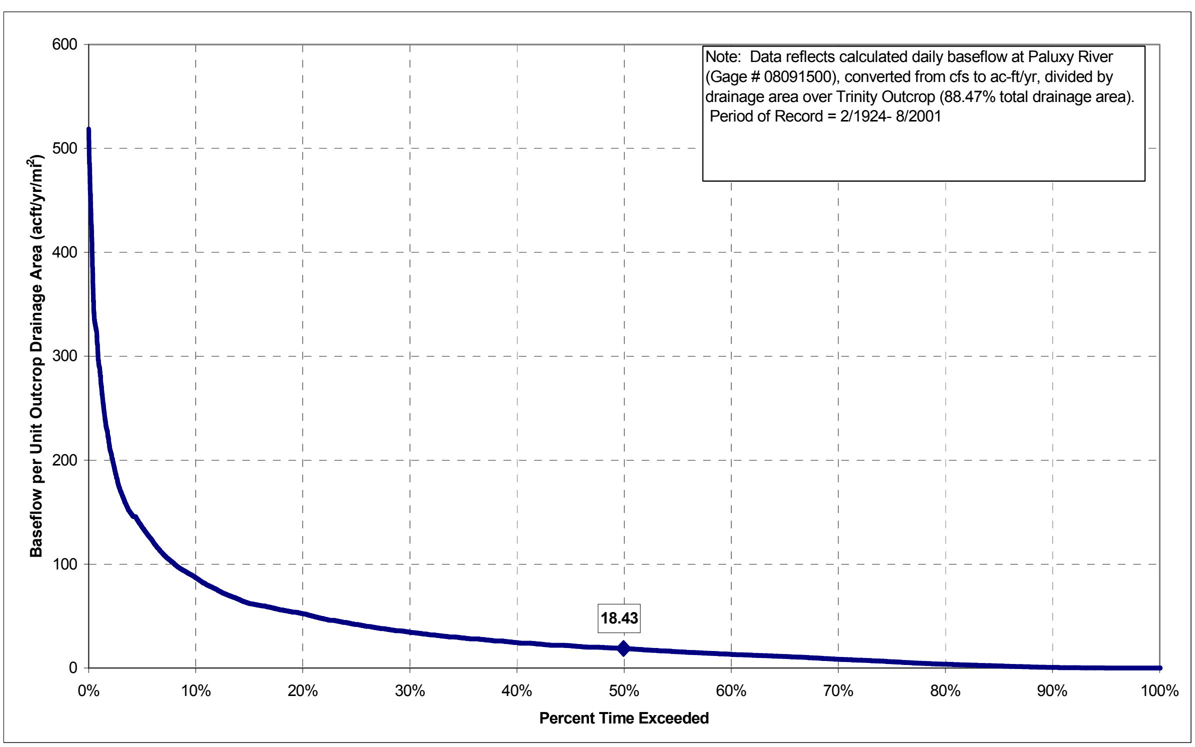



**Figure 4.53 Paluxy River Unitized Baseflow Duration Curve (per Outcrop Drainage Area)**

Source: USGS Surface Water data for USA: Daily Streamflow Statistics



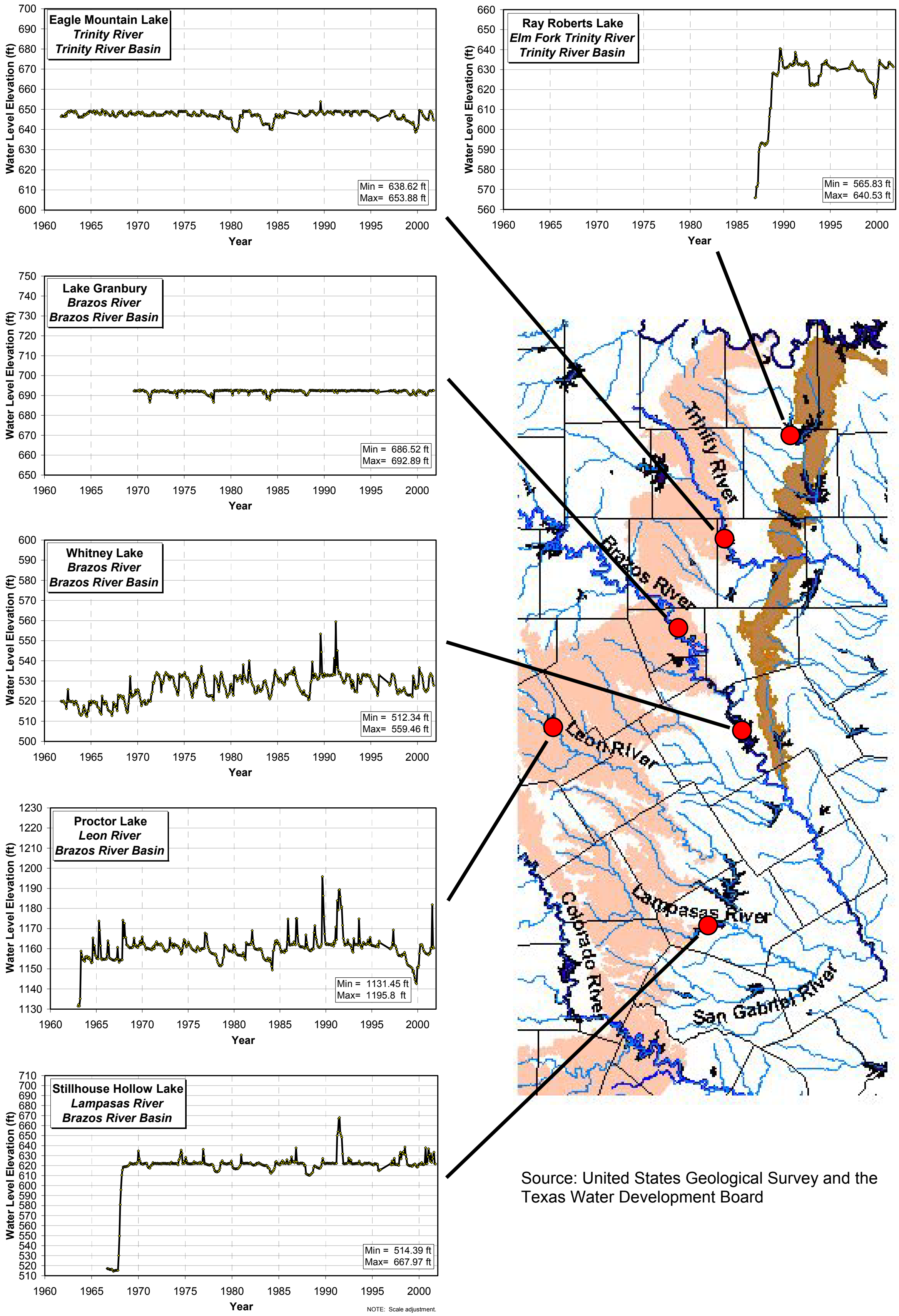
### 4.6.4 Surface Water Reservoirs

Reservoirs can affect local groundwater regimes. As reservoirs are filled, impounded water leaks into the underlying geologic formations, raising local groundwater levels until equilibrium between the reservoir stage and the surrounding water table is achieved. For the purposes of the GAM, it is assumed that reservoirs with a surface area greater than one square mile are candidates for representation in the model. Table 4.14 lists the reservoirs that are large enough to merit explicit simulation in the GAM. Selected reservoir hydrographs are presented in Figure 4.54. The water level elevations were computed using storage data compiled from USGS Water Resources Data for Texas reports and USGS and TWDB elevation-area-capacity (EAC) curves.

## Table 4.14 Reservoirs within the Study Area

| Lake Name | Year Impounded[a] | Water Level Range (ft) | Area (acres) | Dam Elevation (ft-msl) | Spillway Elevation (ft-msl) |
|---|---|---|---|---|---|
| ***Lake Granbury*** | 1969 | 685.3-693.6[f] | 8,700[g] | 707 | |
| ***Squaw Creek Lake*** | 1977 | 773.0- 779.1[f] | 3,228 | | |
| ***Lake Pat Cleburne*** | 1964[b] | 724.9-738.5[f] | 1,550[e] | 753[b] | 744[b] |
| ***Whitney Lake*** | 1951 | 509.5- 570.3 | 23,560 | 584 | 533 |
| ***Aquilla Lake*** | 1983 | 533.7- 551.9 | 3,280 | 582.5 | 564.5 |
| ***Waco Lake*** | 1965 | 445.1- 488.5 | 7,270 | 510 | 465 |
| ***Proctor Lake*** | 1963 | 1,142.2- 1,197.6 | 4,610 | 1,206 | 1,162 |
| ***Belton Lake*** | 1954 | 553.1- 634.4 | 12,300 | 662 | 631 |
| ***Stillhouse Hollow Lake*** | 1968 | 610.3- 668 | 6,430 | 698 | 666 |
| ***Lake Georgetown*** | 1980 | 767.7- 835.9 | 1,310 | 861 | 834 |
| ***Granger Lake*** | 1980 | 498.5- 530.1 | 4,400 | 555 | 528 |
| ***Lake Travis*** | 1941[d] | 614.2- 710.4 | 18,622 | 750 | 714 |
| ***Eagle Mtn. Lake*** | 1934[b] | 629.3- 659.9[f] | 9,200[e] | 682[b] | 676[b] |
| ***Lake Worth*** | 1914[b] | 590.0- 598.7[f] | 3,560[e] | 606.3[b] | 594.3[b] |
| ***Lake Weatherford*** | 1957[b] | 890.0- 899.7[f] | 1,210[e] | 914[b] | 906[b] |
| ***Benbrook Lake*** | 1952 | 681.8- 717.5 | 3,770 | 747 | 724 |
| ***Lake Arlington*** | 1957[b] | 536.5- 562.4[f] | 2,275[e] | 572[b] | 559.7[b] |
| ***Ray Roberts Lake*** | 1987 | 615.4- 644.4 | 29,350 | 665 | 645.5 |
| ***Lewisville Lake*** | 1954 | 498.6- 536.7 | 29,592 | 560 | 553 |
| ***Grapevine Lake*** | 1952 | 520.7- 563.5 | 7,280 | 588 | 560 |

NOTE: Area is based on conservation pool; Shapefile provided by TWDB of reservoirs used to cross check data.
[a] Lake Volumetric Studies conducted by TWDB since 1993 (except as noted).
[b] TWDB Report 126 Engineering Data on Dams and Reservoirs in Texas Part II, November 1973.
[c] USGS Conservation Pool Storages & Elevations for Selected Lakes and Reservoirs
[d] Information obtained from LCRA website.
[e] TWDB Report Engineering Data on Dams and Reservoirs in Texas Part I, February 1971.
[f] USGS Water Resources Data Texas Water Year 2002, Volumes 1 & 2. Except Lake Arlington Water Year 2001, Volume 1.
[g] Texas Parks and Wildlife, Freshwater Fishing Report




Source: United States Geological Survey and the Texas Water Development Board

**Figure 4.54 Reservoir Historical Water Level Hydrographs**

### 4.6.5 Stream Bed and Reservoir Bed Conductance

Both the River Package and the Reservoir Package in MODFLOW use identical algorithms to simulate interaction between groundwater and surface water. For a given model cell, a water surface elevation is assigned to the stream or reservoir, and this water level is compared to the calculated head in the aquifer. If the water level in the stream or reservoir is greater then the head in the aquifer, water flows from the surface water body into the aquifer as a function of the conductance of the bed sediments and the difference in heads. If the head in the aquifer is greater than the water level of the surface water body, water will flow from the aquifer to the stream.

The quantity of flow in either direction is calculated by the following equation:

$$Q = C*dh \qquad (1)$$

where $Q$ = Discharge ($L^3/T$)

$dh$ = difference in head between the surface water and groundwater (L)

$C$ = conductance of streambed or reservoir sediments ($L^2/T$).

Conductance is a lumped parameter calculated by the following equation:

$$C = KLW/m \qquad (2)$$

where $K$ = Hydraulic Conductivity (L/T)

$L$ = Length of Stream (or reservoir) Reach in Grid Cell (L)

$W$ = Width of Stream (or reservoir) Reach in Grid Cell (L)

$m$ = Thickness of streambed or reservoir sediments (L)

In the case of a reservoir, the pool elevation is used for the surface water head. Consequently, the direction of flow is from the reservoir into the aquifer. The conductance components of L (length) and W (width) are assigned as the length and width of the finite-difference grid cell. The hydraulic conductivity (K) and bed thickness (m) terms are defined similarly to the Stream Package. However, the hydraulic conductivity value for reservoir representation will be assigned a significantly lower value than in stream representation, because streambeds are composed of alluvial materials with streamflow available as a mechanism to flush out the bed materials and maintain good hydraulic connection with the aquifer. Reservoirs are a much more stagnant system, hydraulically speaking. Reservoir bed sediments are usually composed fine materials such as clay and silt particles that progressively settle out of the water column over time, and there is no mechanism for flushing of these bed materials as in the stream system.

The data and methods used to develop the parameters of the conductance term (length, width, hydraulic conductivity, and bed thickness) for selected streams and reservoirs represented in the GAM are determined as follows:

- Stream Channels — Stream channels were digitized using 1:24,000 scale USGS topographic maps of the study area. This geo-referenced line coverage was then joined with the model finite-difference grid, and an ArcView utility was utilized to determine the length of each line segment within each individual model cell. In some cases of very short segments, or in the case of streams that meandered back and forth into and out of individual stream cells, the stream segment representation was simplified to a single segment per cell, with the total length of any multiple stream segments retained in the one cell.
- Streambed Widths — General alluvium/streambed widths were determined from BEG Geologic Atlas of Texas sheets (BEG, various)
- Streambed thickness and streambed hydraulic conductivity — The parameters are often more conceptual than physical. As a result, very little physical data is available to help develop estimates. Since these properties are component parts of the lumped parameter of conductance, initial values were assigned with the assumption that conductances would be varied during calibration. Streambed thickness was initially assigned at 10 feet, and an initial hydraulic conductivity estimate of 0.1 feet per day (ft/day) was applied to all stream segments.

### 4.6.6 Discussion

The methodology developed to quantify the interaction between aquifers and surface water bodies attempts to develop numerical estimates of quantities which are not directly measurable. Simplifying assumptions were made in order to facilitate the analysis. Several factors may affect the accuracy of the estimates. This section briefly discusses these factors.

The estimates provided by the baseflow methodology may somewhat underestimate aquifer discharge, because stream channel losses due to evaporation and transpiration are occurring between the two gages' measuring points. What is actually measured using this methodology is groundwater discharge from the aquifer minus evapotranspiration losses in the intervening reach. However, this is a valid target for model calibration, when considering a model design that represents evapotranspiration. In addition, uncertainty may be introduced by this method due to gage inaccuracies and lag time for propagation of flow between upstream and downstream gages (in the event that two gages are used).

As discussed in Section 4.6.3, several flow components are not explicitly simulated in the GAM, which result in overestimation of the component of groundwater discharge being modeled in this study. These components include small amounts of instream detention and discharge of surface waters, bank storage/release in alluvial aquifers following flood events, perched groundwater zones, or fractured zone recharge/discharge in the near subsurface.

In addition, this statistical approach does not estimate the seasonal and year-to-year variability of groundwater discharge to streams. Baseflow separation results for the target gages indicate 2 to 3 orders of magnitude of variation in baseflow estimates using daily data. If viewed as a simple system in the context of Darcy's Law (Figure 4.55), with groundwater flow direction perpendicular towards the stream, the quantity of discharge (Q) to the stream is proportional to the K, i, and area.

$$Q = KiA$$

where: K = Hydraulic conductivity

i = Hydraulic gradient of groundwater flow

A = Cross-sectional area of flow.

Of these parameters, hydraulic conductivity and cross-sectional area of flow remain constant with time. The hydraulic gradient is a factor of lateral distance (x-direction), which remains constant, and the vertical head (z-direction), which changes. However, groundwater level fluctuations in the outcrop are generally only on the order of 5 to 10 feet, and with all other factors essentially remaining constant, it may be argued that the quantity of aquifer discharge does not vary as markedly as indicated from the baseflow methodology presented here, and the median value is the most meaningful value. In addition, a succession of large storms would tend to increase the baseflow estimate if there were not adequate time between storms for the hydrograph recession limb to return to its pre-storm level.

In addition, the relative altitude of a stream gage, or the degree of incision of a river channel may affect the amount of groundwater discharge, as a deeply incised channel will offer a larger cross-sectional area through which groundwater may enter the river than a gently sloping floodplain with no significant incision. There is no consideration of factors such as gage altitude or stream incision in this analysis.

An additional factor that is lost in the context of annual stress periods is the seasonal variability of streamflow. As previously mentioned, several of the streams modeled in this GAM are intermittent, going dry during the summer months but maintaining flow through the winter. Although the intermittent streams analyzed have smaller values of groundwater flux than perennial streams, this variability is not represented in annual stress periods; future work that incorporates shorter stress periods could attempt to simulate this seasonal variability.

It has been suggested that recent groundwater development would result in values of groundwater discharge that are lower than historical, pre-development values. However, the unit annual values calculated during the baseflow analysis were examined and revealed no evidence of a decreasing trend with time. As discussed previously, seasonal variability in baseflow for perennial streams may not fluctuate as significantly as indicated by the baseflow analysis results.

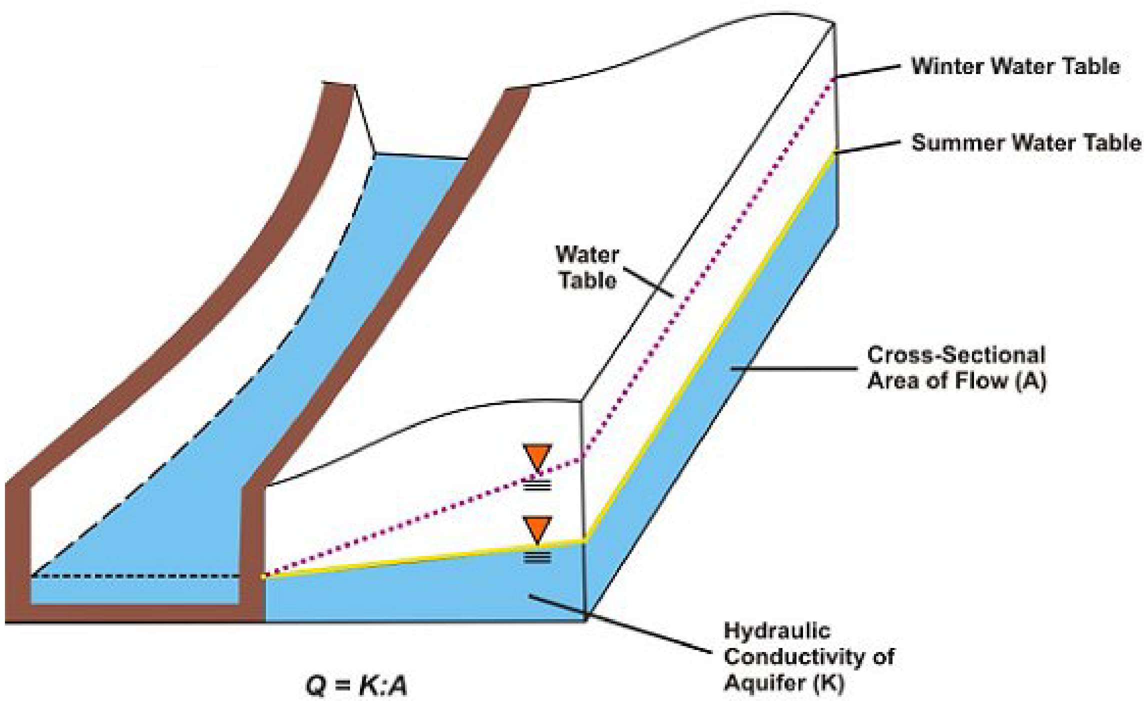



**Figure 4.55 Simplified Diagram of Stream/Aquifer Interaction**

## 4.7 Groundwater Evapotranspiration

The removal of water from the saturated groundwater zone by evaporation and plant transpiration represents two important modes of discharge from the Trinity/Woodbine. Because the effects of evaporation and transpiration are indistinguishable on a regional scale, the collective term evapotranspiration (ET) is used to refer to the discharge of groundwater due to both of these natural processes.

Evaporation of groundwater in the Trinity/Woodbine occurs when water in the liquid phase is transformed into the vapor phase by energy radiated by the sun and lost to the atmosphere. Because the process is primarily driven by solar radiation, the rate of evaporation is maximized in areas where groundwater levels are near to or intersect the ground surface, and diminishes rapidly as groundwater levels deepen. High rates of evaporation generally occur in low-lying areas such as river and stream valleys, but significant rates of evaporation may also occur in "perched" sections of the aquifer. This situation exists in areas where erosion has cut through aquifer sediments, which exposes bands of sandy material along cliffs and hillsides and promotes the formation of seeps. Evaporation rates within the study area vary. In the far western portion, the average annual gross lake surface evaporation is about 60 inches per year, while approximately 40 inches per year are reported in the northeastern section of the model (Figure 2.8).

Like evaporation, plant transpiration is also a near-surface process. The rate of groundwater withdrawal and depth of influence is highly dependent upon the type of vegetation present. Most types of plants extend roots to depths ranging from 5 to 25 feet, but certain types of phreatophytes have been known to develop roots that reach depths of over 100 feet (Canadell et al., 1996). Consequently, the determination of the rate of groundwater transpiration that can be attributed to specific types of vegetation is difficult to establish. However, analysis of data reported by the Texas Parks and Wildlife Department suggests that, on average, the rate of transpiration flux is about 20 inches per year for the most common types of vegetation in the model area. Figure 4.56 presents the mapped vegetation types in the study area.

Four key parameters that influence the evapotranspiration flux within the aquifer system are:

- The maximum rate of evapotranspiration;
- The elevation (surface) at which maximum evapotranspiration occurs;
- The depth below ground level at which evapotranspiration no longer occurs (extinction depth) and;
- The variation in plant types and land use that effect the distribution of the maximum rate of transpiration.

The maximum evapotranspiration rate is primarily a function of the local climate, vegetation type, soil characteristics, and depth of the water table below ground level. Ground level, or the elevation of a surface water body when present, is generally assumed to be the surface at which maximum evapotranspiration occurs. The extinction depth is dependent upon climate, vegetation type, and soil characteristics. However, analysis of the rooting depths associated with plants common to the study area suggests that vegetation type is the dominant factor in the assessment of extinction depth. Figure 4.57 illustrates the average root depth distribution throughout the study area. Figures depicting soil characteristics, climate, and vegetation type are included in previous sections.

The Evapotranspiration Package (ET) was used to simulate: 1) evaporation of soil moisture in the shallow subsurface, 2) transpiration of groundwater by plants, 3) small seeps and springs, and 4) discharge to streams not specifically modeled by the Stream Package. As a first step in the distribution of the ET rate, lake evaporation data were collected from the TWDB website. Next, plant type and land use factors were applied to these evaporation data, such that lake evaporation rates applied to surface water bodies, while lesser evaporation rates were distributed according to the estimated maximum transpiration rates of the plants distributed throughout the Trinity/Woodbine outcrop. These estimated ET rates were then compiled into a triangulated irregular network (TIN) surface that was used as input for the maximum model ET rate. Model ET extinction depth was assigned according to the average plant rooting depth within a given cell. Figure 4.58 illustrates the distribution of the plant type evapotranspiration factors multiplied by lake evaporation data during the construction of model inputs. Estimates for Oklahoma, where no vegetation types were mapped, were based on the average values for Texas.

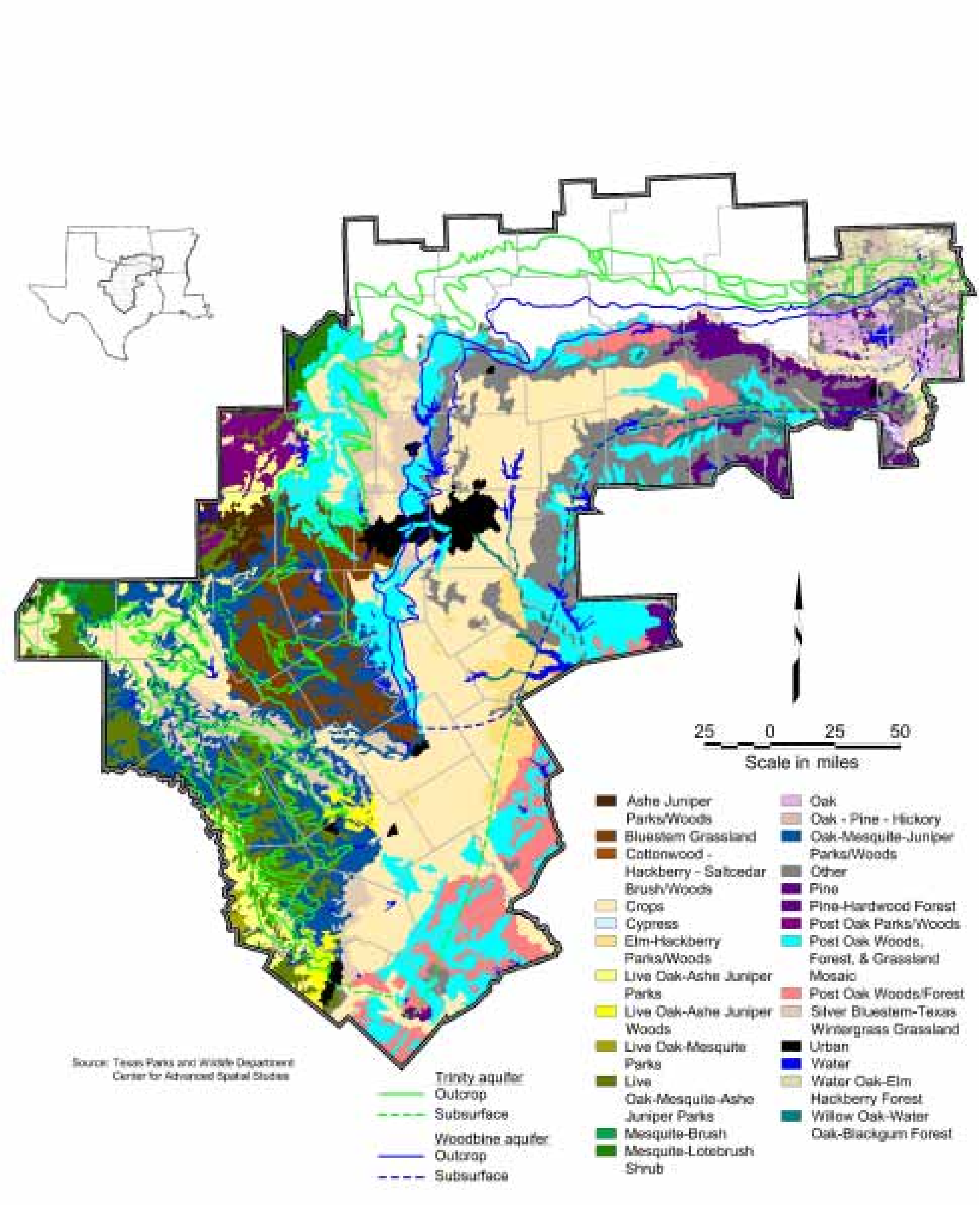



**Figure 4.56 Vegetation Type**
*(Vegetation data not available for Oklahoma)*

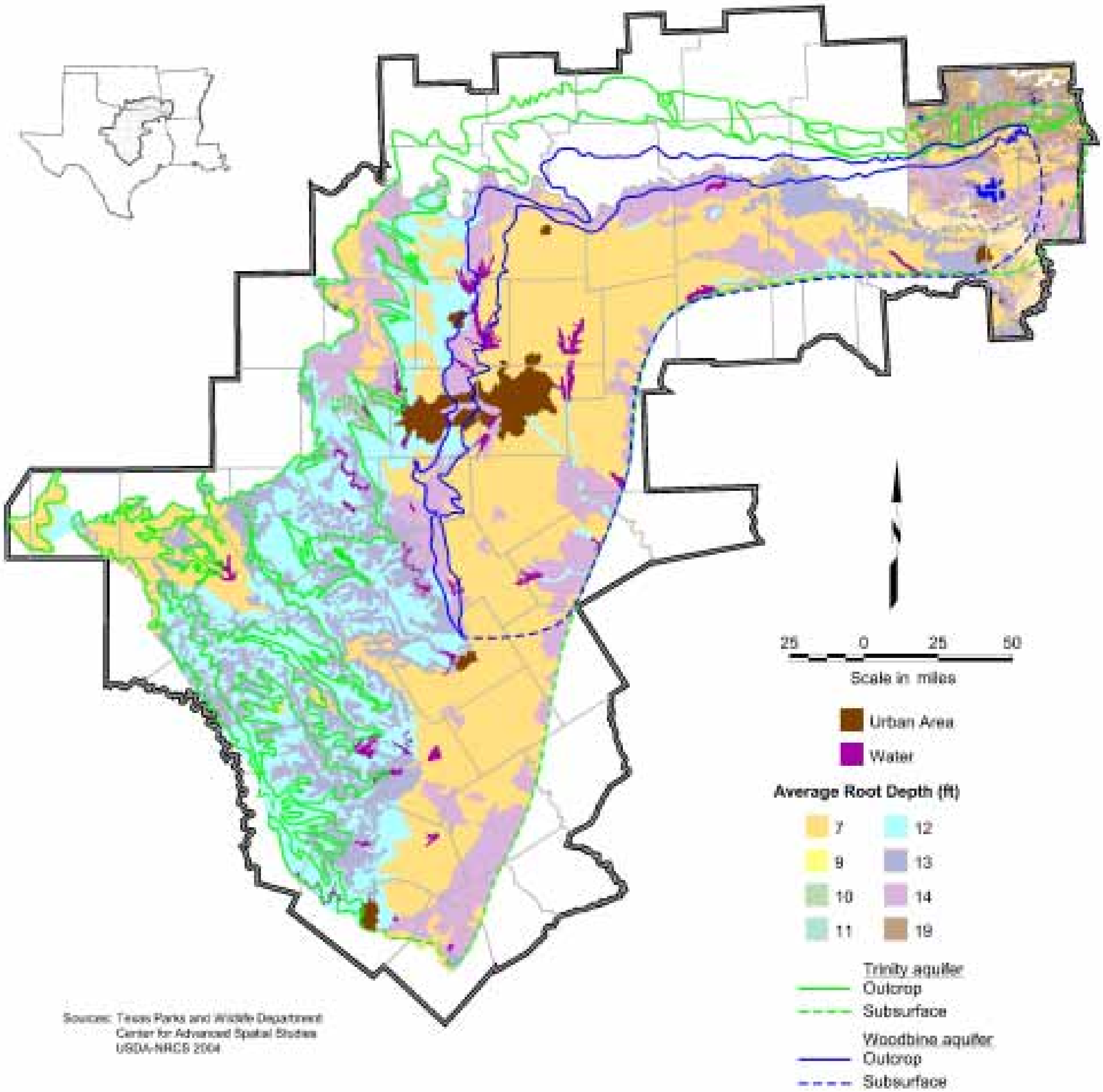



**Figure 4.57 Average Root Depth**

*(Root depth data not available for Oklahoma)*

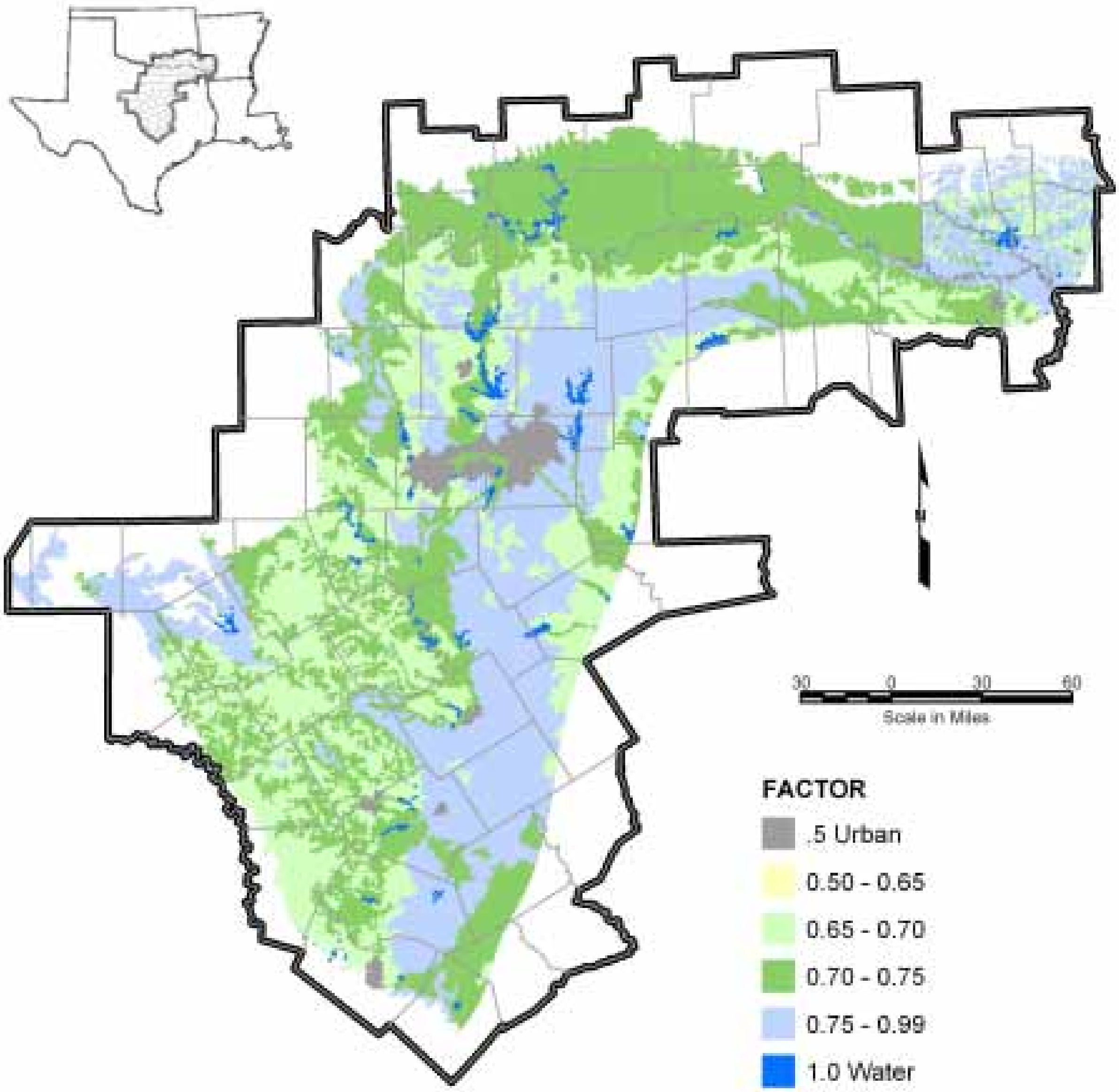



**Figure 4.58 Plant Type Evapotranspiration Rate Factors**

## 4.8 Hydraulic Properties

This section presents an analysis of the hydraulic properties of the Northern Trinity/Woodbine. The data analyzed includes the results of numerous pumping and specific capacity tests performed on wells completed within the Trinity/Woodbine.

There are four main aquifer units within the Trinity/Woodbine system: 1) the Woodbine, 2) the Paluxy, 3) the Hensell, and 4) the Hosston. Like the analyses of Hosston water levels and quality described in previous sections, the data pertaining to the Hosston were combined with the Travis Peak, Twin Mountains, and Antlers Formations in an effort to depict regional trends in the hydraulic properties of the Trinity.

There are various methods for measuring or estimating the hydraulic properties of an aquifer. A pumping test is a controlled field test in which multiple field measurements of water levels in the pumping well and any monitor wells are recorded during drawdown and recovery of aquifer water levels. Data reported from drawdown and recovery pump tests are preferred for determining aquifer properties at or near a pumped well. However, because they can be expensive and time consuming, pumping tests are performed on a small minority of the total number of wells constructed. In most cases, drillers only measure the specific capacity of the well, which is determined by pumping the well at some rate (usually estimated) and recording a single measurement of the drawdown observed in the pumping well. Specific capacity data reported by drillers are notoriously inaccurate, and were only utilized in the GAM as a crosscheck to pump test results and when no other data was available.

For the Northern Trinity GAM study area, there are 220 transmissivity values derived from pumping tests. When transmissivity values derived from specific-capacity data (Mace, 2001) were added, this number grew to 1,461 values. There are 35 values of hydraulic conductivity from pumping tests published in Nordstrom (1982), and Myers (1969) has compiled 57 hydraulic conductivity values from pumping tests for the four water-producing aquifers in the study area. There are 41 other pumping test hydraulic conductivity values in the Myers report, which are designated as Trinity aquifer values but not assigned specifically to the Woodbine, Paluxy, Hensell, or Hosston.

### 4.8.1 Hydraulic Conductivity and Transmissivity

Figure 4.59 shows the distribution of transmissivity data from pumping test analyses for each of the four Trinity/Woodbine aquifers. Transmissivity data from pumping tests combined with values derived from specific-capacity data are shown in Figure 4.60. The distribution of published hydraulic conductivity data for each of the Trinity/Woodbine aquifer units is presented in Figure

4.61. There are very few storativity data available in available published reports. Figure 4.62 shows the locations of all of the available data pertaining to storage coefficients.

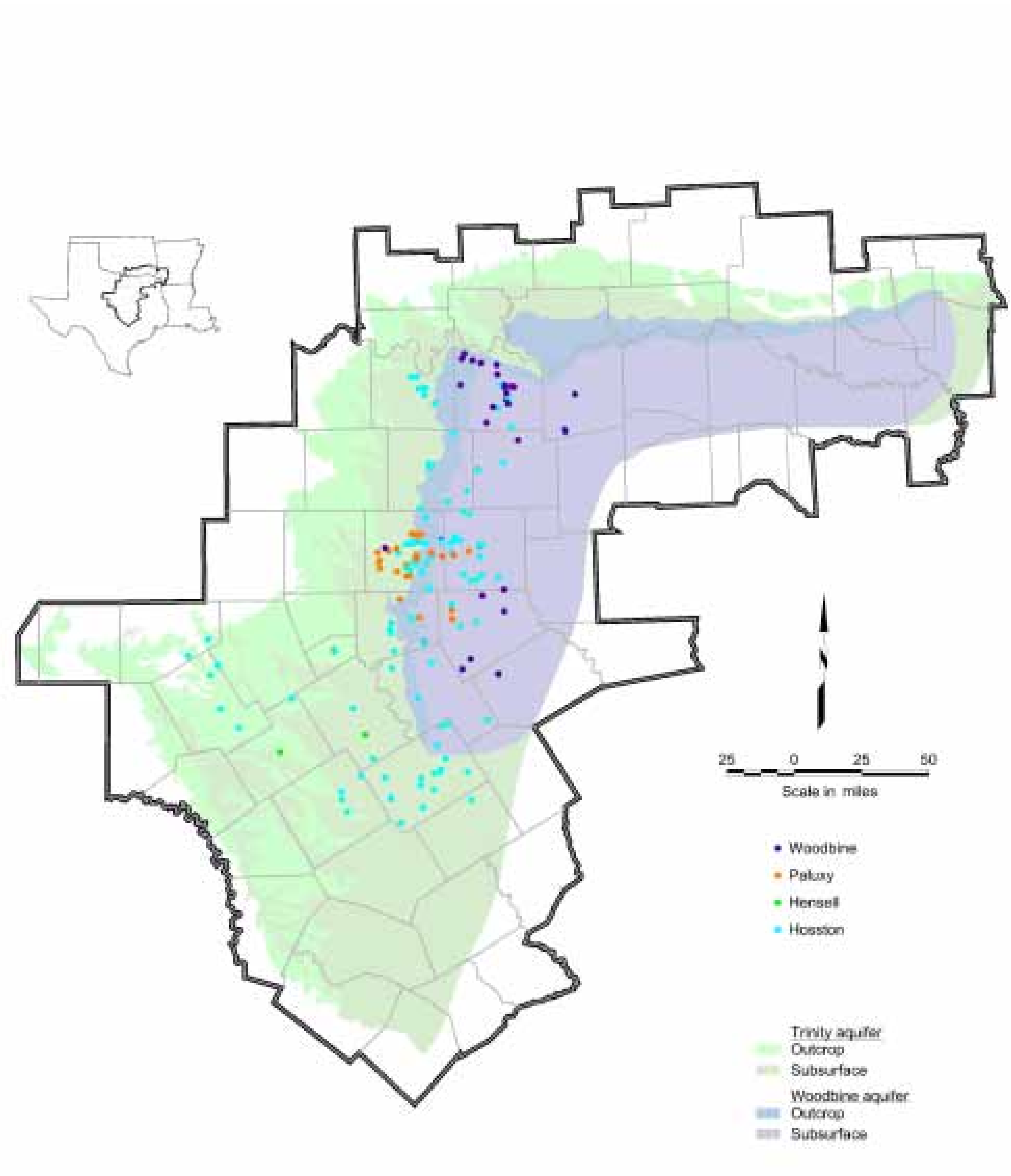



**Figure 4.59 Transmissivity Data Control from Pump Tests**

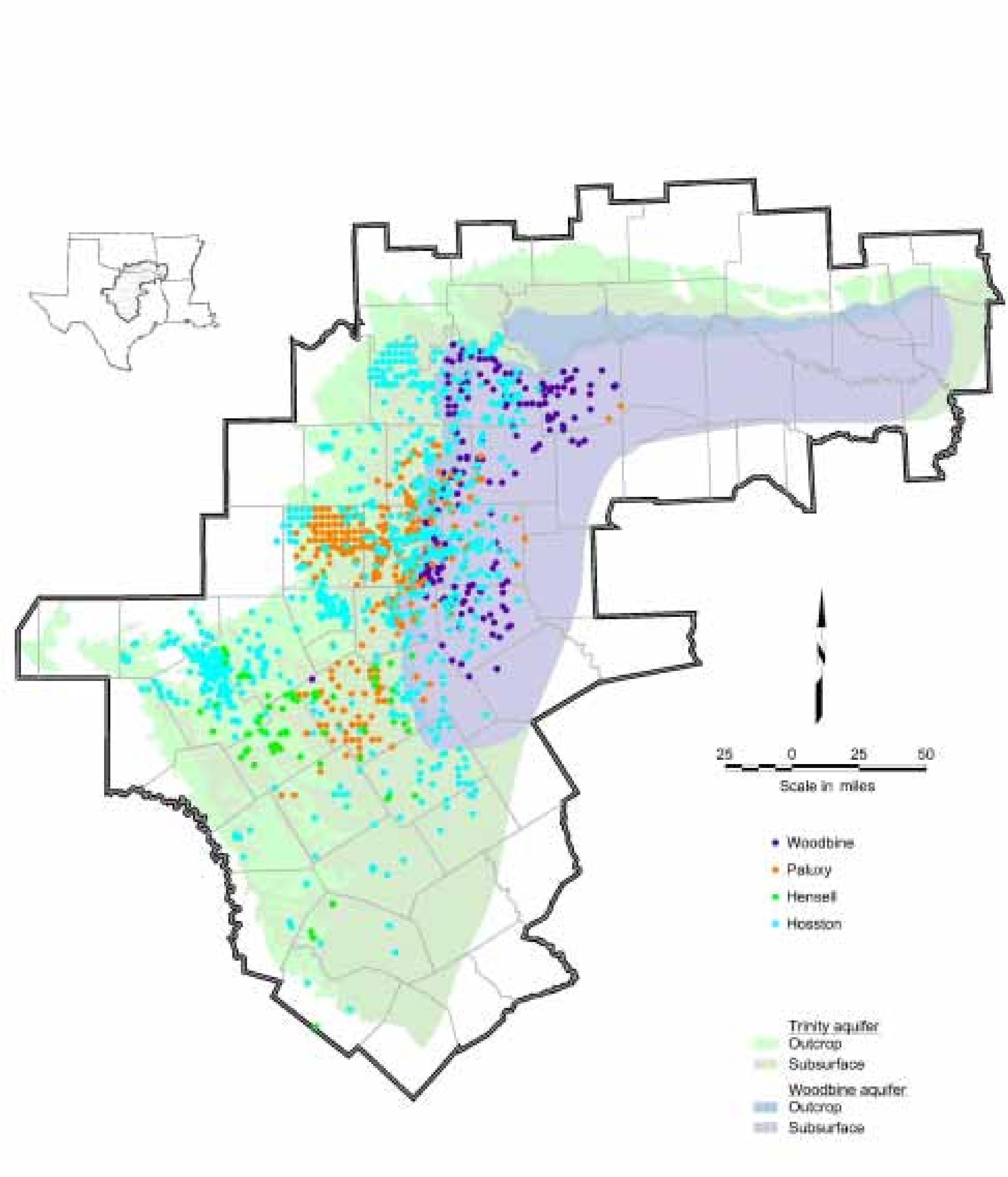



**Figure 4.60 Transmissivity Data Control from All Sources**

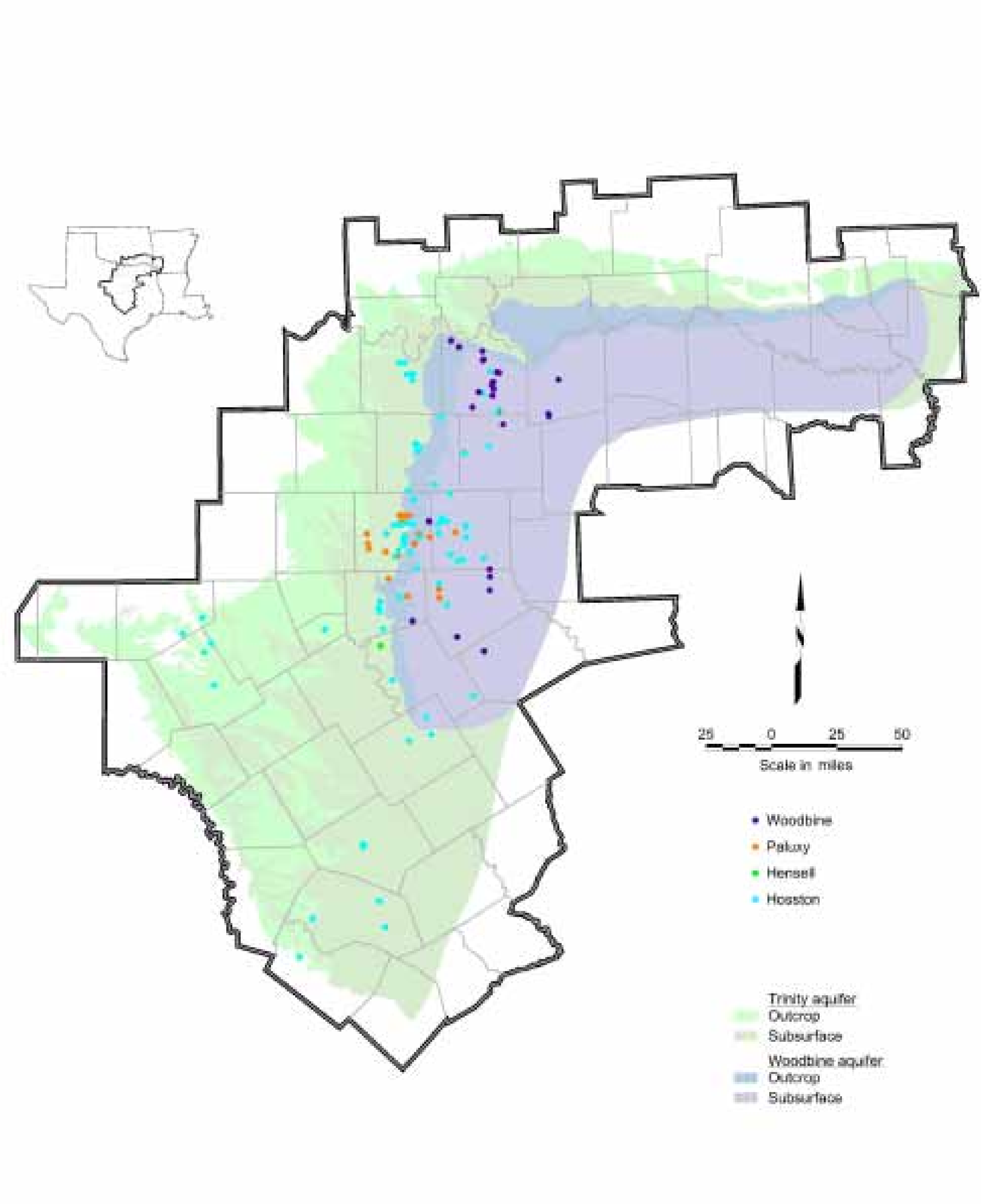



**Figure 4.61 Hydraulic Conductivity Data Control**

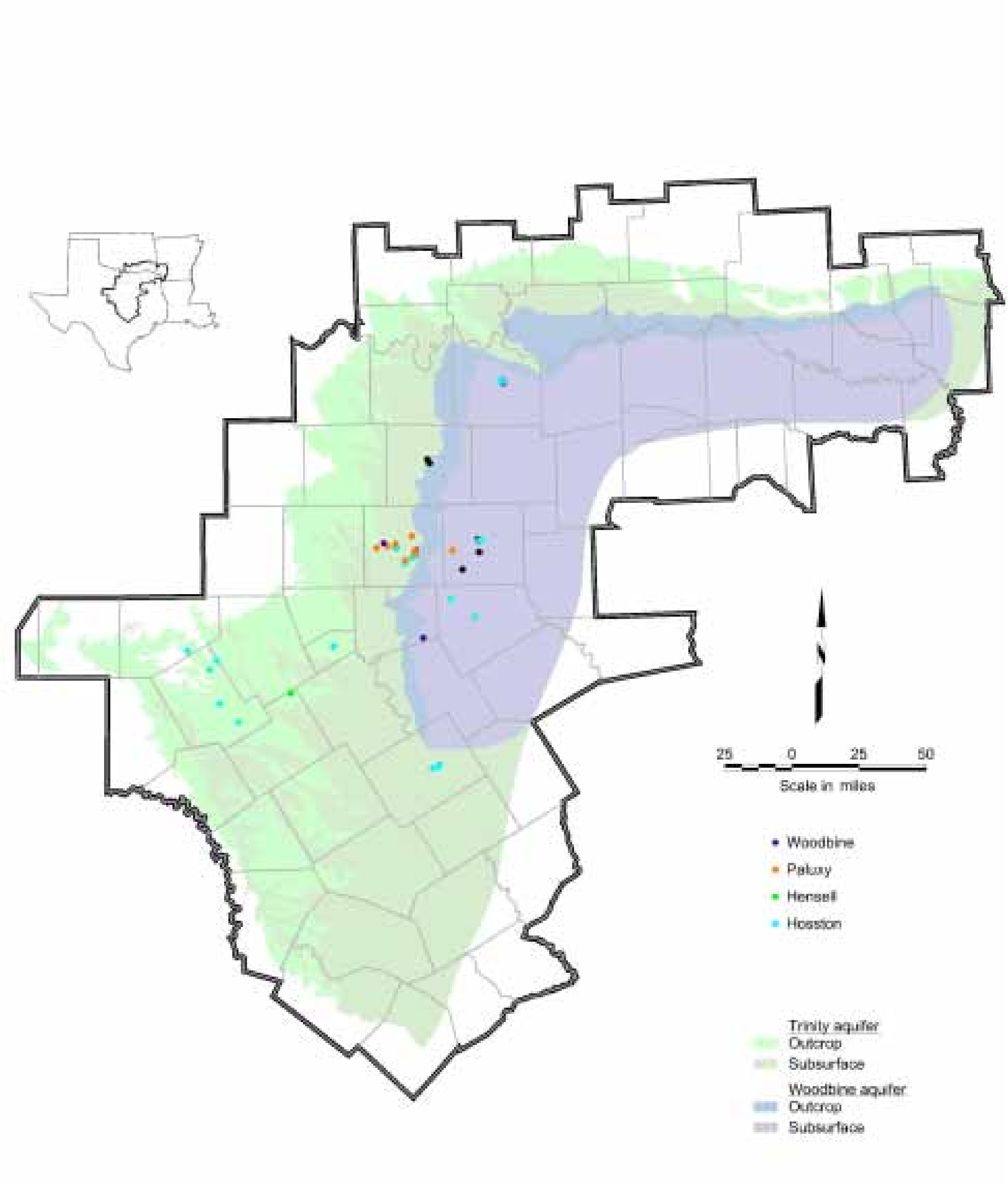



**Figure 4.62 Storativity Data Control**

***Woodbine*** - Pumping test results in the outcrop areas indicate transmissivities ranging from 1,052 to 2,232 feet squared per day ($ft^2$/day). Downdip pumping tests resulted in transmissivities ranging from 176 to 1,965 $ft^2$/day. Using seismic methods (Nordstrom, 1982), the specific yield was estimated to be 15 percent in the outcrop areas. Downdip, the aquifer is under artesian (confined) conditions and the storativity is estimated to be approximately $1.5 \times 10^{-4}$ (Nordstrom, 1982).

A statistical analysis of the available hydraulic conductivity data for the Woodbine is presented in Table 4.15 and Figure 4.63. The average of 32 hydraulic conductivity values is 8.7 feet per day (ft/day) with a standard deviation of 7.2 ft/day. The geometric mean of these 32 samples is 5.8 ft/day. Summary statistics of all the transmissivity data from pumping tests are presented in Table 4.16 and Figure 4.64. There are 35 transmissivity values for the Woodbine with an average of 660 $ft^2$/day and a standard deviation of 758 $ft^2$/day. The geometric mean of the Woodbine transmissivities is 398 $ft^2$/day.

**Table 4.15 Statistical Summary of Woodbine Hydraulic Conductivity (ft/day)**

| Woodbine | Value |
|---|---|
| ***Number of Samples*** | 32 |
| ***Average K*** | 8.7 |
| ***Standard Deviation K*** | 7.2 |
| ***Average of Log K*** | 0.8 |
| ***Standard Deviation of Log K*** | 0.44 |
| ***Geometric Mean K*** | 5.8 |

**Figure 4.63 Woodbine Hydraulic Conductivity Histogram**

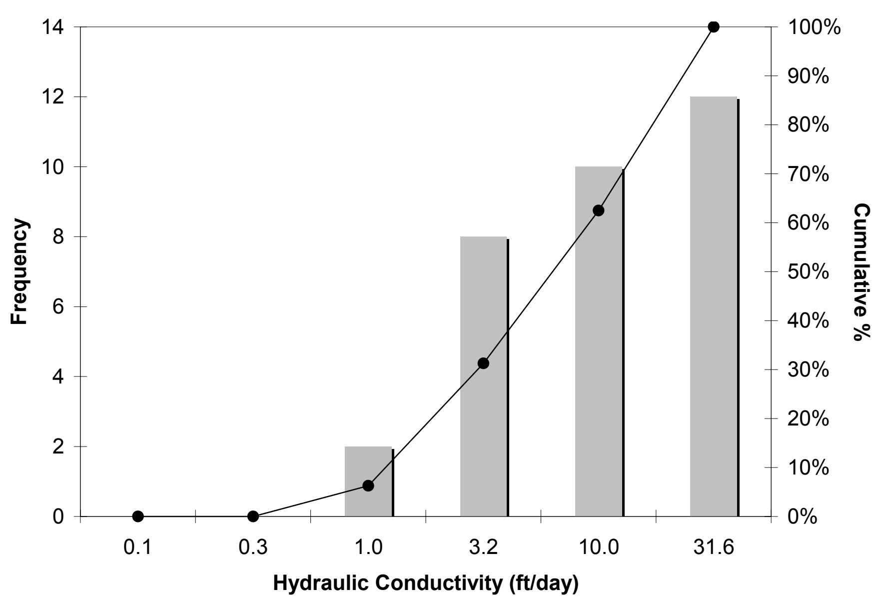
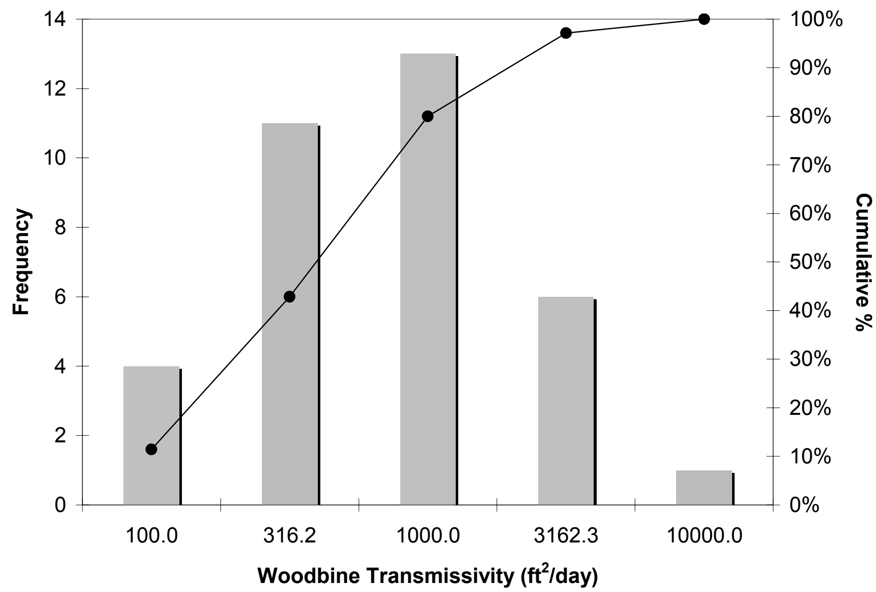


**Table 4.16 Statistical Summary of Woodbine Transmissivity from Pumping Tests ($ft^2$/day)**

| Woodbine | Value |
|---|---|
| ***Number of Samples*** | 35 |
| ***Average T*** | 660.2 |
| ***Standard Deviation T*** | 757.7 |
| ***Average of Log T*** | 2.6 |
| ***Standard Deviation of Log T*** | 0.45 |
| ***Geometric Mean T*** | 398.5 |

**Figure 4.64 Woodbine Transmissivity Histogram**




***Paluxy*** - Transmissivity estimates from these pumping tests ranged from 169 to 1,846 $ft^2$/day. Storage coefficients were reported to range from 1.4 x $10^{-4}$ to 3.4 x $10^{-4}$ and specific yields were approximately 15 to 20 percent.

A statistical analysis of the available hydraulic conductivity data for the Paluxy is presented in Table 4.17 and Figure 4.65. There are 29 values of hydraulic conductivity from pumping tests with an average of 5.8 ft/day and a standard deviation of 3.5 ft/day. The geometric mean of the hydraulic conductivity is 4.9 ft/day. Transmissivity statistics from pumping tests in the Paluxy are presented in Table 4.18 and Figure 4.66. An average transmissivity of 730 $ft^2$/day with a standard deviation of 439 $ft^2$/day was calculated from 35 pumping tests.. The geometric mean of the Paluxy transmissivities is 612 $ft^2$/day.

**Table 4.17 Statistical Summary of Paluxy Hydraulic Conductivity (ft/day)**

| Paluxy | Value |
|---|---|
| *Number of Samples* | 29 |
| *Average K* | 5.8 |
| *Standard Deviation K* | 3.5 |
| *Average of Log K* | 0.7 |
| *Standard Deviation of Log K* | 0.27 |
| *Geometric Mean K* | 4.9 |

**Figure 4.65 Paluxy Hydraulic Conductivity Histogram**

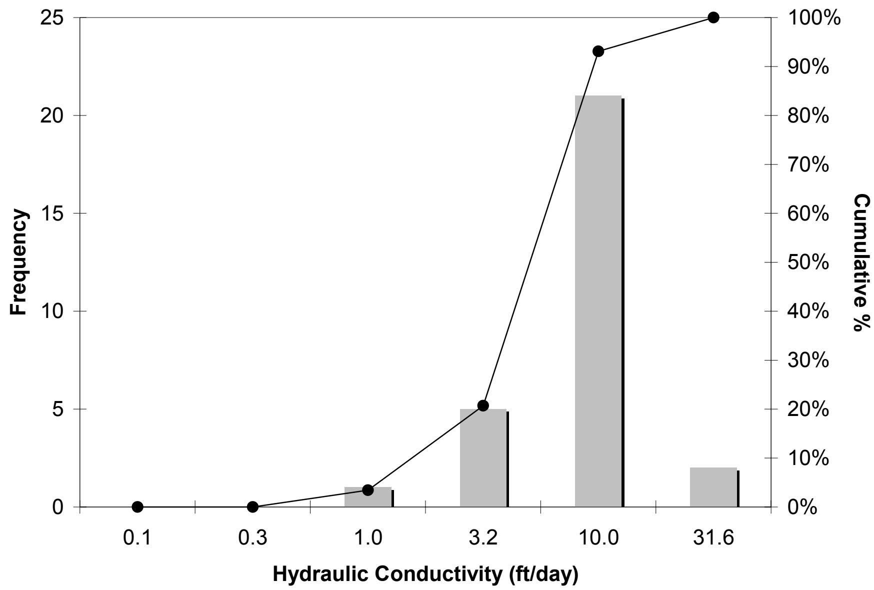
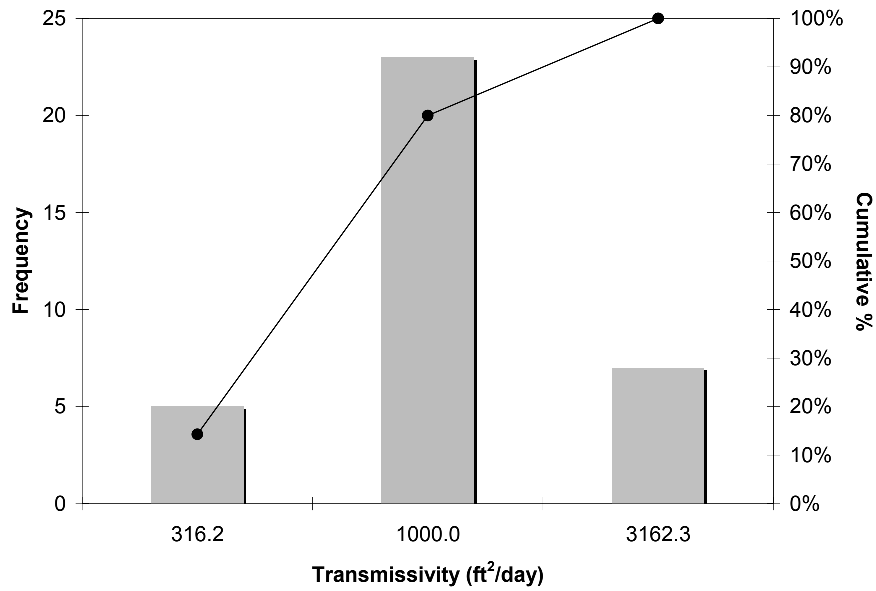



**Table 4.18 Statistical Summary of Paluxy Transmissivity from Pumping Tests ($ft^2$/day)**

| Paluxy | Value |
|---|---|
| *Number of Samples* | 35 |
| *Average T* | 730.5 |
| *Standard Deviation T* | 439.4 |
| *Average of Log T* | 2.8 |
| *Standard Deviation of Log T* | 0.27 |
| *Geometric Mean T* | 612.0 |

**Figure 4.66 Paluxy Transmissivity Histogram**




***Hensell*** - The Hensell member of the Travis Peak Formation is an important water-bearing formation in the study area. In the central portion of the study area, the Hensell is productive and has been extensively developed. In other parts of the study area, the Hensell is not as productive and therefore, data on the hydraulic properties is limited.

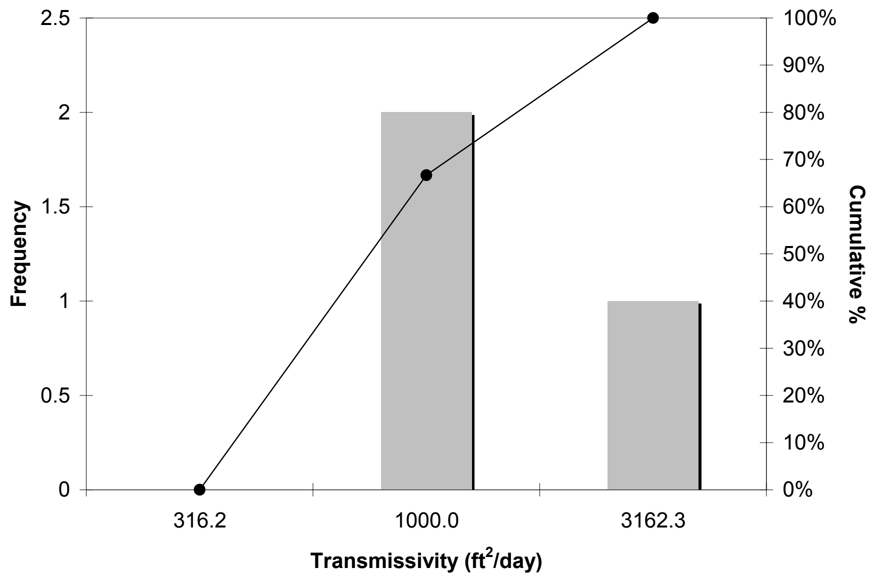
According to Klemt et al. (1975), in the artesian portions of the Hensell, coefficients of hydraulic conductivity range from 3.5 to 17 ft/day. Because the Hensell thins and pinches out down dip, transmissivities can range from nearly zero where it pitches out to 2,000 $ft^2$/day. There is one reported hydraulic conductivity value of 13.3 ft/day, which was obtained from a pumping test in Central Texas. Likewise, there is only one measured storativity value, 8 x $10^{-4}$, which was calculated from the results of a test conducted in Hamilton County.

Table 4.19 shows the statistical analysis of transmissivity values from the pumping tests results for the Hensell. Based on data in Klemt et al. (1975), there are three transmissivity values reported for the Hensell specifically. The average transmissivity of these three values is 932 $ft^2$/day with a standard deviation of 536 $ft^2$/day. The geometric mean of the Hensell transmissivities is 842 $ft^2$/day. The chart in Figure 4.67 displays the distribution of Hensell transmissivities reported by Klemt et al.

**Table 4.19 Statistical Summary of Hensell Transmissivity from Pumping Tests ($ft^2$/day)**

| Hensell | *Value* |
|---|---|
| ***Number of Samples*** | 3 |
| ***Average T*** | 931.6 |
| ***Standard Deviation T*** | 536.4 |
| ***Average of Log T*** | 2.9 |
| ***Standard Deviation of Log T*** | 0.23 |
| ***Geometric Mean T*** | 841.6 |

**Figure 4.67 Hensell Transmissivity Histogram**




***Hosston*** –A statistical analysis of hydraulic conductivity data from pumping tests for the Hosston is presented in Table 4.20 and Figure 4.68. The average hydraulic conductivity value is 12 ft/day with a standard deviation of 11 ft/day for 117 values calculated from pump test results. The geometric mean of hydraulic conductivity for the Hosston is 8 ft/day. Transmissivity statistics for the Hosston pumping test results are presented in Table 4.21 and Figure 4.69. There are 146 pumping test results with an average transmissivity of 1,098 $ft^2$/d and a standard deviation of 685 $ft^2$/d. The Hosston transmissivity data has geometric mean of 862 $ft^2$/d.

**Table 4.20 Statistical Summary of Hosston Hydraulic Conductivity (ft/day)**

| Hosston | Value |
|---|---|
| ***Number of Samples*** | 117 |
| ***Average K*** | 12.1 |
| ***Standard Deviation K*** | 10.7 |
| ***Average of Log K*** | 0.9 |
| ***Standard Deviation of Log K*** | 0.44 |
| ***Geometric Mean K*** | 7.9 |

**Figure 4.68 Hosston Hydraulic Conductivity Histogram**

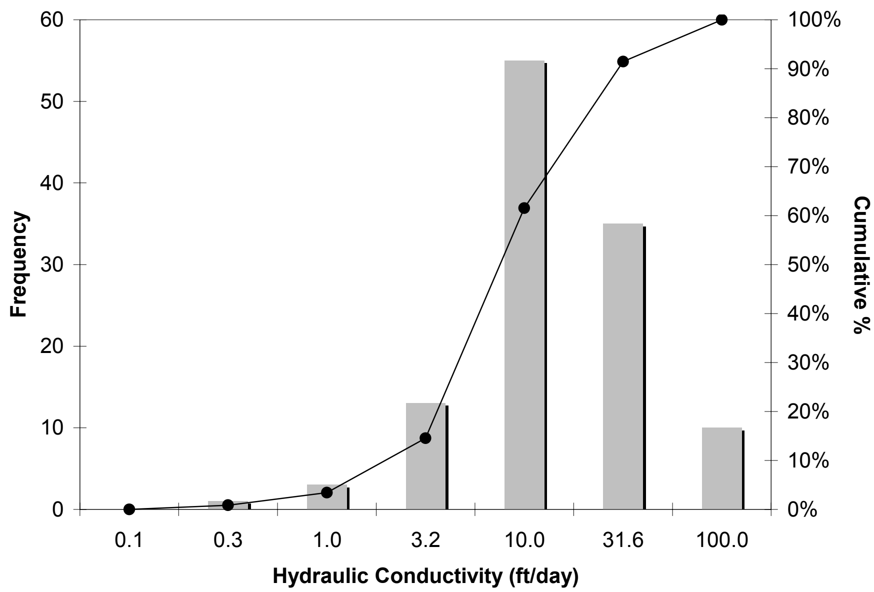
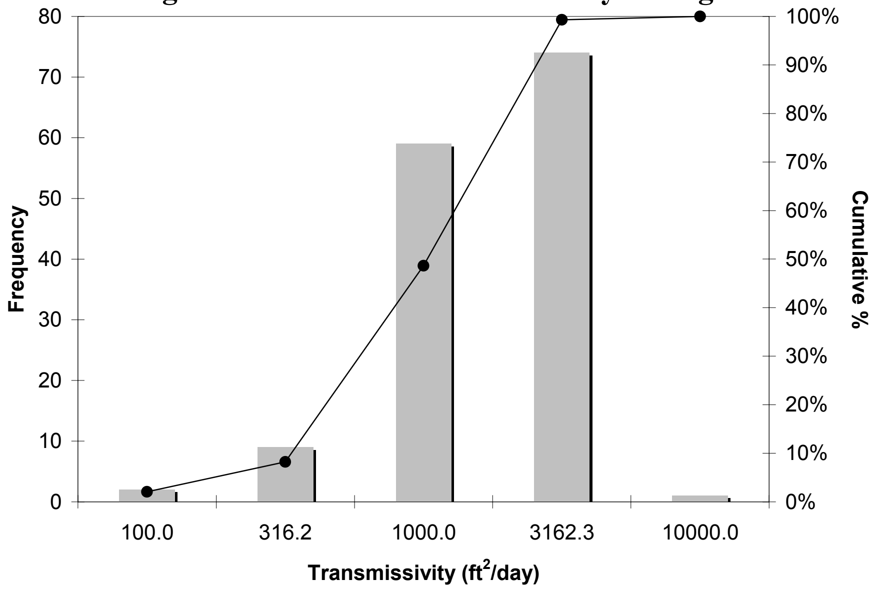



**Table 4.21 Statistical Summary of Hosston Transmissivity from Pumping Tests ($ft^2$/day)**

| Hosston | Value |
|---|---|
| ***Number of Samples*** | 146 |
| ***Average T*** | 1098.0 |
| ***Standard Deviation T*** | 684.8 |
| ***Average of Log T*** | 2.9 |
| ***Standard Deviation of Log T*** | 0.35 |
| ***Geometric Mean T*** | 862.4 |

Figure 4.69 Hosston Transmissivity Histogram




### 4.8.2 Aquifer Storage Coefficients

There is comparatively little data pertaining to the storage coefficients of the aquifers in the study area. Of the 65 reported storativity values, seven relate to the Woodbine and range from $2.0 \times 10^{-5}$ to $7.4 \times 10^{-4}$ and have an average of $2.1 \times 10^{-4}$. There are nine storativity values for the Paluxy that range from $4.0 \times 10^{-5}$ to $1.9 \times 10^{-2}$ with an average of $2.23 \times 10^{-3}$. As mentioned above, there is only one storativity record for the Hensell with a value of $8 \times 10^{-4}$. The remaining 48 values pertain to the Hosston. The average of these data is $1.07 \times 10^{-2}$ with a range from $2.0 \times 10^{-5}$ to 0.13.

## 4.9 Discharge

Natural discharge from the Trinity/Woodbine occurs through various avenues. Discharge to rivers, streams, springs, seeps, and evapotranspiration represent groundwater releases at or near the surface in outcrop areas. In downdip areas, natural discharge from the Trinity/Woodbine aquifers occurs as leakage across the Luling-Mexia-Talco Fault Zone, and as vertical, interformational leakage.

As shown in Figure 4.70 through 4.72, numerous springs are distributed throughout the model area, with the greatest concentrations in the northern and central portions of Texas (Brune, 2002). The discharge from these springs is generally small (less than 1 cubic foot per second), and likely show significant seasonal variation. The amount of groundwater lost to seeps is much more difficult to quantify; the locations and fluxes of seeps in the Trinity/Woodbine outcrop have never been documented due to the difficulty of doing so. Given the incised, dendritic nature of the drainage pattern associated with the aquifer outcrop zones, the amount of discharge that is attributable to seeps is likely an important portion of the aquifer water budget. Evapotranspiration includes the removal of groundwater from the water table through transpiration by plants and by direct evaporation at the surface and shallow subsurface. Although the rates of evaporation are poorly known, published potential evapotranspiration and lake evaporation rates suggest that up to several feet of water per year in outcrop zones may be extracted from the aquifer sediments by this mechanism when water table levels are near the surface (Dingman, 1994).

Groundwater released to surface water bodies including lakes, rivers, and streams also serves as a means of aquifer discharge. However, the magnitude and scope of this discharge is heavily dependent upon the local permeability of lake and riverbed sediments, as well as the relative position of surface and groundwater levels. The interactions between Trinity/Woodbine surface and groundwater are discussed in Section 4.6.

A large number of wells were completed in the Trinity/Woodbine during the last 120 years. The location and amount of groundwater withdrawal shifted as population density and the utilization of surface water sources fluctuated over time. Complete records of historical pumpage do not readily exist. Pumpage records beginning in 1980 were obtained from the TWDB. Pumpage records were also obtained from the Oklahoma Water Resource Board. Pumpage for Arkansas was collected from a past water plan report and extrapolated into the future. Prior to 1980, it was assumed for the modeling purposes of this study that a linear increase in pumpage occurred from 1880 to the 1980 level. Assignments of pumpage for later years (1980 – 2050) required the review and analysis of data from many sources. Figure 4.73 graphs the total pumpage applied to the model through time and Tables 4.22 and 4.23 list the total pumpage assigned to the model in acre-feet per year (ac-ft/yr) by county for the Trinity and Woodbine, respectively. It should be noted that pumpage within the model boundary that is allocated to hydrostratigraphic units other than the Trinity and/or Woodbine (ex: Fredericksburg, Washita, and Wilcox Groups) is not included in Tables 4.22 and 4.23. In addition, many county, river basin, and census block areas straddle the active model boundary. In these regions, only the percentage of the total estimated use (corresponding to the percentage of areal coverage of the active model area) is included in the totals listed. The following discussions describe the methods used to assign pumpage within the model area.

### 4.9.1 Municipal, Power, Mining, and Manufacturing Discharge

Water use survey data compiled by the Texas Water Development Board were used in point source assignment of discharge. The point sources consisted of municipal, power, mining and manufacturing discharge.

Texas Water Development Board water use survey reported discharge was assigned a physical location(s) that existed either in the Texas Water Development Board groundwater database or the TCEQ Public Water Supply (PWS) database. Water use survey discharge without a corresponding physical location in either database were manually assigned an estimated physical location based on the pumping entities physical location.

Water use survey reported discharge was vertically distributed based on the aquifer code and well screen/model layer analysis from the respective database.

### 4.9.2 Rural Domestic Discharge

Rural domestic discharge was spatially distributed based on population density. Coverages of 1990 and 2000 US Census data at the block level were used to estimate population densities. Rural domestic discharge was not distributed to US Census blocks that were potentially being supplied groundwater by a municipal source. Census blocks potentially being supplied groundwater by a municipal source were identified as those census blocks that coincided with city limits that were within 1 mile of an identified point source of municipal discharge as identified in the Texas Water Development Board Water Use Survey.

Rural domestic discharge amounts were derived from a per capita use estimation compiled by the Texas Water Development Board. This discharge was then spatially distributed to the non-city US Census blocks based on population density. US Census data from the 1990 census were used to spatially distribute water use survey discharge from 1980 to 1990 (Figure 4.74). US Census data from the 2000 census were used to spatially distribute water use survey discharge from 1991 to 1999 (Figure 4.75).

The spatially distributed discharge was then vertically distributed to the model layers based on the ratio of existing domestic wells in the Texas Water Development Board groundwater database completed in the corresponding model layer in the same basin/county unit.

### 4.9.3 Irrigation Discharge

Land cover data derived from early 1990s 1-km resolution Advanced Very High-Resolution Radiometer (AVHRR) imagery were used to delineate areas with potential irrigation production. The coverage of the Texas Water Development Board 1994 irrigated farmlands survey was found to correspond well with the AVHRR coverage where farmlands survey coverage existed. The farmlands survey coverage was sparse in the model area and therefore the AVHRR was used to delineate areas of potential irrigation production. The coverage of land use data derived from mid 1970s to mid 1980s LANDSAT Thematic Mapper Imagery coverage (Anderson Level 1 classification: 2-Agricultural Land) matched consistently with delineations from the AVHRR coverage (Land Cover Class Definitions 83-Row Crops and 83-Small Grains). The AVHRR coverage was used to define areas of potential irrigation production as they provided a good estimation of average acre-ft per acre irrigation values as compared to that reported by the 1998 Farm & Ranch Irrigation Survey Census of Agriculture. The AVHRR coverage was utilized rather than the LANDSAT coverage because of its use of a modified Anderson Classification scheme using a breakdown of row crops and small grains which match the crop descriptions used for estimating historical discharge.

Irrigation discharge was derived from a cooperative survey effort by the Texas Water Development Board, Texas State Soil and Water Conservation Board, and the U.S. Natural Resources Conservation Service and compiled by the Texas Water Development Board. These discharge values were then spatially distributed to the coverage delineated by the AVHRR imagery on an area-weighted basis.

The spatially distributed discharge was then vertically distributed to the model layers based on the ratio of existing irrigation wells in the Texas Water Development Board groundwater database completed in the corresponding model layer in the same basin/county unit. This vertical distribution ratio was augmented by model layer thickness and interpretation of productivity potential.

### 4.9.4 Livestock Discharge

Land use data derived from mid 1970s to mid 1980s LANDSAT Thematic Mapper Imagery were used to delineate areas with potential livestock production. The Anderson Level 2 classifications of 31 herbaceous rangeland, 32 shrub and brush rangeland and 33 mixed rangeland were used to approximate areas of potential livestock production. Land cover data derived from early 1990s 1-km resolution AVHRR imagery were not used to delineate potential livestock as it did not contain a breakdown classification that would appropriately identify potential livestock production areas. The nearest classification in MRCL would have been 51-Shrubland or 71-Grasslands/Herbaceous or possibly 81-Pasture/Hay. None of these classifications effectively mapped to a reasonable distribution of rangeland. Using an overlay of stock wells from the Texas Water Development Board groundwater database it was determined that the USGS LULC 250 files would give a much better definition of rangeland delineation for potential livestock production areas.

Historical livestock discharge was estimated from reported animal populations and assigned a per-head annual water usage value by the Texas Water Development Board. These discharge values were then spatially distributed to the coverage delineated by the LANDSAT imagery on an area-weighted basis.

The spatially distributed discharge was then vertically distributed to the model layers based on the ratio of existing livestock wells in the Texas Water Development Board groundwater database completed in the corresponding model layer in the same basin/county unit. This vertical distribution ratio was augmented by model layer thickness and weighted more heavily to upper model layers.

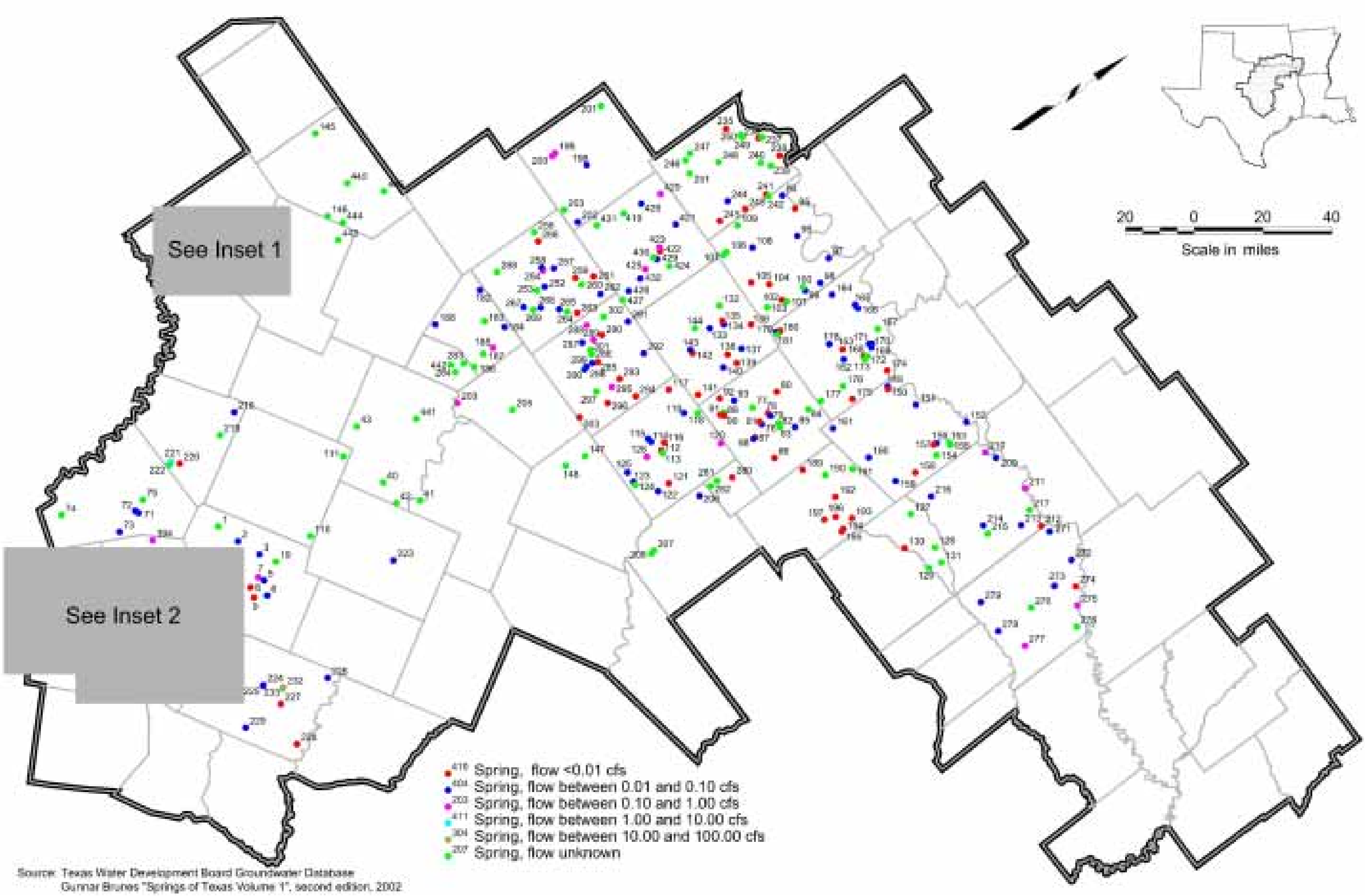



**Figure 4.70 Spring Locations**

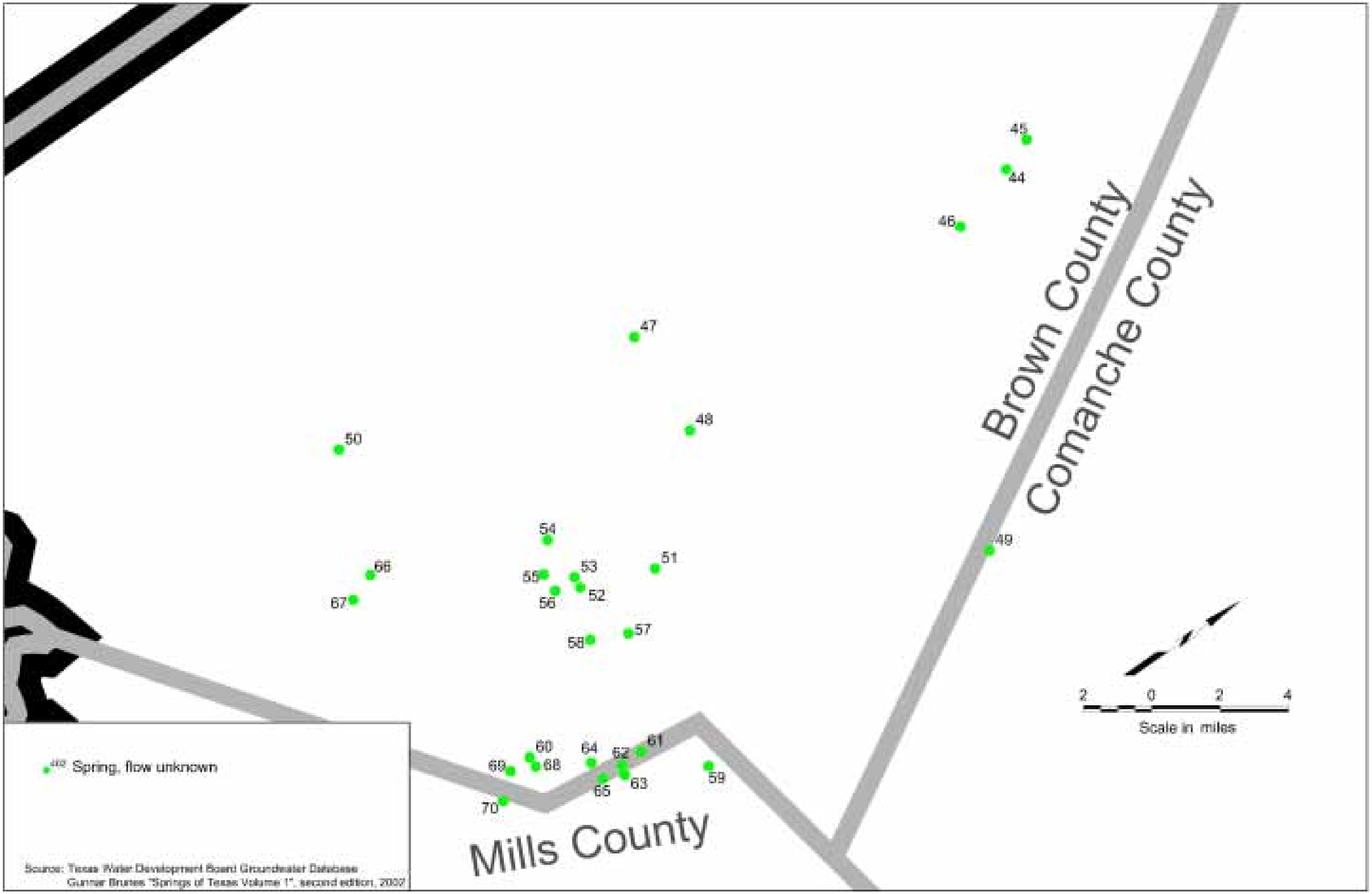



**Figure 4.71 Spring Locations – Inset 1**

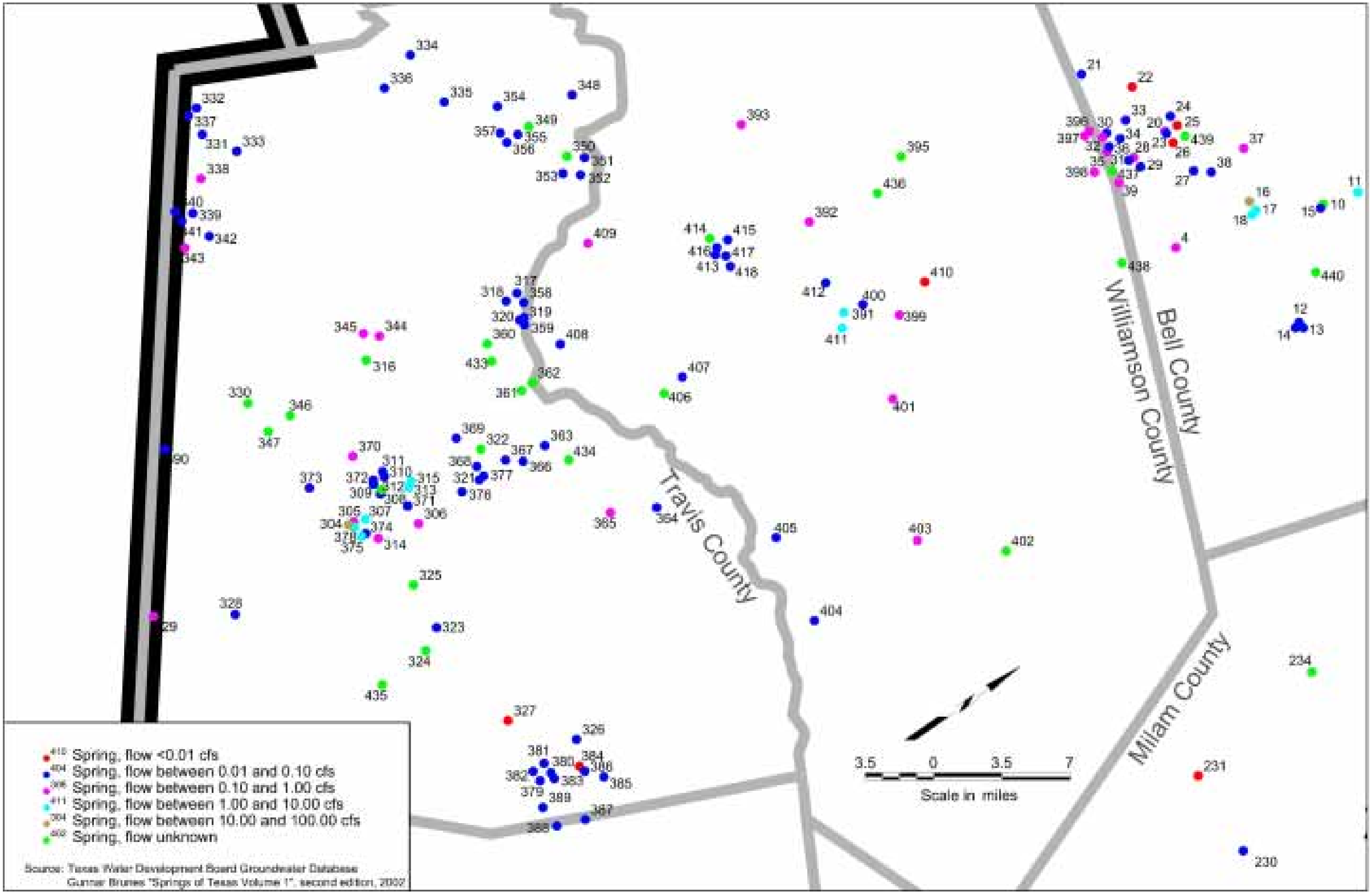



**Figure 4.72 Spring Locations – Inset 2**

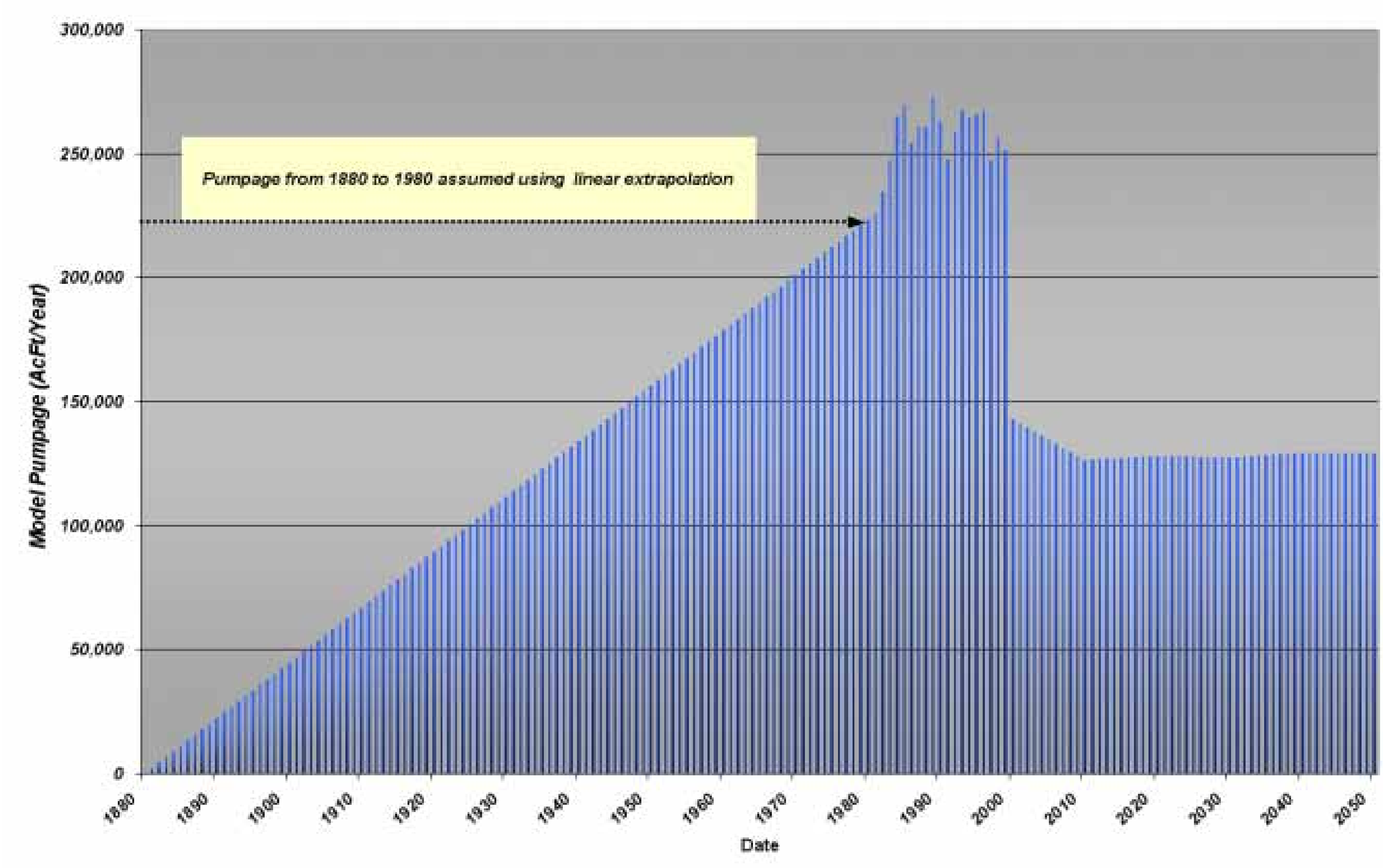



**Figure 4.73 Yearly Historical and Predictive Pumpage**

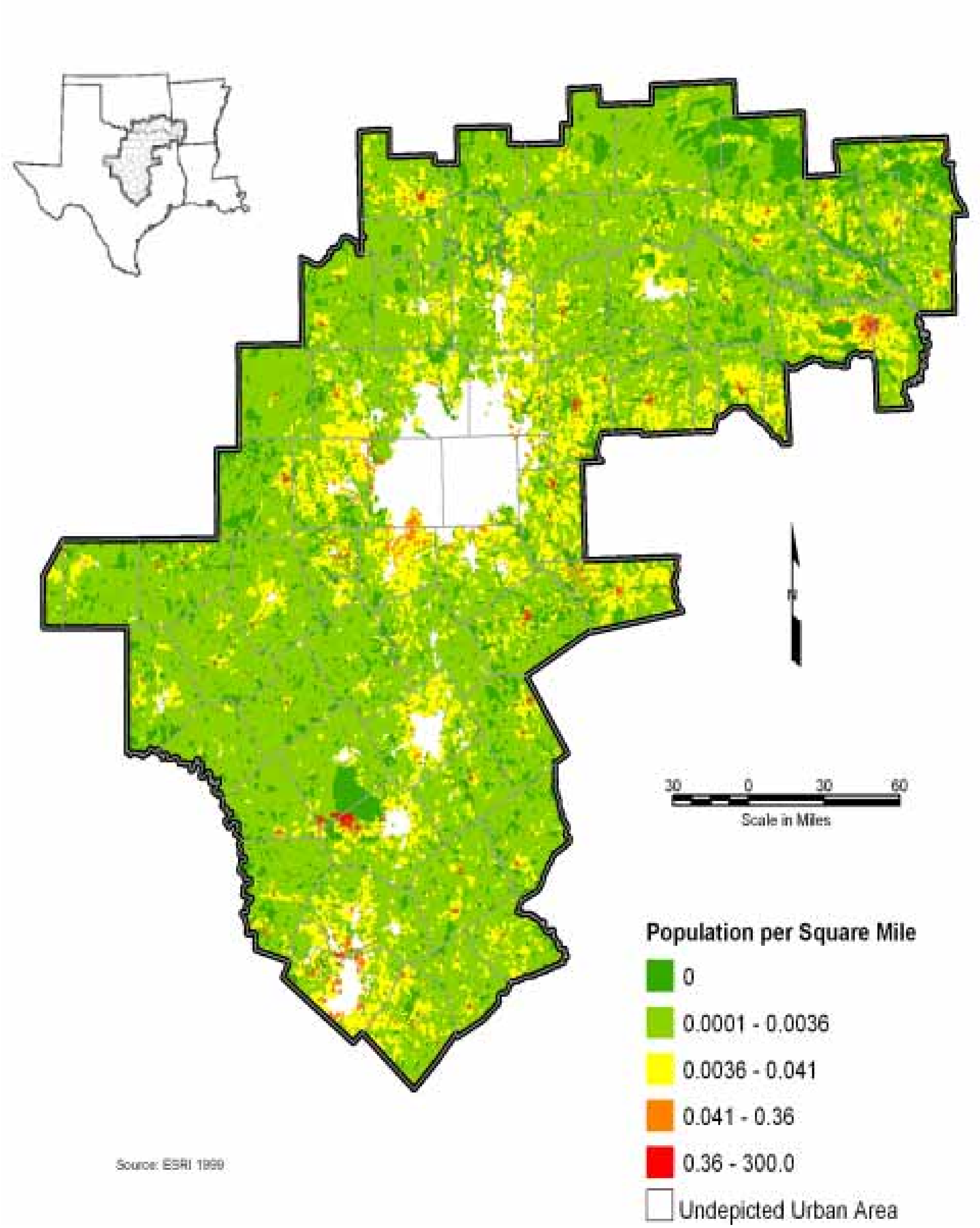



**Figure 4.74 Rural Population Density 1990**

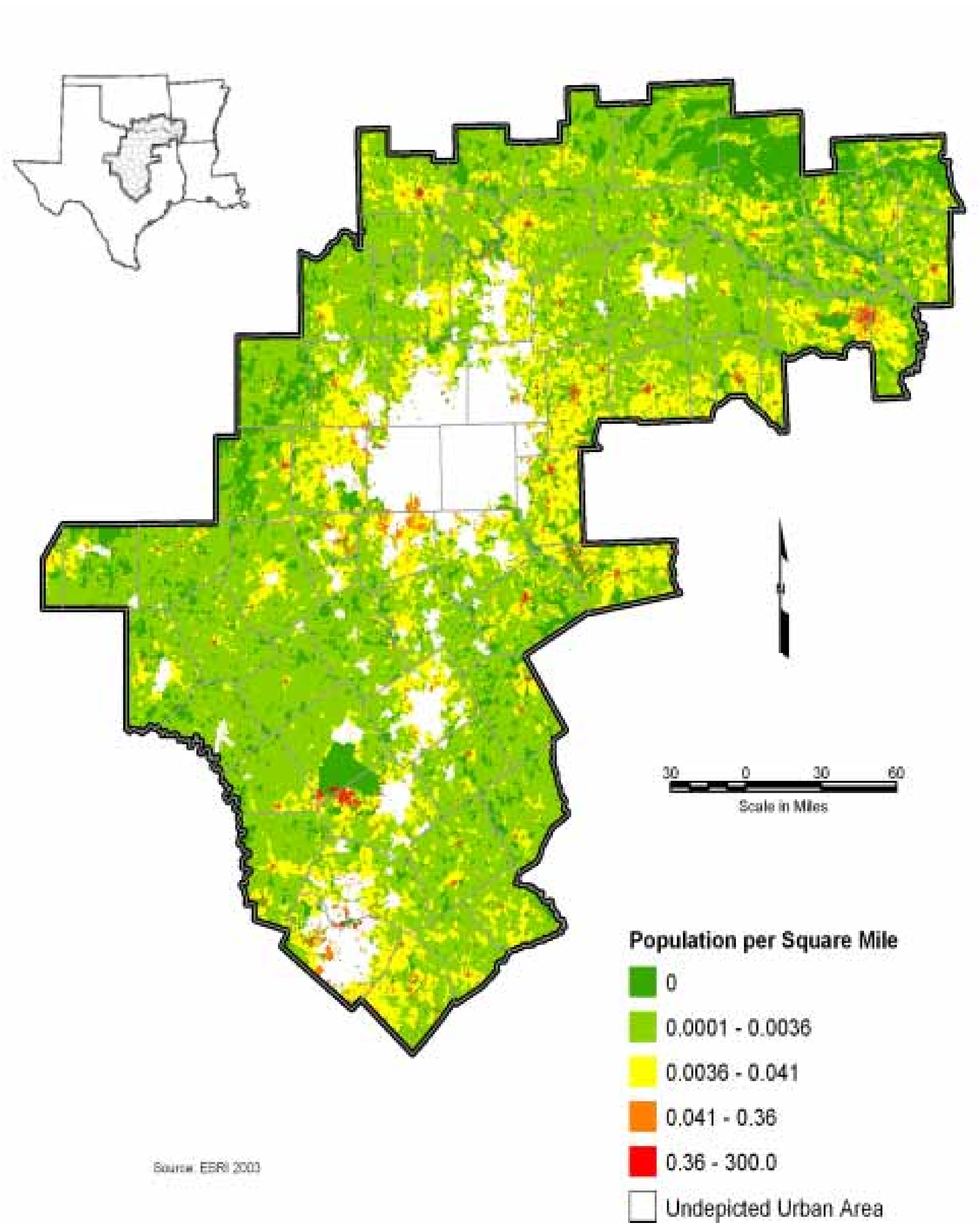



**Figure 4.75 Rural Population Density 2000**

## Table 4.22 Historical and Projected Trinity Groundwater Use (ac-ft/yr)

| | County | 1980* | 1990* | 2000** | 2010** | 2020** | 2030** | 2040** | 2050** |
|---|---|---|---|---|---|---|---|---|---|
| Texas | ***Bastrop*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Bell*** | 2,322 | 2,251 | 511 | 505 | 573 | 632 | 646 | 658 |
| | ***Bosque*** | 2,813 | 3,665 | 1,560 | 1,375 | 1,418 | 1,464 | 1,521 | 1,656 |
| | ***Bowie*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Brown*** | 839 | 1,042 | 1,823 | 1,769 | 1,786 | 1,805 | 1,802 | 1,787 |
| | ***Burleson*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Burnet*** | 501 | 712 | 676 | 742 | 833 | 882 | 897 | 889 |
| | ***Callahan*** | 1,338 | 1,117 | 1,858 | 1,809 | 1,704 | 1,632 | 1,556 | 1,528 |
| | ***Collin*** | 1,414 | 2,056 | 1,114 | 1,792 | 2,410 | 2,450 | 2,646 | 2,595 |
| | ***Comanche*** | 11,171 | 26,538 | 21,053 | 21,033 | 21,018 | 21,014 | 21,010 | 21,018 |
| | ***Cooke*** | 5,809 | 5,977 | 6,995 | 3,961 | 3,936 | 3,402 | 3,454 | 3,517 |
| | ***Coryell*** | 4,237 | 1,911 | 1,551 | 1,564 | 1,582 | 1,581 | 1,562 | 1,540 |
| | ***Dallas*** | 14,581 | 7,402 | 4,869 | 5,078 | 3,163 | 3,514 | 3,550 | 3,450 |
| | ***Delta*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Denton*** | 8,041 | 8,919 | 6,216 | 4,365 | 5,034 | 4,585 | 4,747 | 4,569 |
| | ***Eastland*** | 9,643 | 8,496 | 6,762 | 6,761 | 6,824 | 6,807 | 6,795 | 6,778 |
| | ***Ellis*** | 2,767 | 5,030 | 4,649 | 2,833 | 2,940 | 2,621 | 2,714 | 2,770 |
| | ***Erath*** | 13,757 | 14,219 | 14,440 | 13,640 | 13,721 | 13,799 | 13,817 | 13,857 |
| | ***Falls*** | 133 | 66 | 43 | 41 | 42 | 43 | 45 | 47 |
| | ***Fannin*** | 0 | 0 | 425 | 392 | 422 | 368 | 358 | 342 |
| | ***Franklin*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Grayson*** | 6,707 | 6,593 | 5,455 | 3,934 | 4,033 | 4,028 | 3,575 | 3,706 |
| | ***Hamilton*** | 2,617 | 2,072 | 1,603 | 1,547 | 1,498 | 1,390 | 1,358 | 1,296 |
| | ***Henderson*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Hill*** | 1,852 | 1,094 | 748 | 740 | 749 | 789 | 826 | 861 |
| | ***Hood*** | 2,684 | 4,182 | 3,969 | 3,950 | 4,448 | 4,898 | 5,104 | 5,315 |
| | ***Hopkins*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Hunt*** | 0 | 0 | 193 | 194 | 195 | 192 | 194 | 171 |
| | ***Jack*** | 0 | 0 | 534 | 508 | 494 | 475 | 447 | 421 |
| | ***Johnson*** | 5,408 | 6,725 | 1,901 | 1,749 | 1,872 | 2,014 | 1,938 | 2,024 |
| | ***Kaufman*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Lamar*** | 56 | 56 | 282 | 690 | 676 | 607 | 607 | 519 |
| | ***Lampasas*** | 978 | 1,009 | 743 | 736 | 736 | 737 | 739 | 742 |
| | ***Lee*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Limestone*** | 11 | 13 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***McLennan*** | 10,748 | 10,853 | 1,517 | 1,455 | 1,434 | 1,458 | 1,435 | 1,436 |
| | ***Milam*** | 0 | 0 | 136 | 139 | 140 | 140 | 140 | 139 |
| | ***Mills*** | 1,164 | 1,088 | 1,242 | 1,222 | 1,210 | 1,172 | 1,156 | 1,115 |
| | ***Montague*** | 253 | 278 | 431 | 402 | 394 | 380 | 368 | 349 |
| | ***Morris*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Navarro*** | 0 | 0 | 32 | 34 | 35 | 37 | 38 | 39 |
| | ***Palo Pinto*** | 0 | 0 | 114 | 128 | 141 | 145 | 148 | 156 |
| | ***Parker*** | 3,155 | 5,646 | 4,468 | 2,326 | 2,846 | 2,186 | 2,587 | 2,568 |
| | ***Red River*** | 169 | 162 | 29 | 29 | 26 | 28 | 28 | 28 |
| | ***Robertson*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Rockwall*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Somervell*** | 1,053 | 1,134 | 1,173 | 755 | 816 | 882 | 962 | 1,053 |
| | ***Tarrant*** | 19,929 | 17,983 | 6,013 | 4,121 | 3,820 | 3,830 | 4,188 | 4,036 |
| | ***Taylor*** | 9 | 11 | 593 | 565 | 549 | 549 | 550 | 556 |
| | ***Titus*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Travis*** | 4,177 | 6,061 | 204 | 207 | 274 | 516 | 529 | 451 |
| | ***Williamson*** | 4,116 | 6,415 | 895 | 736 | 867 | 989 | 1,098 | 1,161 |
| | ***Wise*** | 2,939 | 3,788 | 4,043 | 3,426 | 3,599 | 2,869 | 3,159 | 2,997 |

**Table 4.22 Historical and Projected Trinity Groundwater Use (ac-ft/yr) – Continued**

| | County | 1980* | 1990* | 2000** | 2010** | 2020** | 2030** | 2040** | 2050** |
|---|---|---|---|---|---|---|---|---|---|
| Oklahoma | ***Atoka*** | 112 | 233 | 200 | 200 | 200 | 200 | 200 | 200 |
| | ***Bryan*** | 1,469 | 1,145 | 2,597 | 2,597 | 2,597 | 2,597 | 2,597 | 2,597 |
| | ***Carter*** | 82 | 139 | 66 | 66 | 66 | 66 | 66 | 66 |
| | ***Choctaw*** | 372 | 412 | 490 | 490 | 490 | 490 | 490 | 490 |
| | ***Johnston*** | 58 | 576 | 726 | 726 | 726 | 726 | 726 | 726 |
| | ***Love*** | 3,074 | 2,177 | 1,932 | 1,932 | 1,932 | 1,932 | 1,932 | 1,932 |
| | ***Marshall*** | 964 | 588 | 1,038 | 1,038 | 1,038 | 1,038 | 1,038 | 1,038 |
| | ***McCurtain*** | 90 | 77 | 143 | 143 | 143 | 143 | 143 | 143 |
| | ***Pushmataha*** | 5 | 7 | 10 | 10 | 10 | 10 | 10 | 10 |
| Arkansas | ***Hempstead*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Howard*** | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 |
| | ***Little River*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Miller*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Pike*** | 23 | 23 | 23 | 23 | 23 | 23 | 23 | 23 |
| | ***Sevier*** | 1,530 | 1,530 | 1,530 | 1,530 | 1,530 | 1,530 | 1,530 | 1,530 |

Note: Only includes use within the active model area.
* Values derived from reported historical pumpage.
** Values derived from predicted annual pumpage (RWPG and TWDB estimates).

## Table 4.23 Historical and Projected Woodbine Groundwater Use (ac-ft/yr)

| | County | 1980* | 1990* | 2000** | 2010** | 2020** | 2030** | 2040** | 2050** |
|---|---|---|---|---|---|---|---|---|---|
| Texas | ***Bastrop*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Bell*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Bosque*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Bowie*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Brown*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Burleson*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Burnet*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Callahan*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Collin*** | 1,786 | 2,353 | 787 | 1,075 | 1,518 | 1,500 | 1,670 | 1,605 |
| | ***Comanche*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Cooke*** | 79 | 108 | | 77 | 75 | 84 | 82 | 81 |
| | ***Coryell*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Dallas*** | 3,593 | 2,117 | 2,800 | 2,671 | 2,419 | 2,600 | 2,628 | 2,574 |
| | ***Delta*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Denton*** | 1,815 | 2,302 | 1,258 | 820 | 879 | 898 | 929 | 912 |
| | ***Eastland*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Ellis*** | 3,155 | 5,202 | 1,777 | 978 | 1,039 | 1,113 | 1,156 | 1,201 |
| | ***Erath*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Falls*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Fannin*** | 1,432 | 2,072 | 2,741 | 2,554 | 2,707 | 2,841 | 2,919 | 3,002 |
| | ***Franklin*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Grayson*** | 11,074 | 11,340 | 6,329 | 4,646 | 4,621 | 4,667 | 4,799 | 4,691 |
| | ***Hamilton*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Henderson*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Hill*** | 883 | 866 | 851 | 837 | 840 | 851 | 946 | 1,120 |
| | ***Hood*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Hopkins*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Hunt*** | 79 | 103 | 583 | 633 | 834 | 805 | 815 | 820 |
| | ***Jack*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Johnson*** | 1,480 | 2,386 | 798 | 759 | 786 | 829 | 813 | 832 |
| | ***Kaufman*** | 97 | 80 | 117 | 96 | 96 | 96 | 96 | 96 |
| | ***Lamar*** | 140 | 145 | 2,450 | 2,400 | 2,352 | 2,365 | 2,318 | 2,344 |
| | ***Lampasas*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Lee*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Limestone*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Mclennan*** | 0 | 0 | 14 | 14 | 14 | 14 | 14 | 14 |
| | ***Milam*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Mills*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Montague*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Morris*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Navarro*** | 58 | 80 | 152 | 155 | 157 | 161 | 162 | 163 |
| | ***Palo Pinto*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Parker*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Red River*** | 3 | 3 | 143 | 143 | 143 | 143 | 143 | 143 |
| | ***Robertson*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Rockwall*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Somervell*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Tarrant*** | 349 | 445 | 621 | 728 | 740 | 670 | 732 | 676 |
| | ***Taylor*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Titus*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Travis*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Williamson*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Wise*** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 4.23 Historical and Projected Woodbine Groundwater Use (ac-ft/yr) – Continued**

| | County | 1980* | 1990* | 2000** | 2010** | 2020** | 2030** | 2040** | 2050** |
|---|---|---|---|---|---|---|---|---|---|
| Oklahoma | Atoka | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Bryan | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Carter | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Choctaw | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Johnston | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Love | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Marshall | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Mccurtain | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Arkansas | Pushmataha | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Hempstead | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Howard | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Little River | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Miller | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Pike | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Note: Only includes use within the active model area.
* Values derived from reported historical pumpage.
** Values derived from predicted annual pumpage (RWPG and TWDB estimates).

# 5.0 CONCEPTUAL MODEL OF FLOW IN THE TRINITY/WOODBINE

The construction and implementation of reliable groundwater models is a multi-step process. The development of a basic understanding and appreciation of the fundamental processes that drive groundwater flow in an aquifer is paramount in this procedure. This overall understanding is defined as a conceptual model, which affects all other model construction tasks, as well as the interpretation of model predictions. In its most basic form, the conceptual model identifies and defines the hydrostratigraphic units of interest, their recharge and discharge relationships, hydraulic properties and boundary conditions. An in-depth assessment of pertinent geologic structure, lithology and stratigraphy, physiography, groundwater uses, surface/groundwater interaction, and climate of the model region is necessary to properly define the hydrodynamic conceptual model of the Trinity/Woodbine.

The conceptual model for the Trinity/Woodbine aquifer system is one of a water table (unconfined) aquifer on the outcrop, and an artesian (confined) aquifer in downdip regions where less permeable units underlie and cap aquifer sediments. The groundwater flux into the aquifer units occurs through downward percolation of precipitation and water from surface bodies (lakes and streams) to the water table in outcrop areas, and through interformational leakage through confining units. Modes of natural discharge from the Trinity/Woodbine aquifers include surface/groundwater interaction, interformational leakage and evapotranspiration.

Groundwater movement along or across the Luling-Mexia-Talco Fault Zone in the downdip portion of the study area is probably minimal. The clastic texture of the sediments that comprise the displaced aquifer units results in the smearing of relatively insoluble sediments within the fault planes. These pulverized and smeared sediments tend to clog pore spaces and retard groundwater flow. Measurements showing an increase in groundwater salinity near the Luling-Mexia-Talco Fault Zone appear to corroborate this assessment. The increasing salinity gradient suggests that far downdip portions of the aquifer system have experienced comparatively little interaction with fresher, updip groundwater. Therefore, the downdip boundary of the model domain is considered the Luling-Mexia-Talco Fault Zone.

Since the late 1800s, the Trinity/Woodbine has undergone relatively heavy use. As a result, the primary mode of downdip discharge from the Trinity/Woodbine aquifers has been altered. Prior to significant pumpage from the system, outflow from the Trinity/Woodbine in downdip zones occurred primarily through upward percolation of water through confining units to younger sediments (Figure 5.1). However, the exceptionally small hydraulic gradients associated with the estimated predevelopment artesian potentiometric surface coupled with data indicating that the units confining the artesian portion of the system are relatively thick and impermeable suggests that the rate of upward percolation in downdip areas was likely very slow. As a result, the rate of downdip movement of water from outcrop zones within the Trinity/Woodbine was also slow.

Following the introduction of substantial groundwater development, the principal mode of discharge from the Trinity/Woodbine aquifers shifted from natural upward percolation in downdip areas to pumpage by groundwater wells (Figure 5.2). Discharge from these wells created cones of depression in artesian pressure levels that induced interformational leakage from adjoining formations to the production zone. As was the case during predevelopment times, the generally impermeable nature of the confining units dictated that the rate of vertical leakage toward developed sections of the aquifers was low compared to the rate of intra-formational (horizontal) flow toward the wells. The increased horizontal flow increased the rate and amount of groundwater flow from outcrop areas to downdip areas. However, historical measurements indicate that although large reductions in artesian pressure have occurred in downdip areas, significant water level declines have not occurred in unconfined (outcrop) zones during the last 50 years (Figures 4.23 and 4.24). The presence of a hydrologic boundary between pumpage centers and outcrop areas may explain the stability of water table levels. However, the available data indicates generally continuous aquifer sands and an absence of fault and/or permeability boundaries within the model area that could effectively isolate outcrop areas from downdip pumpage centers.

Given the absence of regional hydrologic boundaries, and assuming the historical water level measurements are not in error, this lack of decline in outcrop water levels may be explained in several ways: 1) the volume withdrawn from the aquifer system is small in relation to the water in storage in unconfined zones, and therefore the water table response has been attenuated over time; 2) the capture of surface recharge that was previously not allowed to enter the system (rejected recharge) has maintained outcrop water levels; 3) a combination of large relative storage and recovery of rejected recharge. Regardless of the cause, the lack of water table declines suggests that although the Trinity/Woodbine has been heavily developed, the level of use has not resulted in a significant reduction in the volume of water in storage within the Trinity/Woodbine system.

Figure 8.1 in Section 8 and Figure 9.1 in Section 9 illustrate the application of the conceptual model to specific MODFLOW packages.

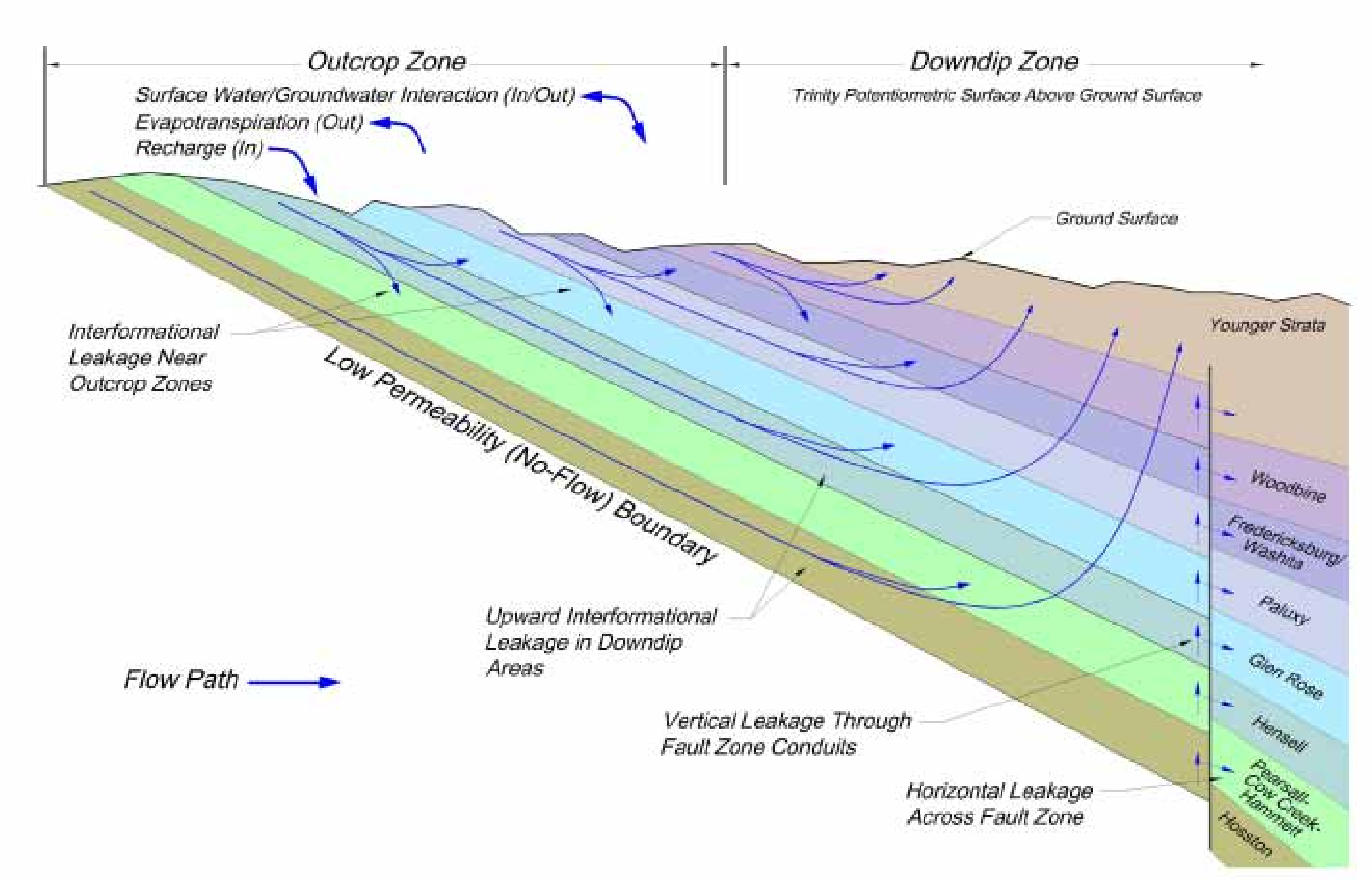



**Figure 5.1 Conceptual Flow – Predevelopment**

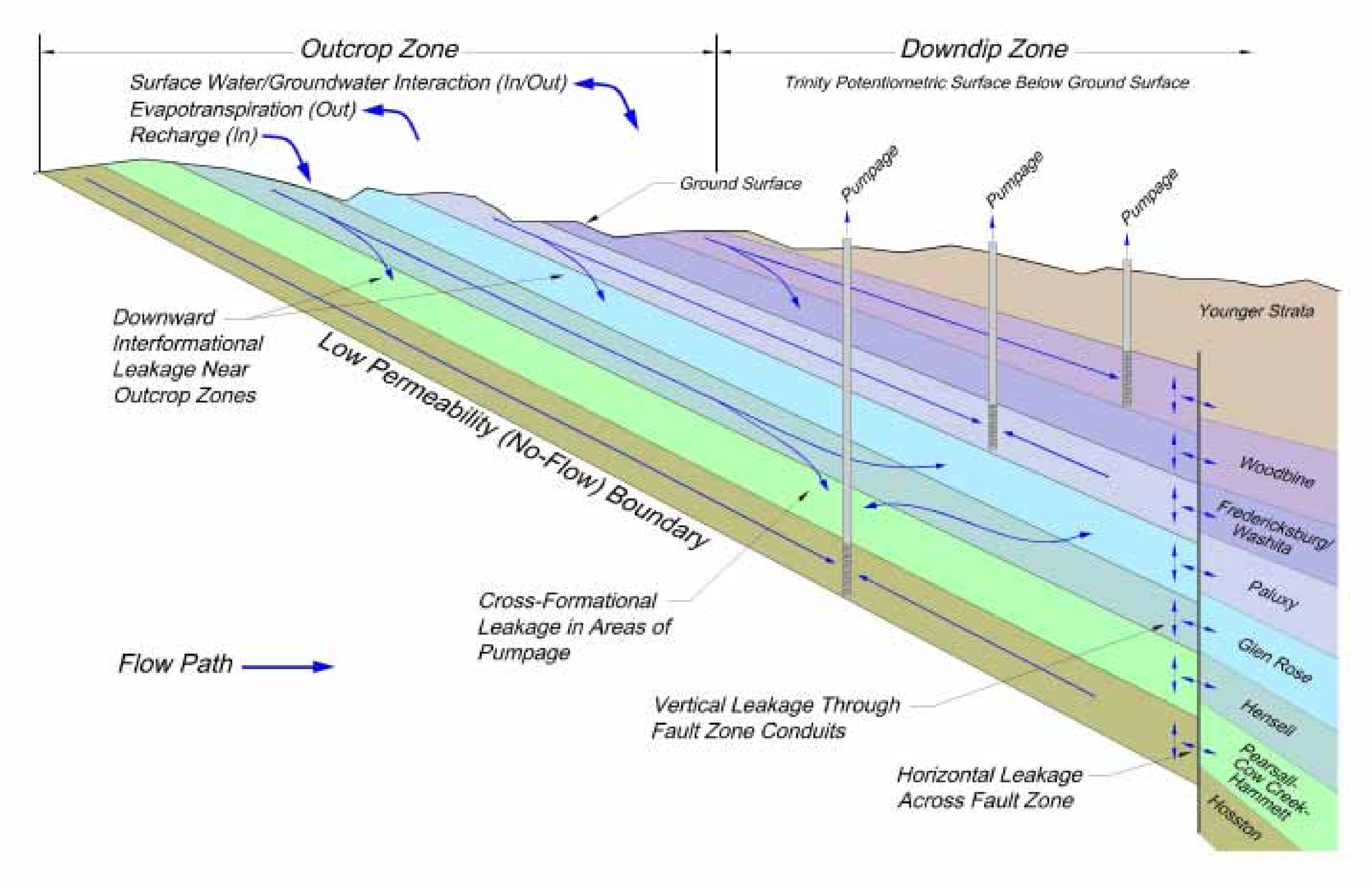



**Figure 5.2 Conceptual Flow – Postdevelopment**

# 6.0 MODEL DESIGN

Model design involves the procedure of determining the best way to apply the fundamental principles of the conceptual model to the framework of the numerical model. This process includes the selection of layer type and geometry, boundary conditions, temporal and spatial discretization, and the model component(s) most suitable to the individual simulated process (i.e. evapotranspiration, recharge, surface/groundwater interaction, etc.). Because model design influences the way in which flows are calculated, this procedure must be tempered with an understanding of the limitations inherent in finite difference numerical simulations and, just as importantly, the purpose of the model.

## 6.1 Numerical Code and Processor

For this project, the MODFLOW-96 code distributed by the USGS (Harbaugh and McDonald, 1996) was utilized. Various versions of MODFLOW have been widely-used to model groundwater flow systems for more than 20 years. The popularity of MODFLOW is primarily the result of the extensive documentation, versatility, reliability, and relative ease of use of the program. However, in an effort to increase the portability of the code, MODFLOW accepts only data stored in text files as input into the model. Because manually constructing MODFLOW input files for large or complex groundwater systems is not practical, a number of third-party programs (processors) have been developed that aid in the process of assembling the necessary input files. One of the most popular of these third-party processors is Processing MODFLOW™ for Windows™ (PMWIN©) (Chiang and Kinzelbach, 2001). If the user prefers to use a processor other than PMWIN©, the MODFLOW-96 input files included with the model can be read and imported relatively quickly.

The Trinity/Woodbine GAM is a large and complex model, which requires substantial computer processing power in order to be run practically. Because of this, it is recommended that the model be run on a system with a Pentium™ 4 or equivalent processor and at least 250 MB of random access memory.

## 6.2 Layers and Grid

The model is comprised of seven layers, whose lateral extent is bounded by the outcrop zones to the north and west of the study area, and by the Luling-Mexia-Talco Fault Zone in downdip areas.

Of the seven model layers, four layers represent the primary aquifer units of interest to this study: Woodbine (Layer 1), Paluxy (Layer 3), Hensell (Layer 5), and Hosston (Layer 7). Separating these aquifers, and generally acting as confining units, are the Fredericksburg/Washita (Layer 2), Glen Rose (Layer 4), and the Pearsall/Cow Creek/ Hammett/Sligo (Layer 6).

In Texas, the locations of faults and aquifer outcrop areas were digitized from the University of Texas Bureau of Economic Geology (BEG) Geologic Atlas of Texas (BEG, various), and Tectonic Map sheets (Ewing, 1990), while the Oklahoma and Arkansas outcrop delineations were extracted from three USGS Open-File Reports (Marcher et al., 1983), (Hart, 1974), (Abbott et al., 1997), and the USGS/AGC Geologic Map of Arkansas (Haley et al., 1993).

Each model layer consists of 353 columns by 281 rows of cells, totaling 694,351 individual cells within the model domain. Of these cells, 220,858 are active in the solution matrix. All cells have uniform 1-mile by 1-mile lateral dimensions, while the thickness was assigned from information collated from geophysical logs distributed throughout the model domain. Figure 6.1 diagrams the boundaries of the model.

## 6.3 Model Parameters

The spatial distribution of model parameters was accomplished using a variety of software packages including Quicksurf™, MS Access™, and ArcView™. Definition of ground level was assigned by collating National Elevation Dataset (NED) information distributed by the USGS into a matrix of points spaced at 2,000-foot intervals. A triangular irregular network (TIN) was formed using these data, which was then utilized to assign the top surface elevation of grid cells in outcrop areas. In downdip areas, the layer elevations were assigned according to the structure defined from TIN surfaces of elevation data compiled from geophysical logs distributed throughout the model area.

For the four primary aquifer layers (Layers 1, 3, 5, and 7), initial values of horizontal hydraulic conductivity were assigned through analysis of pump test results. First, statistical correlation factors were found between net sand distribution (recorded during inspection of geophysical logs) and recorded pump test transmissivities for each of the aquifer layers. The net sand distribution surfaces were then multiplied by these correlation factors in order to extrapolate aquifer transmissivity to areas where no pump test data are available. Finally, these extrapolated transmissivity data were divided by the layer thickness to obtain initial hydraulic conductivity estimates. Further refinements and adjustments to the initial hydraulic conductivity estimates were made during the calibration/verification process. In most cases, these adjustments were achieved by selecting a different (usually reduced) factor by which to multiply the net sand thickness. A Kh value of 0.5 feet per day (ft/day) was assigned to the updip portions of Layer 2 and Layer 4 in the southern portion of the model, while in all other areas the Kh value for those layers was set to 0.1 ft/day. For Layer 6

(Pearsall/Cow Creek/Hammett/Sligo), a single Kh value of 0.01 ft/day was found to satisfy the model calibration requirements.

Very little data exists pertaining to the vertical hydraulic conductivity of the Trinity/Woodbine aquifers. For this reason, constant values were chosen (when appropriate) for these parameters throughout most of the model. Vertical hydraulic conductivity values of $1 \times 10^{-4}$ ft/day were assigned to the four primary aquifer layers (Layers 1, 3, 5, 7), while conductivities of $1 \times 10^{-6}$ ft/day and $2 \times 10^{-5}$ ft/day were assigned to the Fredericksburg/Washita (Layer 2) and the Pearsall/Cow Creek/Hammett/Sligo (Layer 6), respectively.

As with vertical hydraulic conductivity, reports of the storage coefficients measured within Trinity/Woodbine sediments are scarce and are not evenly distributed throughout the study area. Because of this, constant values were selected for the model as a whole: values of $1 \times 10^{-4}$ and 0.15 were applied to the artesian storage coefficient (storativity) and unconfined storage coefficient (specific yield), respectively.

## 6.4 Model Boundaries

In the model, MODFLOW packages were used to simulate recharge, evapotranspiration, stream/aquifer interaction, reservoir/aquifer interaction, pumping, and outer boundaries. Special notice should be given to the use of the River Package to simulate reservoirs in the Trinity/Woodbine GAM. The Reservoir Package was not used to simulate lakes because there are technical issues associated with the way MODFLOW handles reservoirs that straddle multiple layers. These issues necessitate the compilation and distribution of specialized MODFLOW code in order to run the model with the Reservoir Package engaged. The River Package is mathematically consistent with the Reservoir Package, and does not introduce the technical problems associated with the Reservoir Package. For these reasons, the River Package was used to simulate lake/groundwater interaction, while the Streamflow-Routing Package was used to simulate stream/groundwater interaction.

The formulation of recharge input values was accomplished by multiplying precipitation data by factors relating to soil permeability, land use, and aquifer characteristics (See Section 4.5). Average precipitation data (1960 to 2000) were used to generate recharge data for input into the steady-state/transitional and predictive models, while average yearly data for the interval between 1980 and 2000 were used as the basis for recharge in the calibration/verification model. Precipitation records from 1954 through 1956 were utilized to generate drought of record recharge inputs for the predictive simulations that required them.

The Evapotranspiration Package (ET) was used to simulate: 1) evaporation of soil moisture in the shallow subsurface, 2) transpiration of groundwater by plants, 3) seeps and springs, and 4) discharge to streams not specifically modeled by the Streamflow-Routing Package. As a first step in the distribution of the ET rate, lake evaporation data were downloaded from the TWDB website. Next, plant type and land use factors were applied to these evaporation data, such that lake evaporation rates applied to surface water bodies, while lesser evaporation rates were distributed according to the estimated maximum transpiration rates of the plants distributed throughout the Trinity/Woodbine outcrop. These estimated ET rates were then compiled into a TIN surface that was used as input for the maximum model ET rate. Model ET extinction depth was assigned according to the average plant rooting depth within a given cell. Figure 4.58 in Section 4.7 illustrates the distribution of the plant type evapotranspiration factors utilized during the construction of model inputs.

The General Head Boundary Package (GHB) was used in two ways: 1) to simulate the interaction between Trinity/Woodbine sediments and the wedge of younger units that cap the system, and 2) to simulate the interaction between the Trinity/Woodbine and the Colorado River. Simulation of flow through the overlying sediments was accomplished by applying a GHB to the Woodbine layer (Layer 1) in the artesian zone. Ground level was assigned as the GHB head in these cells, and GHB conductance was calculated using the equation: conductance = (vertical hydraulic conductivity of the overlying sediments) * (cell width) * (cell length) / (overlying wedge thickness), where the vertical hydraulic conductivity was assumed to be 1 x $10^{-6}$ ft/day, and the cell width and length are 5,280 feet. During calibration/verification, it was found that restriction of the Layer 1 GHB conductance to a maximum value of 0.2 square ft/day improved the accuracy of the simulations. The application of GHB boundary conditions to cells on the extreme southern boundary of the model simulated the interaction of the Trinity/Woodbine with the Colorado River. In this area, the GHB head was set to the elevation of the river (or lake). The conductance was set by multiplying the cell thickness by an assumed horizontal hydraulic conductivity of 1.0 ft/day for aquifer units, or 0.25 ft/day for confining units.

Faulting was simulated in the GAM using MODFLOW's Horizontal Flow Barrier (HFB) Package. The distribution of faults was derived from the Texas Bureau of Economic Geology (BEG) Geologic Atlas of Texas (BEG, various), and Tectonic Map sheets (Ewing, 1990). Because the hydraulic properties of the fault boundaries are generally unknown, a constant conductance value of 3.75 x $10^{-4}$ feet squared per day ($ft^2$/day) was assigned to all HFB cells. This value was calculated assuming an average thickness of 20 feet and an average horizontal hydraulic conductivity of 7.5 x $10^{-5}$ feet per day for fault zone materials.

The simulation of the interaction between river/streams and the underlying groundwater system was achieved using the Streamflow-Routing (Stream) Package. For each cell designated as a stream cell, several model inputs must be compiled including: 1) streambed top elevation, 2) streambed bottom elevation, 3) streambed conductance and, 4) stream stage elevation. The elevation of the streambed top and bottom are assigned to 15 and 20 feet below the top of the cell, respectively. Initial estimates of streambed conductance were calculated and distributed as described in Section 4.6, and were subsequently modified during calibration of the model in order to better match the estimated baseflow values. These modifications conformed to the assumption that the streambed thickness ranged from 5 to 20 feet, the vertical hydraulic conductivity of the streambed sediments ranged from $1 \times 10^{-1}$ to $1 \times 10^{-3}$ ft/day, the width of the streambed varied between 50 and 1,500 feet, and that the stream length within a cell was 5,280 feet. Stream stage was input into the model by adding the average measured stage depth to the assigned model streambed top elevation.

For the reasons described above, the River Package was used to simulate reservoir/groundwater interaction in the model. The calibration/verification model incorporated 19 reservoirs of various sizes and impoundment dates, which were then carried through the predictive simulations. The reservoir bed base elevation was set to 15 feet below the top of the cell, and the reservoir bed top elevation was set to 5 feet below the top of the cell. The conductance of each lake cell was calculated assuming a sediment vertical hydraulic conductivity of $1 \times 10^{-6}$ ft/day, a 10-foot bed thickness, and an area of flow equal to the uniform cell size of the model ($5{,}280^2$ square feet).

Pumpage from the model was simulated using MODFLOW's Well Package. Both point and non-point source pumpage was assigned throughout the study area as described in Section 4.9 of this report.

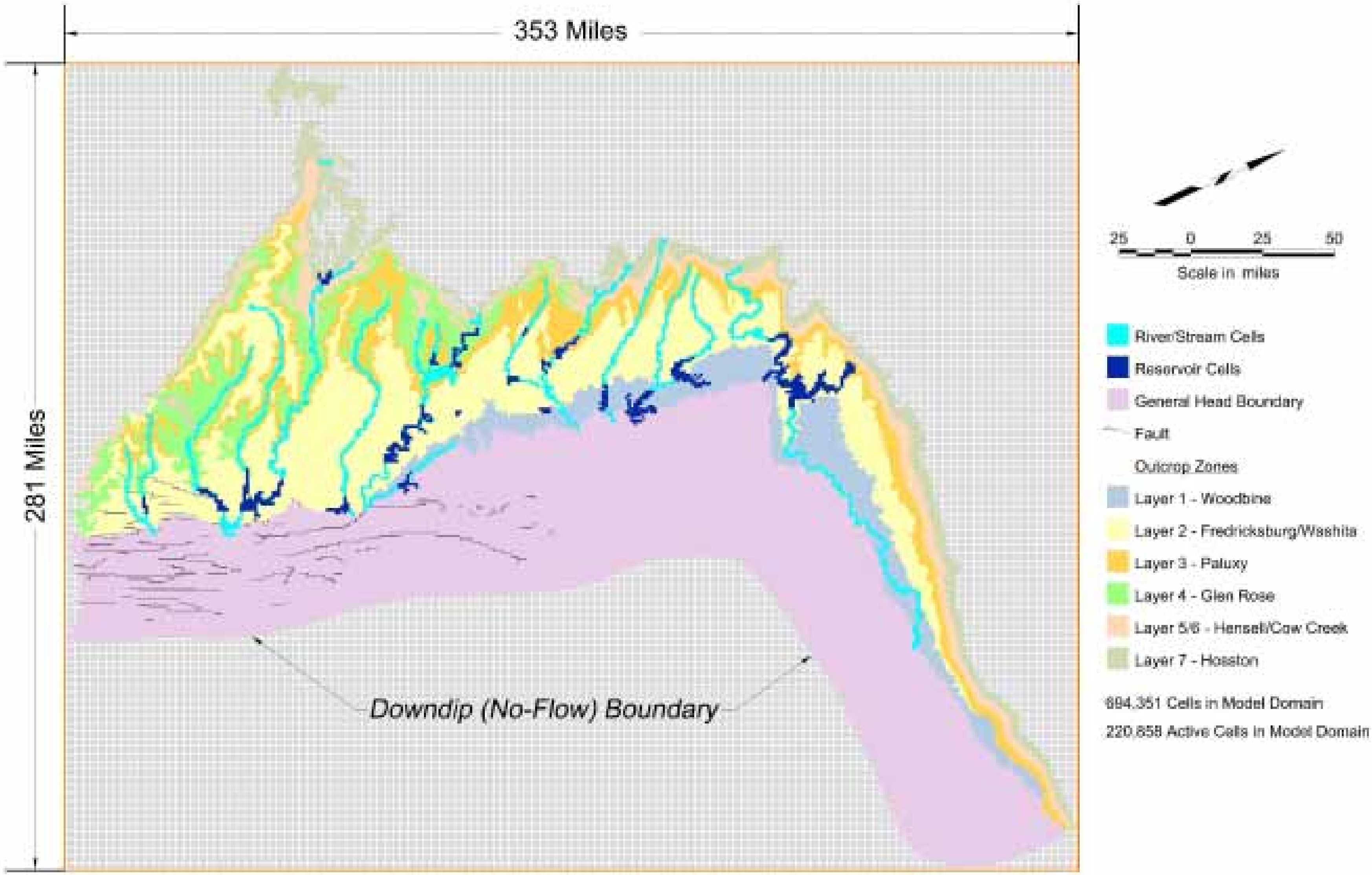



**Figure 6.1 Model Boundaries**

# 7.0 MODELING APPROACH

The creation of the Trinity/Woodbine GAM began with the acquisition, collation, and analysis of the available data and publications pertaining to the aquifer system. As this information was assimilated, an initial estimate of the fundamental processes that drive groundwater flow in the Trinity/Woodbine system was developed. Next, specific boundary conditions and MODFLOW packages were selected that facilitated the simulation of those processes within the framework of the numerical model.

Initially, a steady-state model was developed for the project; however, calibration of a steady-state model to estimated predevelopment water levels was not possible for the Trinity/Woodbine GAM. Research into the conditions under which early water levels were taken suggests that they were not reflective of predevelopment conditions because the relatively large number of flowing artesian wells drilled in the late $19^{th}$ century likely significantly reduced the artesian pressure in the Trinity/Woodbine before measurements were recorded. Therefore, in order to test the simulation accuracy prior to the transient calibration and verification process, a model was constructed that simulated groundwater flow in the interval between 1880 and 1980 (1/1/1880 to 12/31/1979). Labeled herein as a steady-state/transitional model, this model utilized a simplified pumpage data set that was created by taking the known pumpage in 1980 and reverse extrapolating the volume of withdrawal to zero in 1880. The initial heads for the steady-state/transitional model were created by running the model with pumpage disengaged until little or no change in hydraulic head was observed during a very long (greater than 100,000 years) transient model run. The ending heads from this quasi-steady-state simulation were then input as the initial heads for the steady-state/transitional model. The use of a long-interval transient simulation to mimic steady-state model conditions was required in this case in order to avoid the mathematical instability introduced when MODFLOW's steady-state mode of calculation is engaged. Subsequent to the formulation of the initial head surfaces and interpolated pumpage sets, the model was run and calibrated to the aquifer water levels and estimated baseflows reported in 1980.

Once satisfactory calibration of the steady-state/transitional model was completed, a transient model spanning the period between 1980 and 2000 (1/1/1980 to 12/31/1999) was constructed. This model utilized yearly recharge and pumpage inputs, and was calibrated and verified to the aquifer conditions in 1990 and 2000, respectively.

Calibration and verification of the GAM involved an iterative procedure of assessing simulation accuracy (as compared to recorded water levels and baseflow fluxes), and adjustment of model input parameters in order to reduce the differences between the simulated and recorded data. For both the steady-state/transitional and calibration/verification models, the target water levels were selected from the TWDB groundwater/well information database, and the total root mean squared (RMS) residual of each modeled aquifer was less than 10 percent of the measured head drop across the unit for the period simulated.

Following successful calibration and verification, the model was subjected to a sensitivity analysis. During this procedure, input parameters are systematically varied during multiple model runs and the simulation results are monitored and recorded. In this way, the magnitude of the error inherent in the simulation(s) was estimated.

Throughout the modeling process a small percentage (less than 0.25 percent) of outcrop cells became dry during the various simulations. The circumstances surrounding the drying of those cells were investigated, and the probable cause identified. In a few instances, cell drying indicated erroneous model inputs; in those cases the appropriate parameters were modified and the cell(s) no longer dried during model runs. In the majority of occurrences, the cause of this drying is the interaction between the drawdown induced by pumpage, the properties of the aquifer, and the relatively small saturated thickness of those cells. Where this interaction was identified, the impact of the dry cells upon the simulation as a whole was evaluated. Because of the relatively small number of dry cells and the real-world plausibility of aquifer depletion in those areas, no action was taken to artificially retain or induce wetting in cells that dried during the model runs.

Subsequent to the sensitivity analysis of the transient model, six simulations were run that predict the likely aquifer response to various planning scenarios. The first simulation assumes average precipitation conditions for the next 50 years in conjunction with the pumpage rates predicted by the regional water planning groups in the study area. The other five simulations model aquifer response in 2010, 2020, 2030, 2040, and 2050. These simulations assume average precipitation rates followed by a three-year period of drought of record conditions (1954 to 1956) in conjunction with the pumpage rates predicted by the regional water planning groups and the TWDB in the study area.

# 8.0 STEADY-STATE/TRANSITIONAL MODEL

As described in Sections 7, a steady-state/transitional model spanning the interval between 1880 and 1980 (1/1/1880 to 12/31/1979) was constructed such that the initial estimates of aquifer and boundary parameters could be evaluated despite the lack of reliable predevelopment water level measurements. The steady-state/transitional model utilized the completed steady-state model as a foundation but additional stress periods were added to simulate flow between 1880 and 1980. The model incorporated a linearly interpolated, reverse extrapolation of 1980 pumpage estimates. In other words, pumpage is assumed to have been zero prior to 1880, and then incrementally increased to 100% of the 1980 pumpage during the 100-year period between 1880 and 1980. The model results were calibrated to measured 1980 water levels and estimated baseflow fluxes. With the exception of pumpage, all parameters were held constant during the steady-state/transitional model simulations. Figure 8.1 illustrates the types of flow simulated during steady-state conditions (before pumpage was engaged in the model). Figure 9.1 in Section 9.0 diagrams the types of flow modeled during the transitional simulation (after pumpage was engaged in the model).

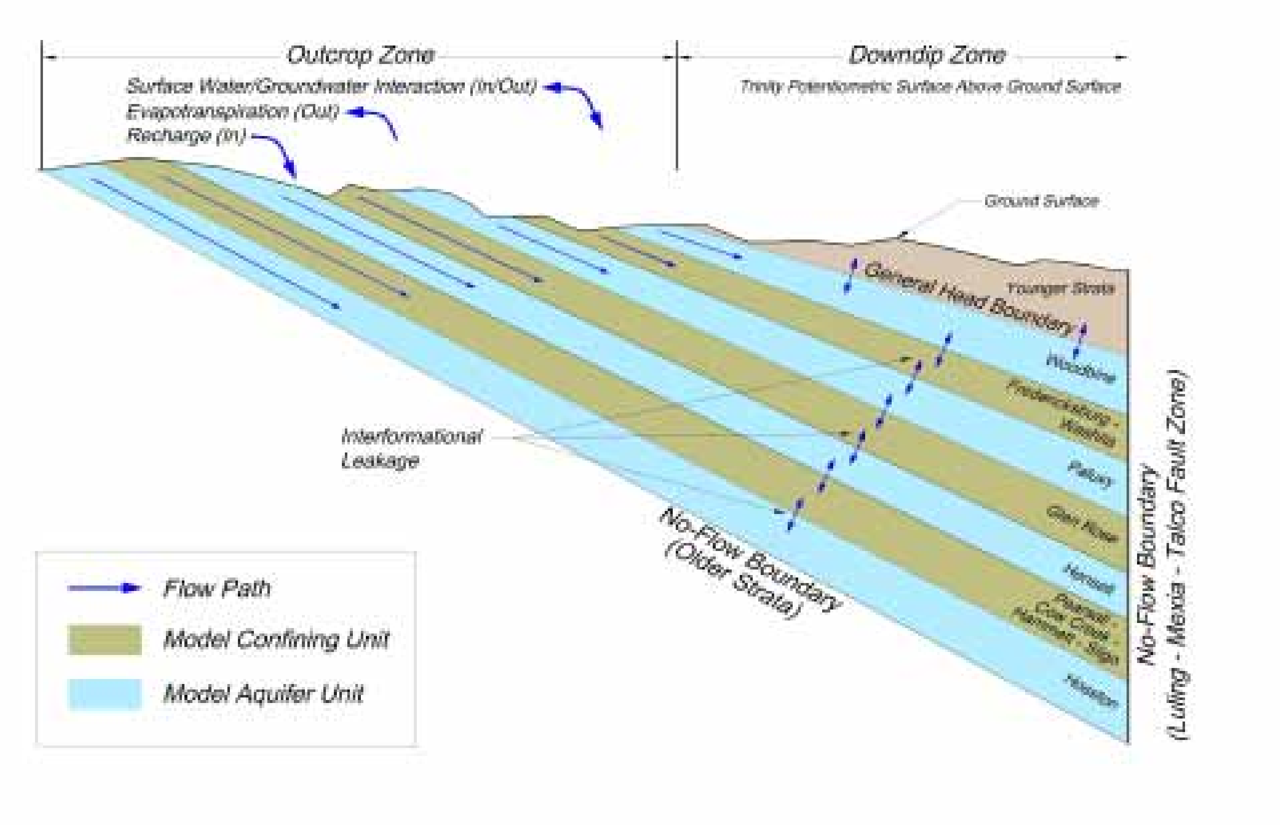



**Figure 8.1 Diagram of Steady-State Flow Components**

## 8.1 Calibration

During the calibration, it was found that adjustment of only a few of the model parameters significantly affected the simulation results. These include horizontal hydraulic conductivity (Kh), vertical hydraulic conductivity (Kv), and artesian storage coefficient (S - storativity). Of these, very little is known of the regional distribution of Kv or S, and while some pump test data do exist that record values for Kh, the majority of the tests were conducted over a relatively short period (three days or less). Because of the short duration of the recorded pumping tests, the values associated with them represent little more than local measurements given the large scale of the model. Further complications result from the heterogeneous nature of the pump test results; values obtained from closely spaced tests of wells penetrating a common aquifer can exhibit a wide range of values.

Given the paucity of data pertaining to the regional characteristics of the modeled aquifers, an "Occam's Razor" approach to modeling the Trinity/Woodbine system was adopted. This principle states that one should not make more assumptions than the minimum needed. In other words, when parameter values are not known, then the best solution is to use the simplest estimate, in most cases the application of a single parameter value that best represents the mean of the variations that will likely be seen. By doing this, there is less chance of introducing inconsistencies, ambiguities and redundancies, and future model users are instantly aware that a given model input is based, in large part, on the judgment of the model builder.

In keeping with the principle of "Occam's Razor" the vertical hydraulic conductivity and artesian storage values input into the model were kept as simple as possible within the constraints of the calibration/verification process. Initially, an artesian storage coefficient of $1 \times 10^{-4}$ was applied to all layers in the model. Subsequent to calibration/verification, application of slightly lower values ($8 \times 10^{-5}$) to Layers 1, 2, 4, and 6 (Woodbine, Fredericksburg/Washita, Glen Rose, and Pearsall/Cow Creek/Hammett/Sligo, respectively), were found to improve the accuracy of the simulation results.

Similarly to the application of the artesian storage parameters, assumptions regarding the regional distribution of Kv were kept to a minimum; initially, a Kv of $1 \times 10^{-4}$ feet per day (ft/day) was input to all model layers. During calibration, modifications to the Kv of Layers 2, 4, and 6 were made. Reduction of the Kv of Layer 2 (Fredericksburg/Washita) to $1 \times 10^{-6}$ ft/day was found to improve model fit. The Kv of Layer 4 (Glen Rose) was reduced to $1 \times 10^{-5}$ ft/day in areas beneath heavily incised valleys in the southern portion of the model (simulating increased leakage in areas where accelerated erosional processes likely occur in the unit), while in all other areas the Kv of Layer 4 was reduced to $5 \times 10^{-6}$ ft/day. Decreasing the Kv of Layer 6 (Pearsall/Cow

Creek/Hammett/Sligo) to 3 x $10^{-5}$ ft/day in the southern portion of the model, and to 3 x $10^{-5}$ ft/day throughout the rest of the model domain enhanced the precision of the simulation results.

The horizontal hydraulic conductivity (Kh) values assigned to each primary aquifer layer (Woodbine, Paluxy, Hensell, and Hosston - Layers 1, 3, 5, and 7, respectively) varied according to the net sand thickness recorded during analysis of geophysical logs within the model area. Statistical correlations relating pumping test transmissivity and net sand thickness were calculated and utilized to extrapolate initial Kh values to all regions of the model. In areas where a hydrostratigraphic unit was not present (ex. Paluxy in the southern portion of the model), a Kh value of 0.1 ft/day was applied. Modification of Kh values occurred throughout the calibration/verification process, and, in general, the calibrated values of Kh were less than the initial estimates. For Layers 1, 3, 5, and 7, the calibrated Kh values were approximately 77, 37, 54, and 59 percent that of the initial estimates, respectively. A Kh value of 0.5 ft/day was assigned to the updip portions of Layer 2 (Fredericksburg/Washita) and Layer 4 (Glen Rose), while the downdip Kh value for those layers was set to 0.1 ft/day. For Layer 6 (Pearsall/Cow Creek/Hammett/Sligo), a single Kh value of 0.01 ft/day was found to satisfy the model calibration requirements. Figures 8.2 through 8.5 show the calibrated Kh fields assigned to each aquifer layer in the model. The horizontal conductivities used for the confining layers (Layers 2, 4, and 6) are as described above. Due to the general uniformity of the Kh distribution of the confining layers throughout the model domain, figures showing the spatial variations in Kh have not been provided.

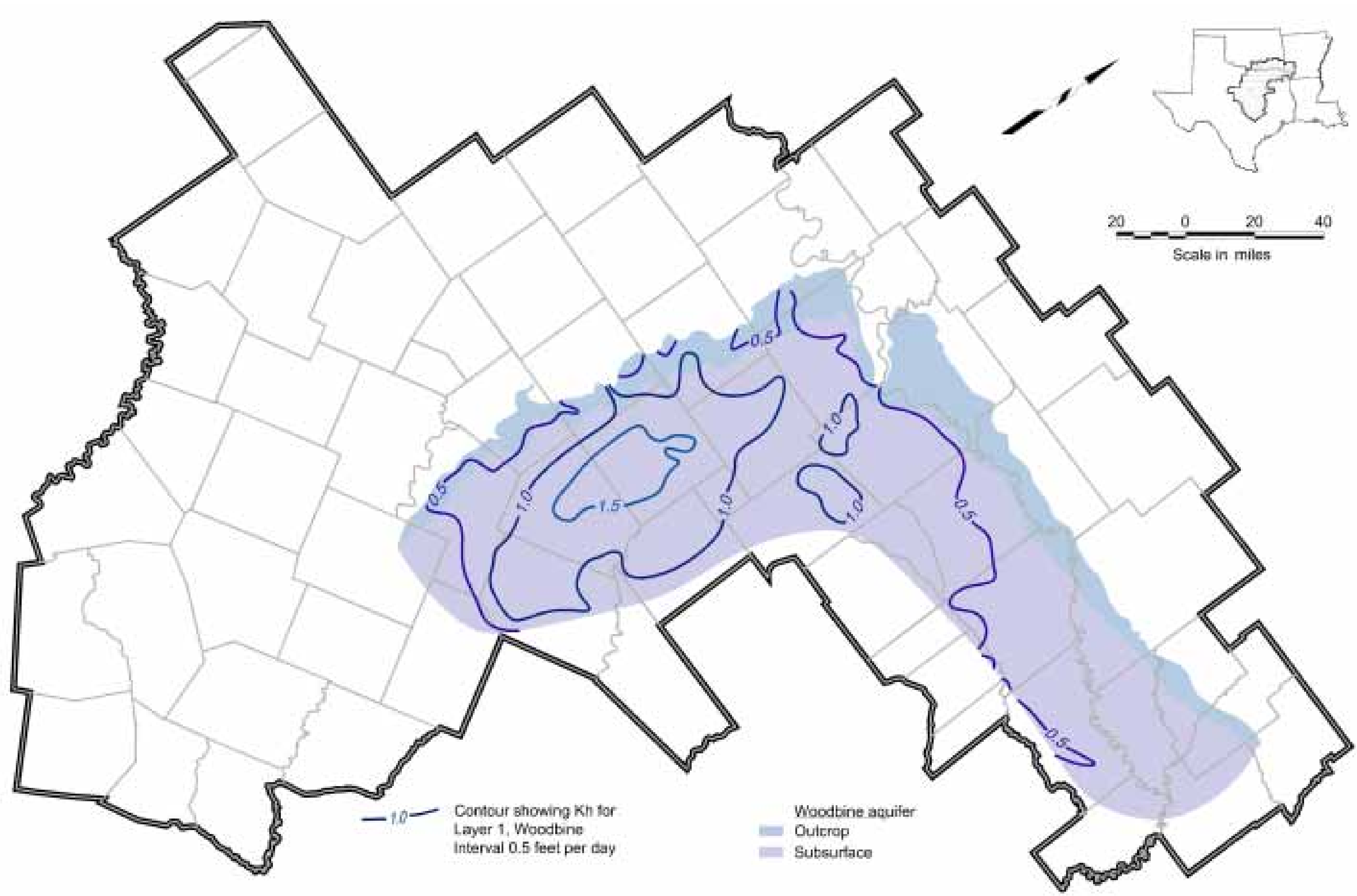



**Figure 8.2 Calibrated Horizontal Hydraulic Conductivity Field – Woodbine (Layer 1)**

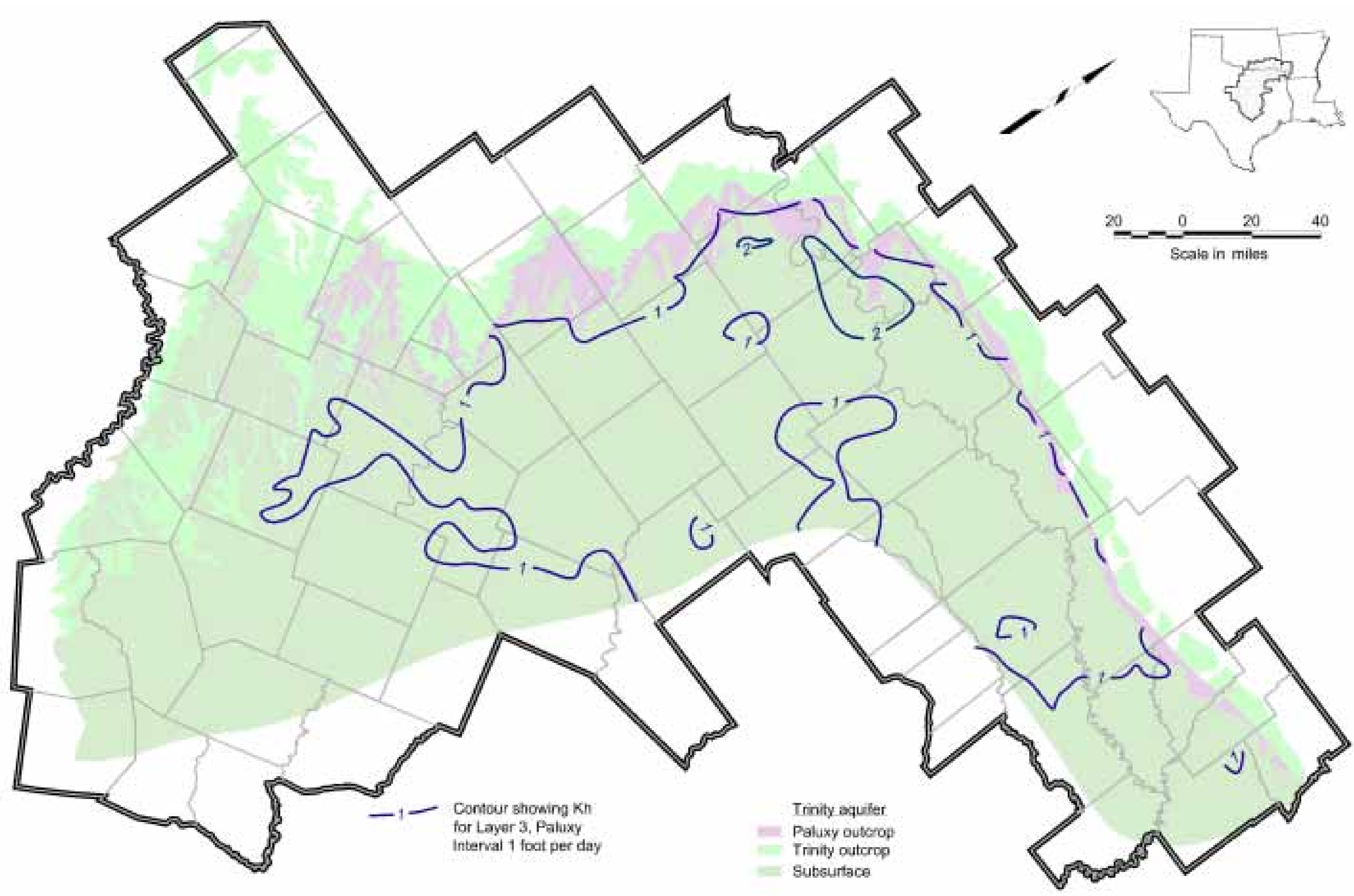



**Figure 8.3 Calibrated Horizontal Hydraulic Conductivity Field – Paluxy (Layer 3)**

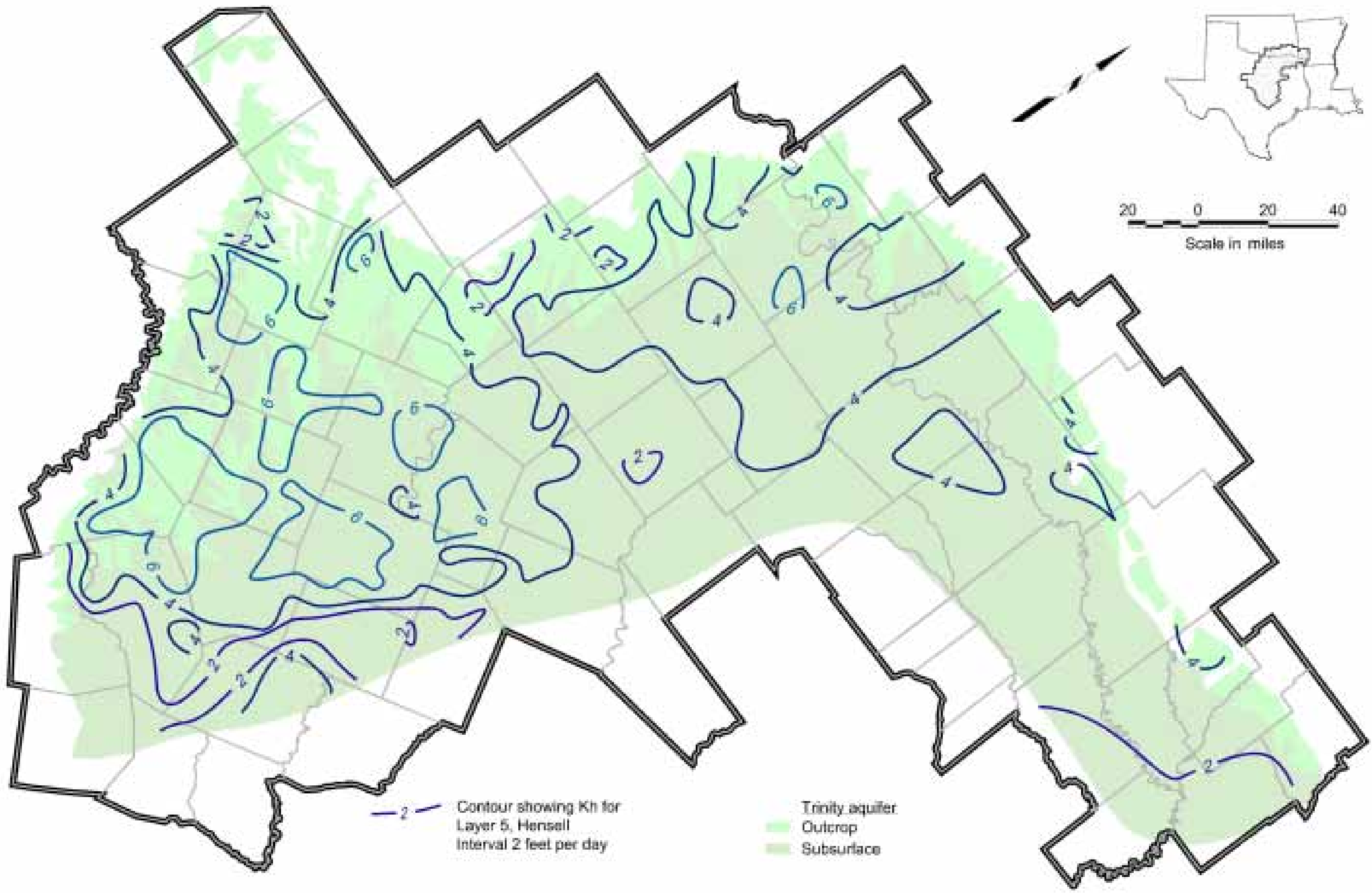



**Figure 8.4 Calibrated Horizontal Hydraulic Conductivity Field – Hensell (Layer 5)**

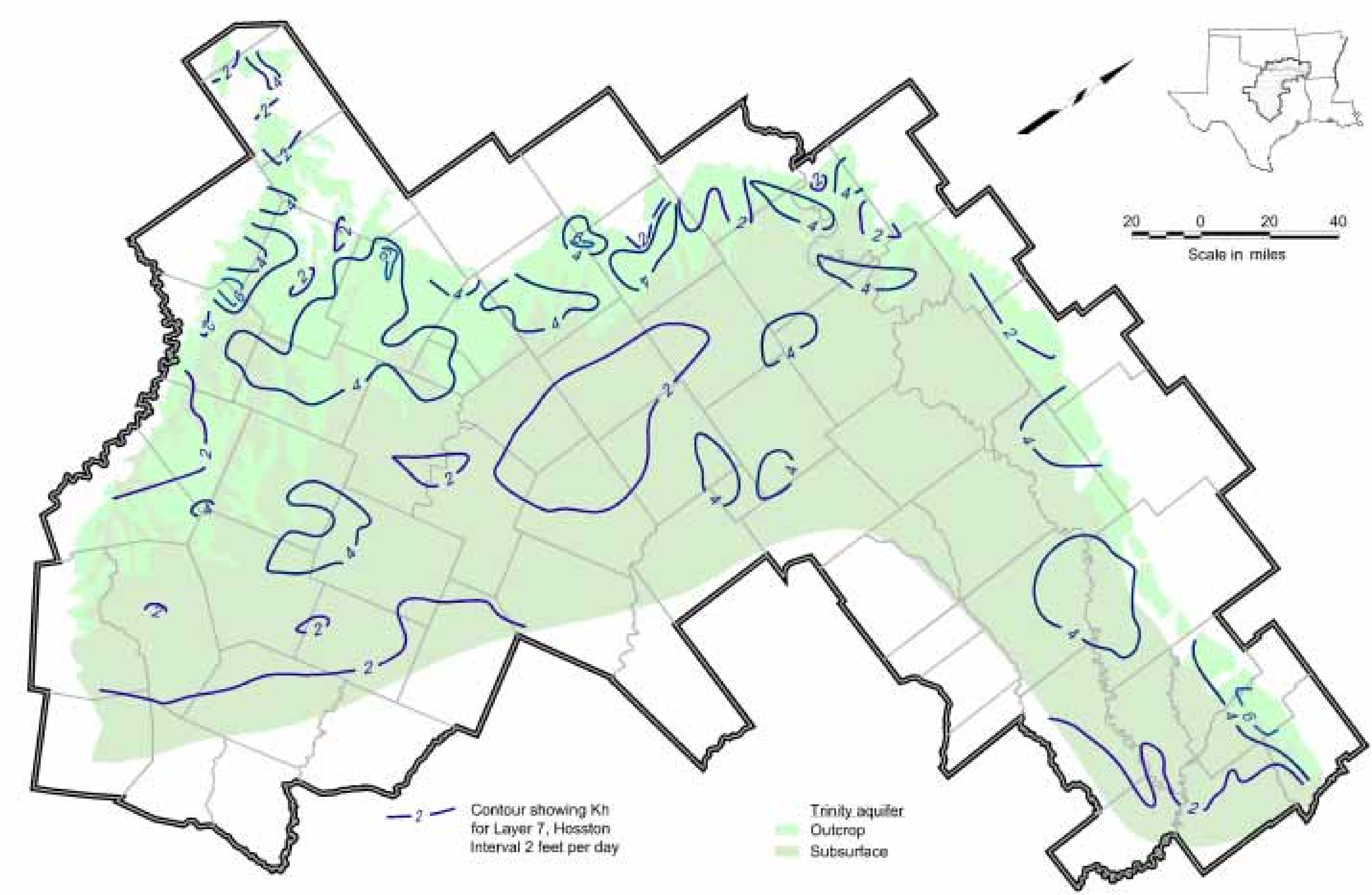



**Figure 8.5 Calibrated Horizontal Hydraulic Conductivity Field – Hosston (Layer 7)**

### 8.1.1 Calibration Results

Figures 8.6 through 8.9 illustrate the spatial distribution of the potentiometric surfaces (hydraulic head) associated with the four primary aquifer units (Woodbine, Paluxy, Hensell, and Hosston). In general, the model reproduces the regional cones of water level depression related to the major pumpage centers. Some variations from measured water levels are apparent. The southern portion of the model (in the vicinity of the Balcones Fault Zone) probably exhibits the most persistent deviations from measured values.

Table 8.1 lists the final calibration statistics associated with the primary aquifer layers. References to residual in this table mean the difference between simulated and measured water levels. Negative values for the mean residual indicate that the simulated water level elevations at the calibration points were, on average, lower than the measured water level elevations. As shown, the results of the steady-state/transitional model calibration varied according to the layer examined, with the root mean squared error (RMS) residual values ranging about 27.7 feet from smallest (Hensell) to greatest (Hosston). The RMS residuals are below 10 percent of the total measured head drop for all of the primary aquifer layers.

**Table 8.1 Steady-State/Transitional Model Calibration Statistics (1980)**

| Aquifer | Mean Residual (ft) | Mean ABS Residual (ft) | RMS Residual (ft) | Total Measured Head Drop (ft) | RMS Percent of Measured Drop |
|---|---|---|---|---|---|
| **Woodbine** | 17.7 | 58.4 | 73.3 | 824 | 8.9% |
| **Paluxy** | 0.0 | 48.8 | 66.3 | 1,699 | 3.9% |
| **Hensell** | 8.4 | 40.3 | 57.8 | 1,672 | 3.5% |
| **Hosston** | -14.6 | 58.7 | 85.5 | 2,639 | 3.2% |

Figures 8.10 through 8.13 illustrate the difference between simulated and measured water level elevations in graphical format for the primary aquifer layers. In these figures, a simulated water level that exactly matches a corresponding measured water level will plot along the unit-slope line. For points that plot above this line, the simulated water level elevation is higher than the measured water level elevation, conversely, points below the unit-slope line represent areas where simulated water level elevations are lower than measured water level elevations. The figures show significant variability in the correlation between measured and simulated water levels. Some water level biases are noticeable in these figures; overall, the Woodbine, Paluxy, and Hensell show a tendency for higher elevations in simulated water levels versus measured water levels (i.e. slightly less drawdown in the simulations than actually measured). These biases are likely due in large part to the

distribution of discharge within the simplified pumpage data set applied to the steady-state/transitional model. Because of the relatively low transmissivity of the Trinity/Woodbine aquifers, small errors in the magnitude and aerial distribution of pumpage can produce comparatively large resultant errors in the simulated hydraulic head surface.

Simulated baseflow of rivers/streams was also compared and calibrated to estimated baseflow values of select streams within the outcrop area of the model. Figure 8.14 shows the distribution of stream segments used during the calibration/verification process. These segments were selected because their flow is primarily within the outcrop boundaries of Trinity/Woodbine sediments, and the associated gage measurements spanned relatively long periods of record. Figure 8.15 charts the estimated baseflow, as compared to the baseflow simulated in the model for the selected stream segments. The simulated baseflow ranges between the $25^{th}$ percentile flow and the median flow in all cases except for the Lampasas River (Segment 10), where the simulated baseflow falls between the $10^{th}$ and $25^{th}$ percentile flows.

It should be noted that the comparison between simulated and estimated baseflow may not be valid for the GAM or for regional groundwater flow models in general. The relatively coarse cell size (one square mile) necessitates the averaging of spatial data and requires the introduction of many assumptions when constructing parameter datasets, some of which can heavily influence simulation results. One example, and probably one of the more influential to modeled streamflow, is the relationship between modeled and measured stream elevations and the ground level of the surrounding highlands. In the GAM, the ground level elevations applied to outcrop cells are necessarily averages of the range of elevations within that cell. In practice, this means that in most cases the elevation assigned is neither the lowest nor the highest elevation that occurs in that area, resulting in a modeled topography that is subdued in comparison to the variable conditions which actually exist. The “flattening” effect is particularly pronounced in areas with high topographic relief, such as the southern portion of the model where incised streams have cut through relatively hard limestone units to form steep canyons and bluffs. The subdued topography of the model can result in a diminished hydraulic gradient between the highlands and the streams, which in turn reduces the simulated baseflow. The regional scale of the model also precludes the accurate simulation of small-scale phenomenon that can significantly affect baseflow to a stream. Small-scale variability in the thickness, width, and hydraulic characteristics of alluvial deposits and of the underlying units all heavily influence the amount of surface/groundwater interaction. Conduit and fracture flow within the carbonate units in the southern portion of the model likely introduces significant volumes to site-specific locations that cannot be accurately simulated by a regional model.

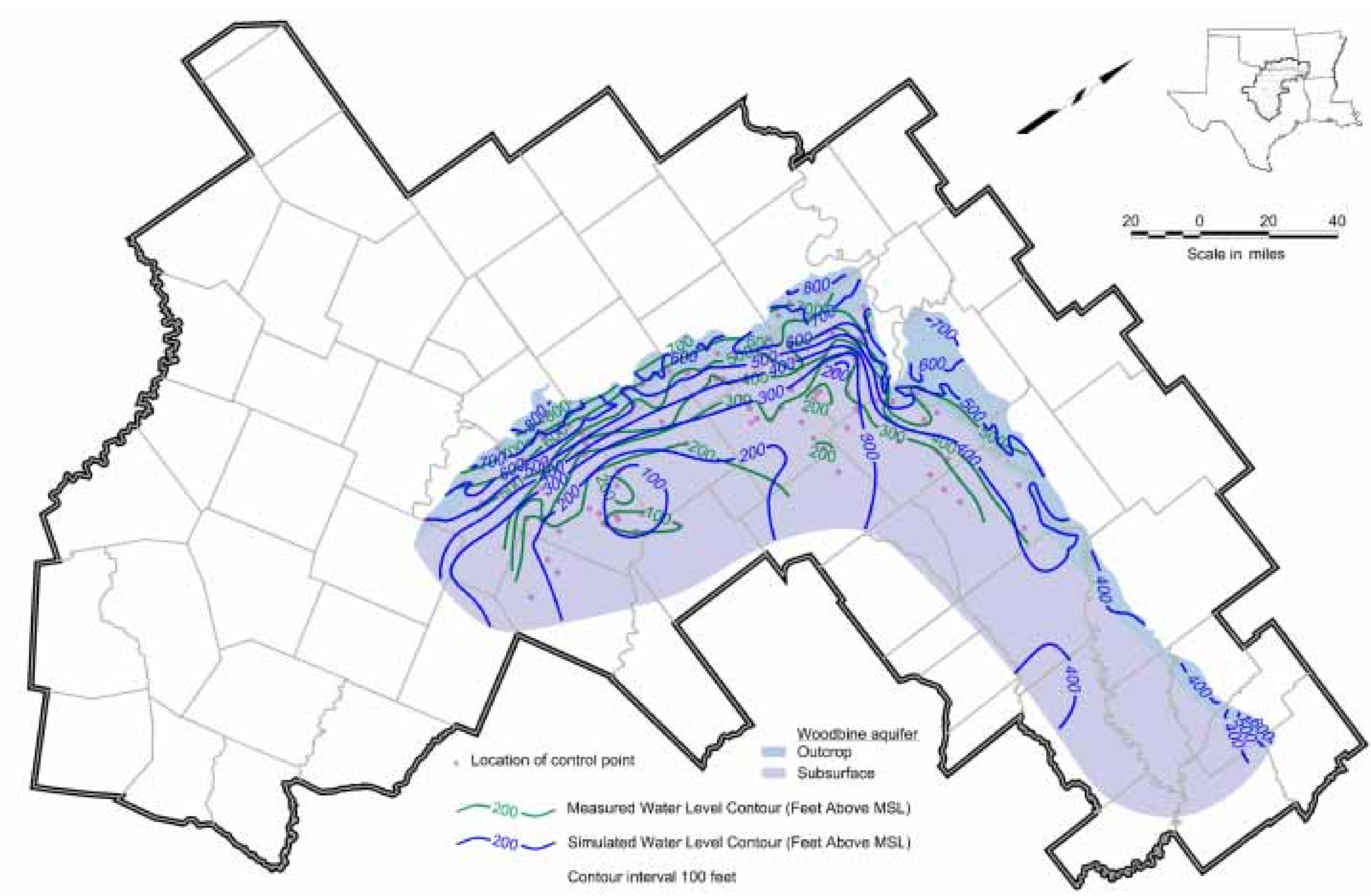



**Figure 8.6 Simulated vs. Measured Hydraulic Head, 1980 – Woodbine (Layer 1)**

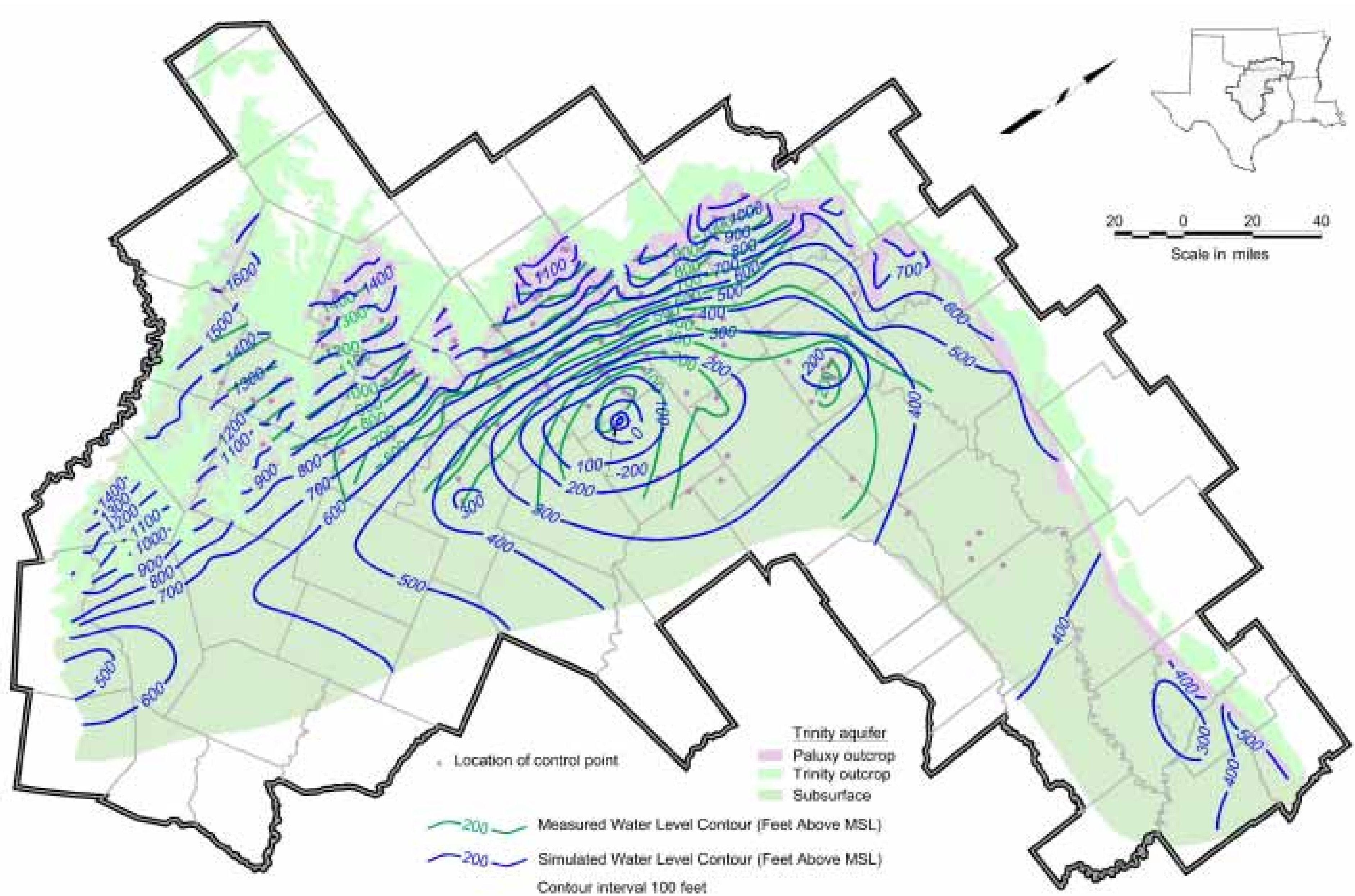



**Figure 8.7 Simulated vs. Measured Hydraulic Head, 1980 – Paluxy (Layer 3)**

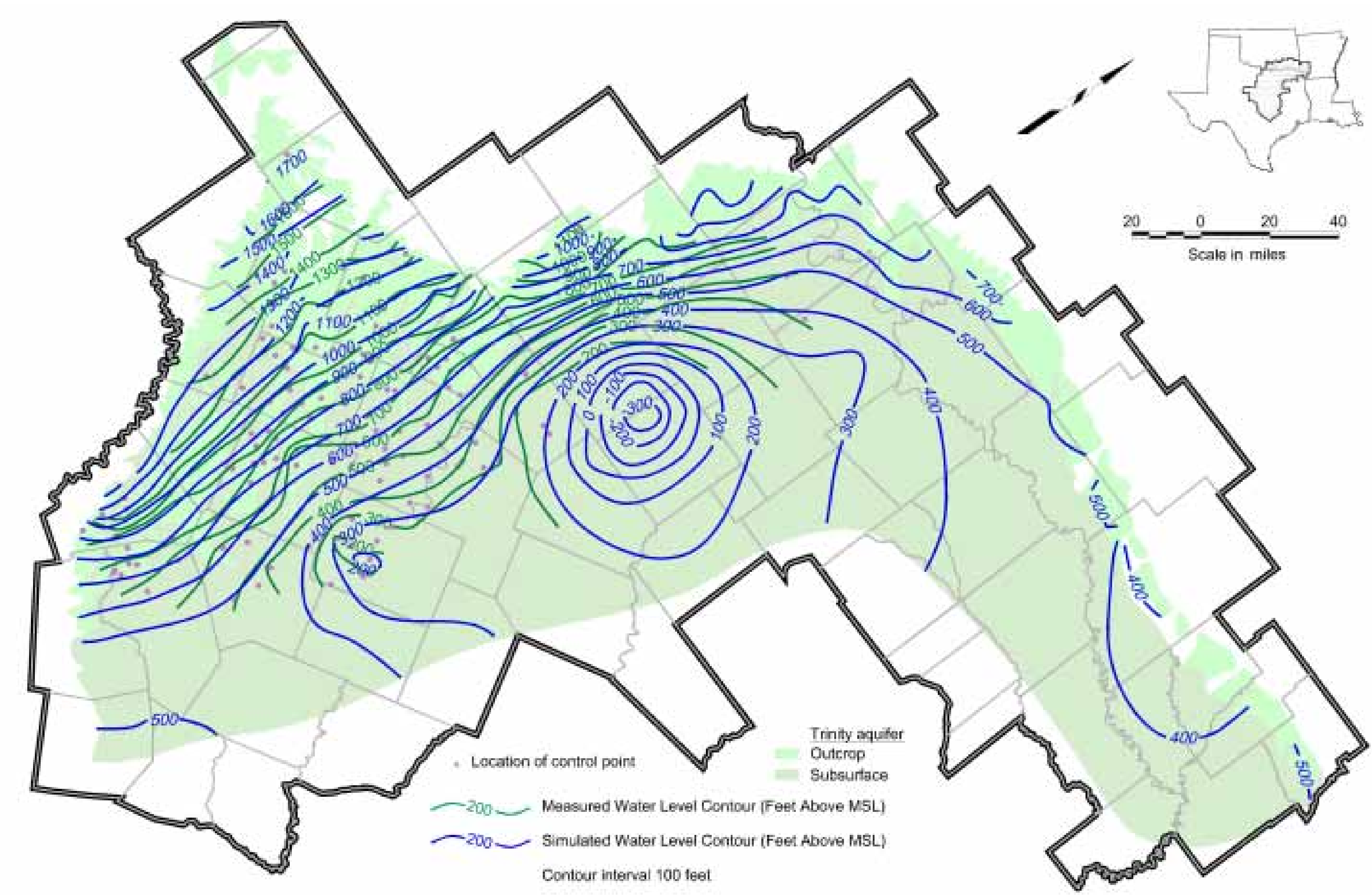



**Figure 8.8 Simulated vs. Measured Hydraulic Head, 1980 – Hensell (Layer 5)**

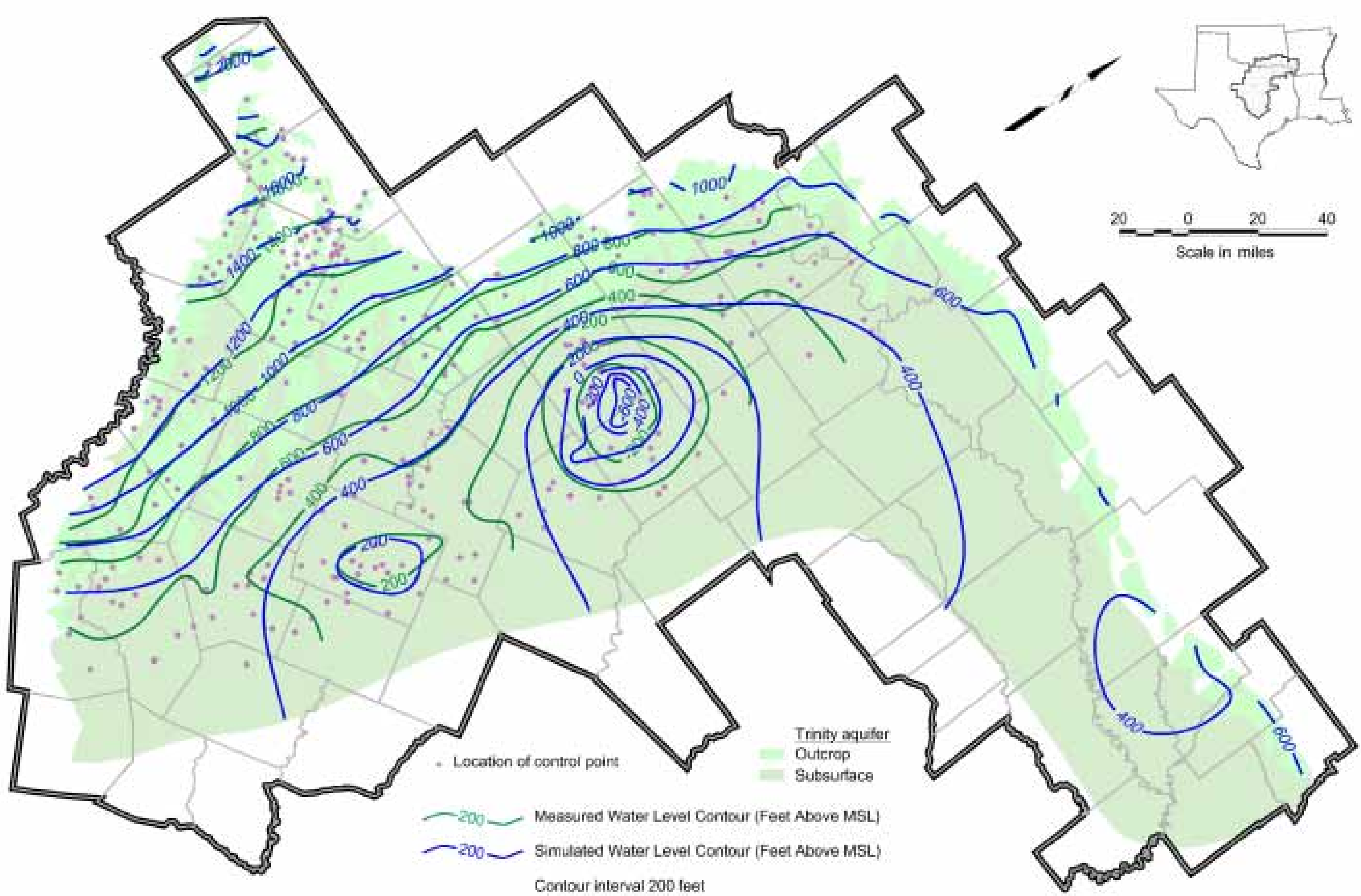



**Figure 8.9 Simulated vs. Measured Hydraulic Head, 1980 – Hosston (Layer 7)**

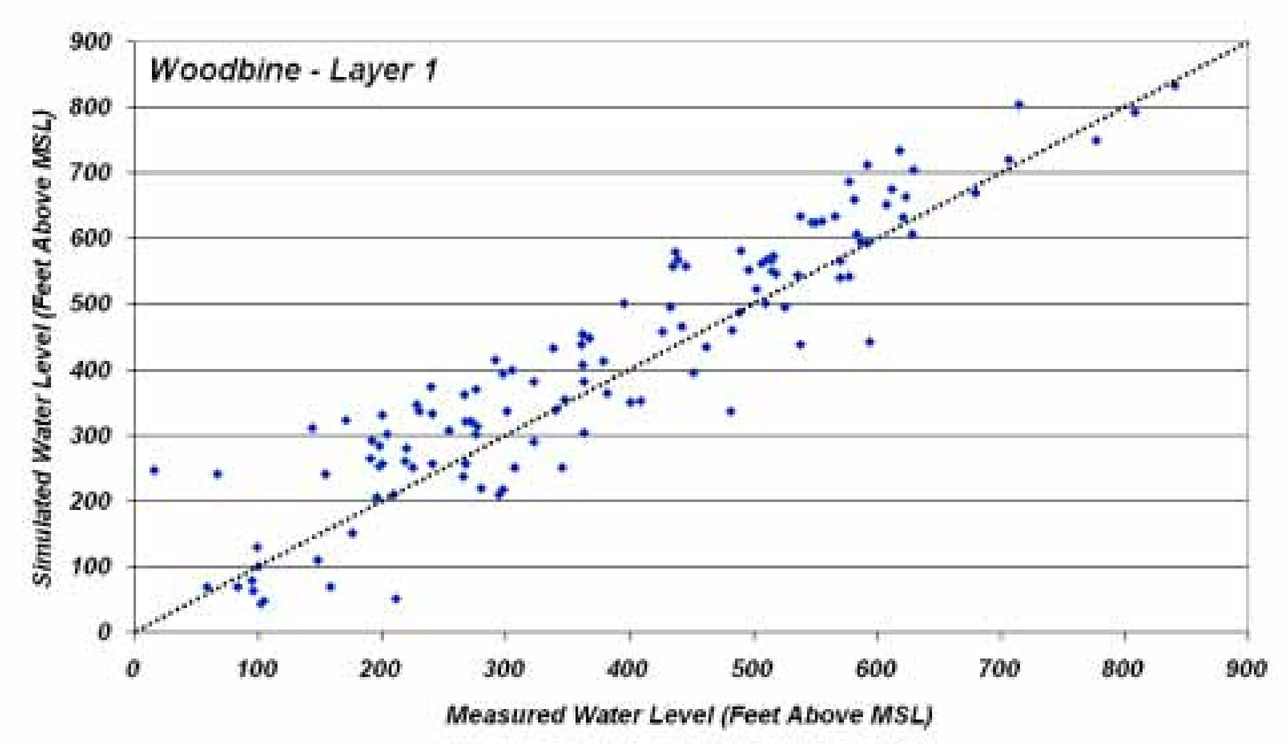



**Figure 8.10 Simulated vs. Measured Hydraulic Head Scatterplot, 1980 – Woodbine (Layer 1)**

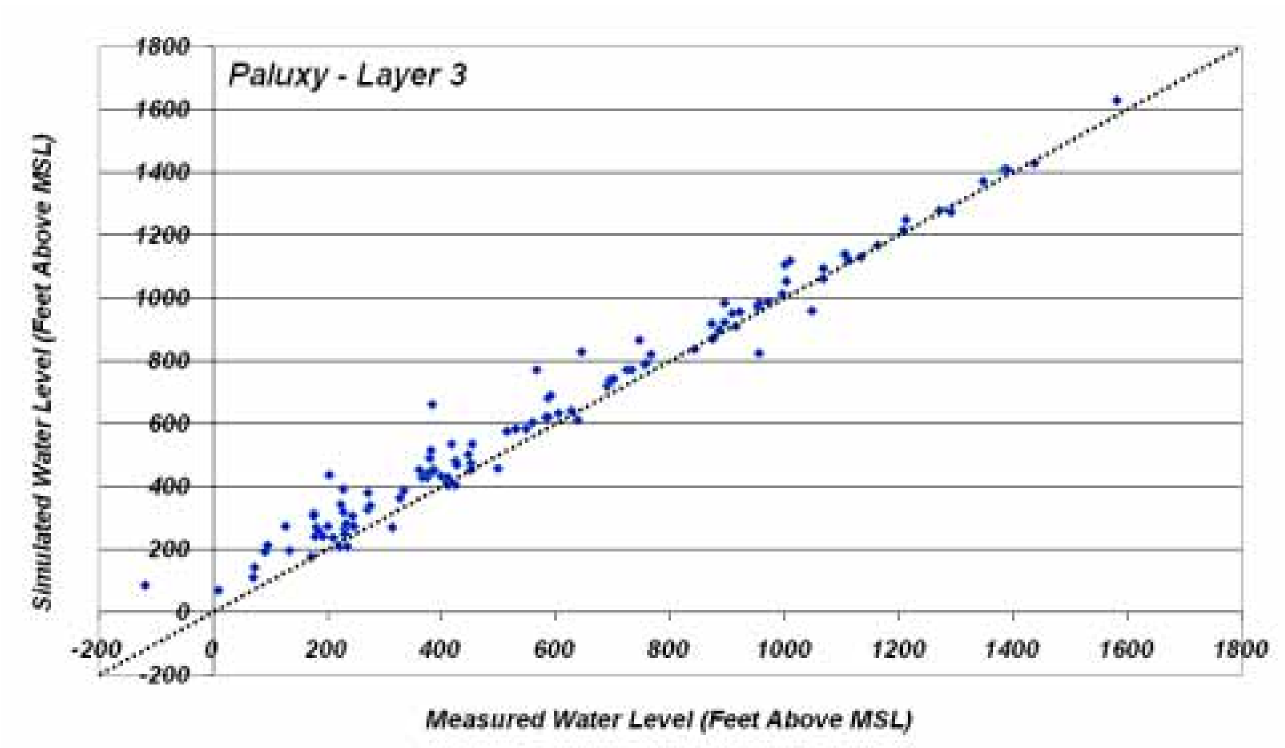



**Figure 8.11 Simulated vs. Measured Hydraulic Head Scatterplot, 1980 – Paluxy (Layer 3)**

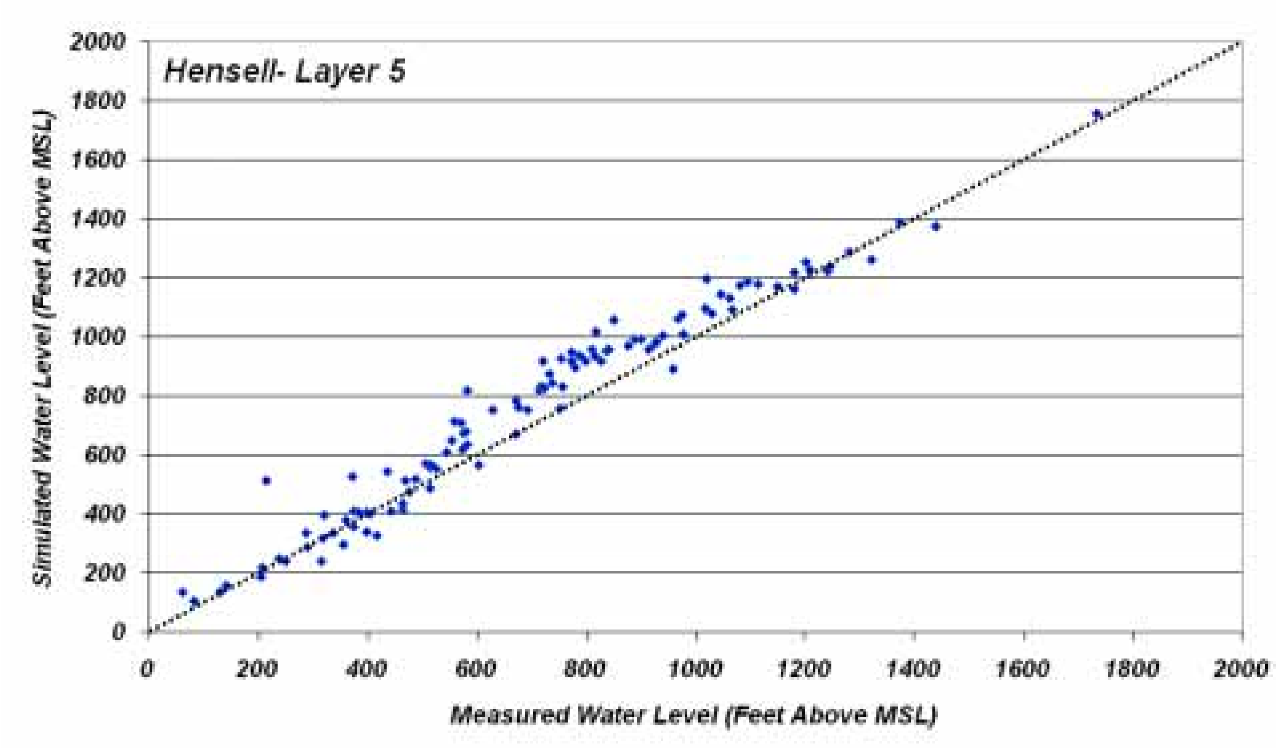



**Figure 8.12 Simulated vs. Measured Hydraulic Head Scatterplot, 1980 – Hensell (Layer 5)**

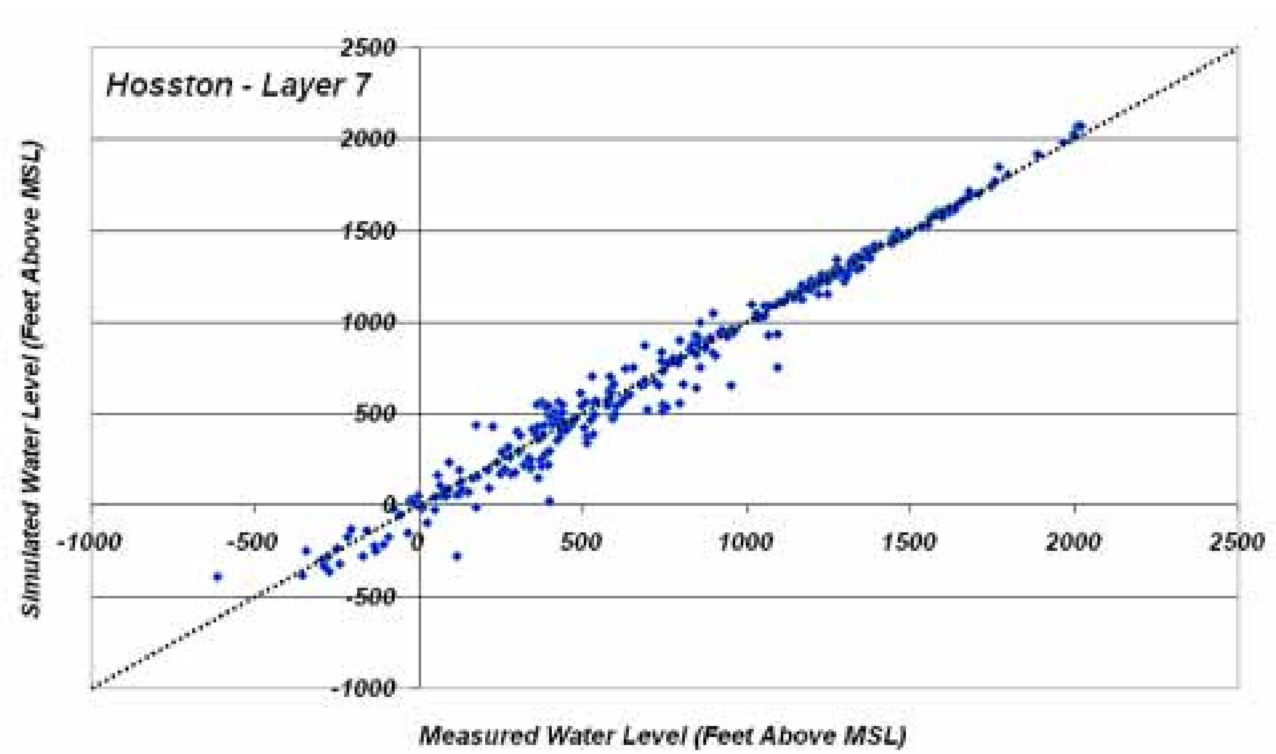



**Figure 8.13 Simulated vs. Measured Hydraulic Head Scatterplot, 1980 – Hosston (Layer 7)**

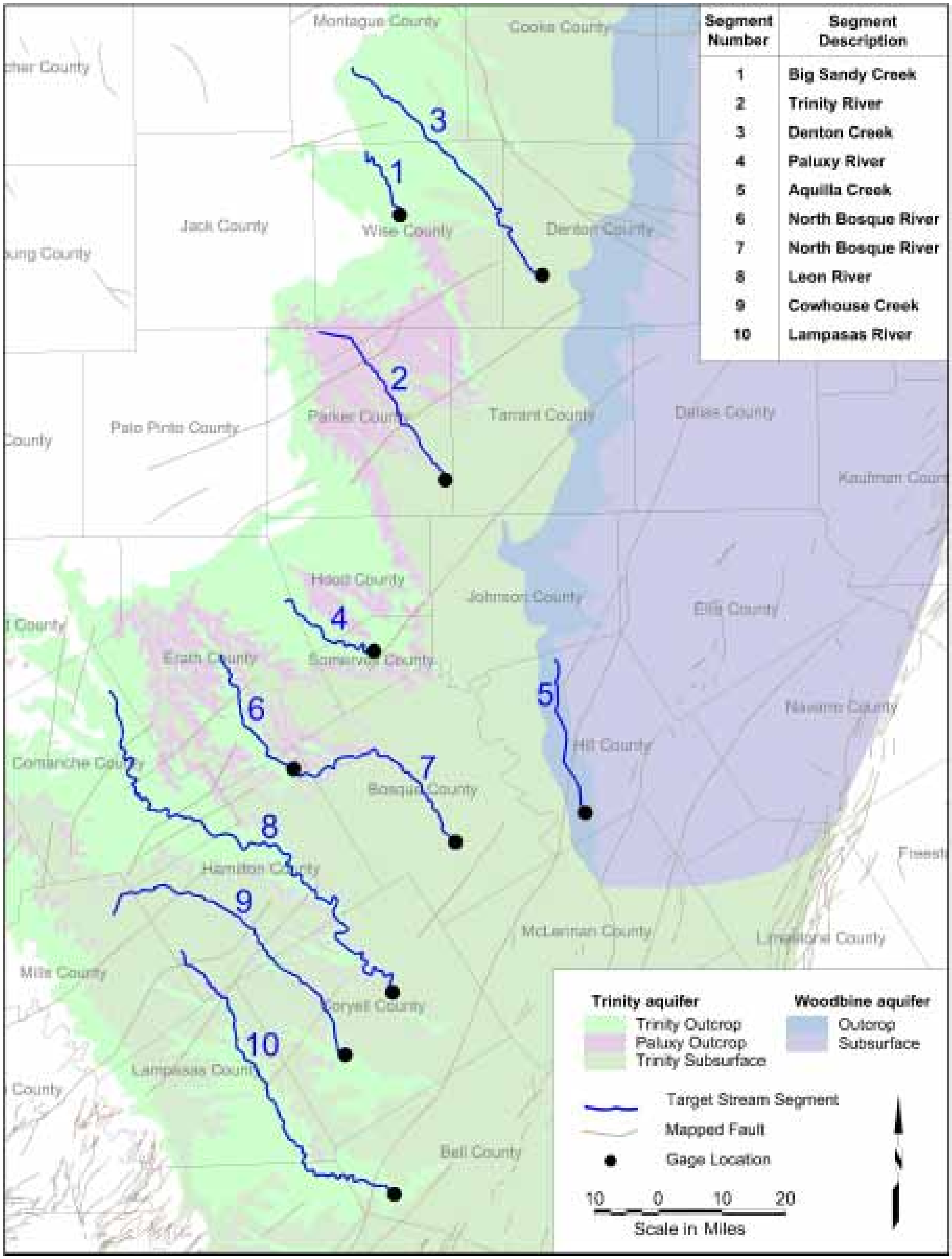



**Figure 8.14 Calibration Stream Segments**

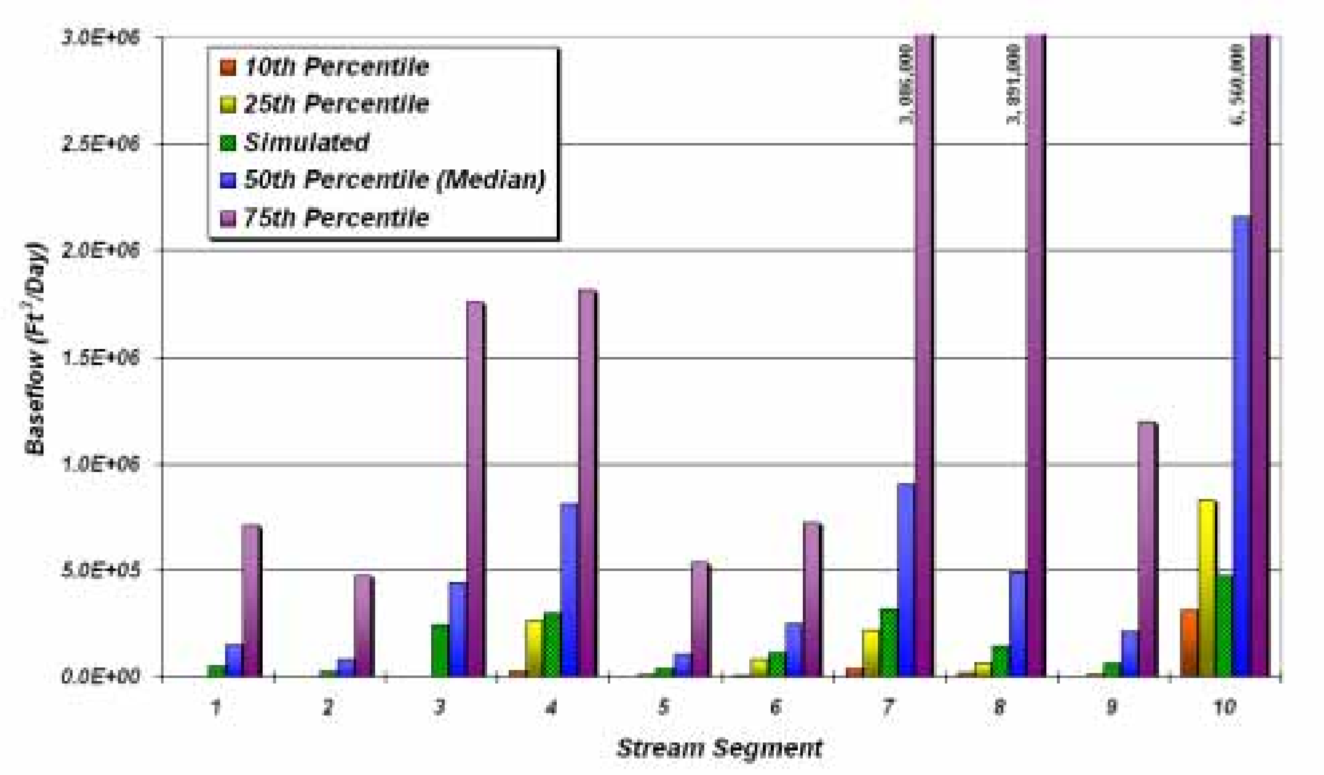



**Figure 8.15 Simulated vs. Estimated Baseflow**

### 8.1.2 Water Budget

The calibrated model was used to investigate the relationships between inflow and discharge mechanisms within the Trinity/Woodbine system. At steady-state conditions, the amount of water entering an aquifer system equals the amount of water exiting or discharging from the aquifer system. In other words, there is no change in storage in the aquifer through time under steady-state conditions. Table 8.2 summarizes the water budget, or the rate of water entering, exiting or transferred within the aquifer system prior to the initiation of pumpage (at steady-state). As shown, approximately 1.8 million acre-feet per year (ac-ft/yr) of water is exchanged within the aquifer system. The types of modeled flow at steady-state conditions include recharge, evapotranspiration, surface/groundwater interaction, interformational flow, and flow between the Trinity/Woodbine system and the overlying sediments (modeled using a general head boundary). Of these flows, recharge and evapotranspiration account for the overwhelming majority of the water exchanged in the model; approximately 1.79 million ac-ft/yr of recharge is applied to the outcrop area, of which 1.72 million ac-ft/yr is extracted by evapotranspiration. It should be noted that the Evapotranspiration Package, as used in the GAM, represents discharge through evaporation, transpiration, seeps/springs, and streams not explicitly modeled with the Streamflow-Routing

Package. This interaction between recharge and evapotranspiration is consistent with the conceptual model of flow. Baseflow to rivers and streams accounts for the next greatest volume reported, with about 70,000 ac-ft/yr discharged prior to development of the aquifer system. Approximately 1,400 ac-ft/yr of groundwater flowed upward into the overlying sediments (Table 8.2: GHB), comprising about 0.08 percent of the total flow reported.

Following the instigation of pumpage from the Trinity/Woodbine, changes in aquifer storage occurred, and the system was no longer at steady-state. Table 8.2 lists the rate of water exchanged at the end of the transitional model period (1980). At the end of the transitional model period, approximately 1.9 million ac-ft/yr is entering, exiting, or transferred within the aquifer system. About 166,000 ac-ft/yr is withdrawn from wells distributed across the model. Because recharge was held constant during the transitional simulation, the recharge applied to the model equals that applied during steady state conditions, about 1.79 million ac-ft/yr. Extraction by evapotranspiration is reduced by 1980 to approximately 1.67 million ac-ft/yr, which is primarily the result of minor water level declines in outcrop areas brought about by pumpage from wells. Another consequence of the simulated reduction in water levels is the rate of reduction in overall storage in the system, calculated to be about 111,000 ac-ft/yr by the end of the transitional model period. Baseflow discharge to streams also decreased in response to lowered aquifer water levels from 70,000 ac-ft/yr during predevelopment times to about 67,000 ac-ft/yr in 1980. A reversal of the vertical hydraulic gradient is also apparent from the reported flow across the upper general head boundary. As shown in Table 8.2, 1,400 ac-ft/yr of net flow moves from the system to the overlying strata during steady-state conditions, while a net flow rate of 22 ac-ft/yr into the aquifer system was reported in 1980.

### Table 8.2 Water Budget for Steady-State/Transitional Model

| Year | Layer | Storage | Top | Bottom | Wells | Recharge | ET | Lakes | GHB | Streams |
|---|---|---|---|---|---|---|---|---|---|---|
| ***SS*** | **1** | 0 | 0 | 399 | 0 | 281,173 | -267,039 | 0 | -93 | -14,451 |
| | **2** | 0 | -399 | 515 | 0 | 604,247 | -577,368 | 0 | 0 | -26,984 |
| | **3** | 0 | -515 | -904 | 0 | 305,800 | -296,638 | 0 | -15 | -7,679 |
| | **4** | 0 | 904 | -2,113 | 0 | 177,210 | -161,448 | 0 | -349 | -14,223 |
| | **5** | 0 | 2,113 | -1,523 | 0 | 191,990 | -187,258 | 0 | 0 | -5,381 |
| | **6** | 0 | 1,523 | -1,525 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **7** | 0 | 1,525 | 0 | 0 | 234,388 | -233,571 | 0 | -895 | -1,493 |
| | **All** | 0 | NA | NA | 0 | 1,794,814 | -1,723,324 | 0 | -1,352 | -70,211 |
| ***1980*** | **1** | 13,151 | 0 | 950 | -26,367 | 281,173 | -255,769 | 0 | 662 | -13,812 |
| | **2** | 3,342 | -950 | -3,698 | -5,506 | 604,184 | -570,599 | 0 | 0 | -26,768 |
| | **3** | 26,842 | 3,698 | -5,254 | -35,816 | 305,863 | -287,968 | 0 | -15 | -7,384 |
| | **4** | 10,561 | 5,254 | -17,192 | -6,161 | 177,210 | -155,501 | 0 | -346 | -13,823 |
| | **5** | 36,112 | 17,192 | -34,696 | -30,334 | 191,990 | -176,081 | 0 | 0 | -4,204 |
| | **6** | 9,798 | 34,696 | -44,312 | -182 | 0 | 0 | 0 | 0 | 0 |
| | **7** | 11,484 | 44,312 | 0 | -62,072 | 234,388 | -226,459 | 0 | -279 | -1,394 |
| | **All** | 111,285 | NA | NA | -166,434 | 1,794,814 | -1,672,381 | 0 | 22 | -67,385 |

Note: Values are in acre-feet per year. For the "Storage" field, positive values indicate water lost from storage. For all other fields positive numbers indicate water entering the aquifer system or layer while negative numbers indicate water leaving the aquifer system or layer. The "Top" and "Bottom" fields indicate interformational leakage into (+) or out of (-) the top and bottom of each layer, respectively. Steady-state (SS) values were obtained by running the model with pumpage disengaged.

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# 9.0 TRANSIENT CALIBRATION/VERIFICATION MODEL

The transient calibration/verification model spans the interval between 1980 and 2000 (1/1/1980 to 12/31/1999). Pumpage was distributed throughout the model as described in Section 4.9, and was varied with each of the yearly stress periods comprising the model. Reservoirs were input into the model (using the River Package) and engaged during the appropriate date of impoundment. Recharge inputs to the model varied on a yearly basis, and were distributed as described in Section 4.5. Once constructed, the model was run and calibrated to 1990 measured water levels and estimated baseflow fluxes. Verification of the calibrated model consisted of comparing simulated end-of-run water levels and estimated baseflow fluxes with values recorded in 2000. Figure 9.1 diagrams the types of flow modeled during the transient simulation.

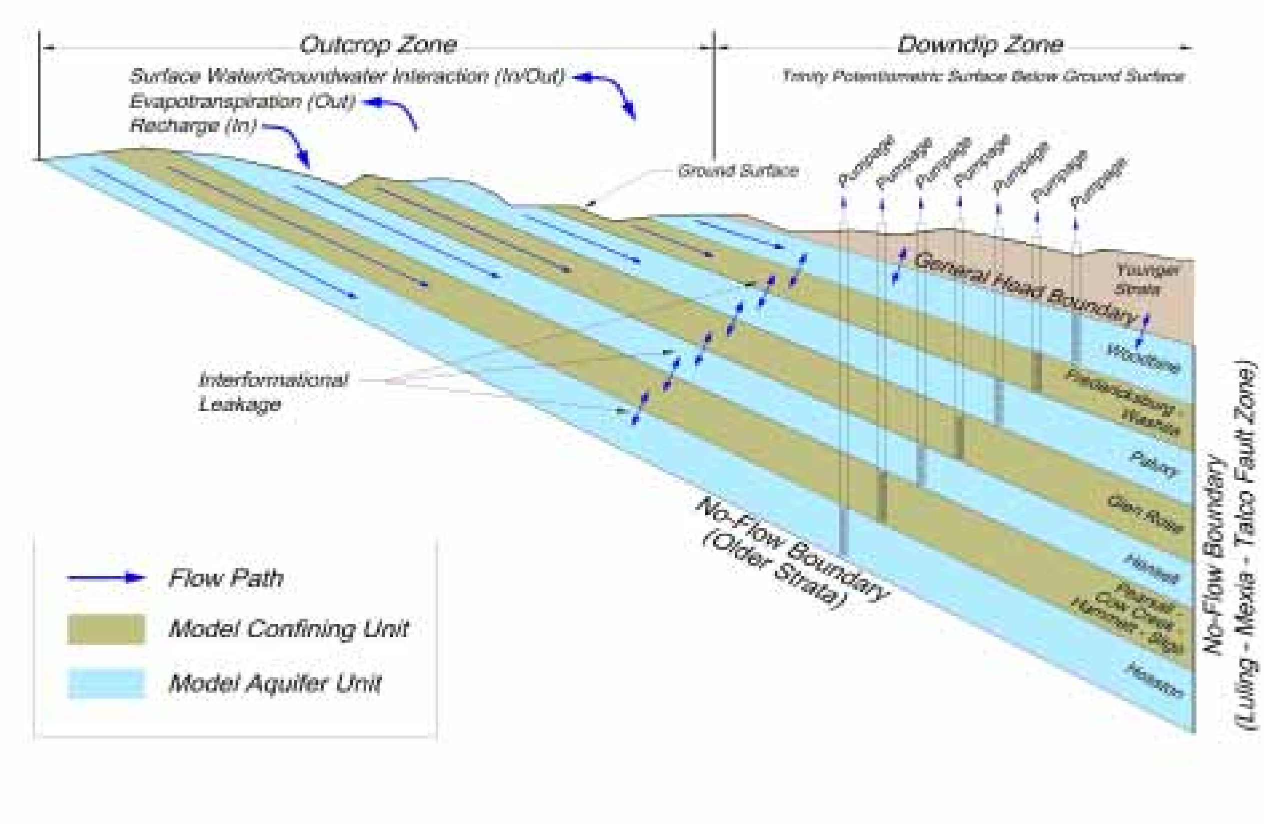



**Figure 9.1 Diagram of Transient Flow Components**

## 9.1 Calibration/Verification

The calibration and verification processes progressed relatively quickly for the transient model. This is due primarily to the nature of the construction and calibration of the steady-state/transitional model, which simulated water level declines from 1880 to 1980. Because the steady-state/transitional model reasonably simulated the aquifer response during the first 100 years of pumpage, it follows that comparable simulation accuracy is maintained during the 1980 to 2000 interval. Only minor adjustments were made to the model during the calibration and verification process, all of which were corrections of isolated, erroneous parameter input values identified during the analysis of the transient simulation.

### 9.1.1 Calibration/Verification Period (1980 – 2000) Results

Figures 9.2 through 9.9 illustrate the spatial differences between the measured and simulated potentiometric surfaces (hydraulic head) associated with the four primary aquifer units (Woodbine, Paluxy, Hensell, and Hosston) in 1990 and 2000. In general, the model reproduces the measured hydraulic head values reasonably well. Figures 9.10 through 9.13 compare the simulated and measured water levels at various wells throughout the model area. Some relatively large local deviations from measured water levels are apparent, and were investigated during the calibration/verification process. Although in most cases the source of the deviation is not known, the results of these investigations suggest that the most likely causes of local variations include: 1) pumpage-influenced or erroneous water level measurements, 2) hydrologic boundaries not included in the model (e.g. unmapped faults), 3) misplaced or unreported historical pumpage, or 4) local variations in aquifer hydraulic parameters and structure that are unknown or cannot be fully addressed in a regional scale model.

Tables 9.1 and 9.2 list the calibration statistics associated with the primary aquifer layers in 1990 and 2000, respectively. References to residual in these tables indicate the difference between simulated and measured water levels. Negative values for the mean residual indicate that the simulated water level elevations at the calibration points were, on average, lower than the measured water level elevations. As shown, the results of the transient calibration/verification model calibration varied according to the layer examined, with the absolute value (ABS) of the mean of the difference between the measured and simulated heads (residuals) ranging from about 38 feet to 70 feet in the Paluxy and Hosston, respectively. The square root of the mean of the squared residual values (RMS) ranges from about 51 feet to 107 feet in the Paluxy and Hosston, respectively. The RMS residuals are below 10 percent of the total measured head drop for all of the primary aquifer layers for both the calibration and verification periods.

**Table 9.1 Transient Model Calibration Statistics (1990)**

| Aquifer | Mean Residual (ft) | Mean ABS Residual (ft) | RMS Residual (ft) | Total Measured Head Drop (ft) | RMS Percent of Measured Drop |
|---|---|---|---|---|---|
| ***Woodbine*** | 13.3 | 65.0 | 79.3 | 822 | 9.7% |
| ***Paluxy*** | 20.9 | 37.5 | 50.7 | 1,572 | 3.2% |
| ***Hensell*** | 18.6 | 67.0 | 99.5 | 1,755 | 5.7% |
| ***Hosston*** | -7.6 | 70.0 | 107.0 | 2,385 | 4.5% |

**Table 9.2 Transient Model Verification Statistics (2000)**

| Aquifer | Mean Residual (ft) | Mean ABS Residual (ft) | RMS Residual (ft) | Total Measured Head Drop (ft) | RMS Percent of Measured Drop |
|---|---|---|---|---|---|
| ***Woodbine*** | 16.8 | 62.9 | 79.8 | 836 | 9.5% |
| ***Paluxy*** | 36.8 | 48.6 | 70.6 | 1,778 | 4.0% |
| ***Hensell*** | 26.8 | 65.9 | 95.8 | 1,783 | 5.4% |
| ***Hosston*** | 4.1 | 74.9 | 106.8 | 2,353 | 4.5% |

Figures 9.14 through 9.21 illustrate the difference between simulated and measured head in graphical format for the four primary aquifer layers. In these figures, a simulated water level that exactly matches a corresponding measured water level will plot along the unit-slope line. For points that plot above this line, the simulated water level is higher than the measured water level. Conversely, points below the unit-slope line represent areas where simulated water levels are lower than measured water levels. The figures show a significant degree of variability in the correlation between measured and simulated water levels. Although there are a significant number of points that plot off the unit-slope line, data points are dispersed both above and below the unit slope line indicating no bias in any one direction.

Simulated baseflow of rivers/streams was also compared and calibrated to estimated baseflow values of select streams within the outcrop area of the model. Figure 8.14 in Section 8 shows the distribution of stream segments used during the calibration/verification process. These segments were selected because their flow is primarily within the outcrop boundaries of Trinity/Woodbine sediments, and the associated gage measurements spanned relatively long periods of record. Figures 9.22 through 9.31 compare the estimated yearly average baseflow and the baseflow simulated in the transient model.

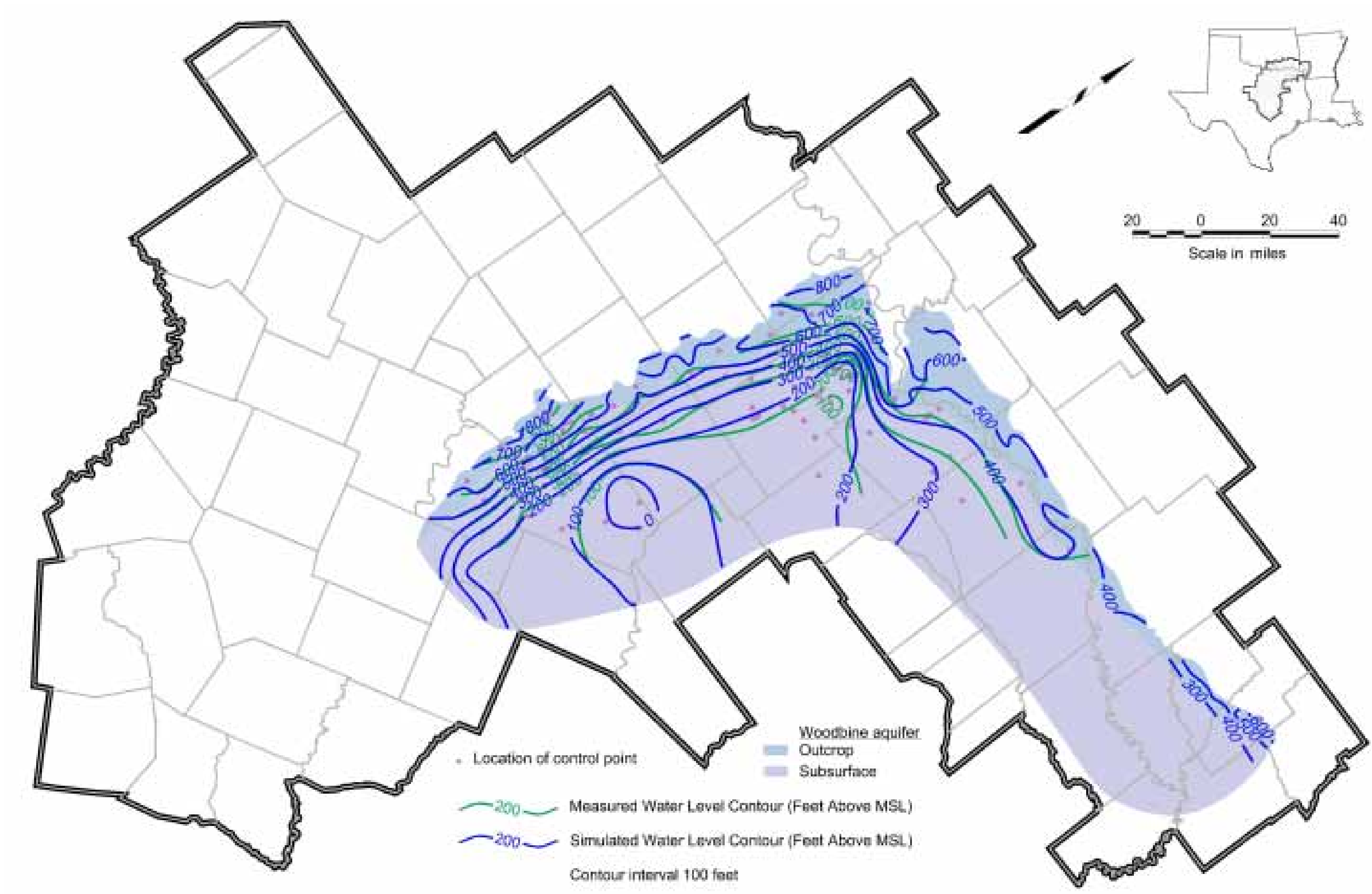



**Figure 9.2 Simulated vs. Measured Hydraulic Head, 1990 – Woodbine (Layer 1)**

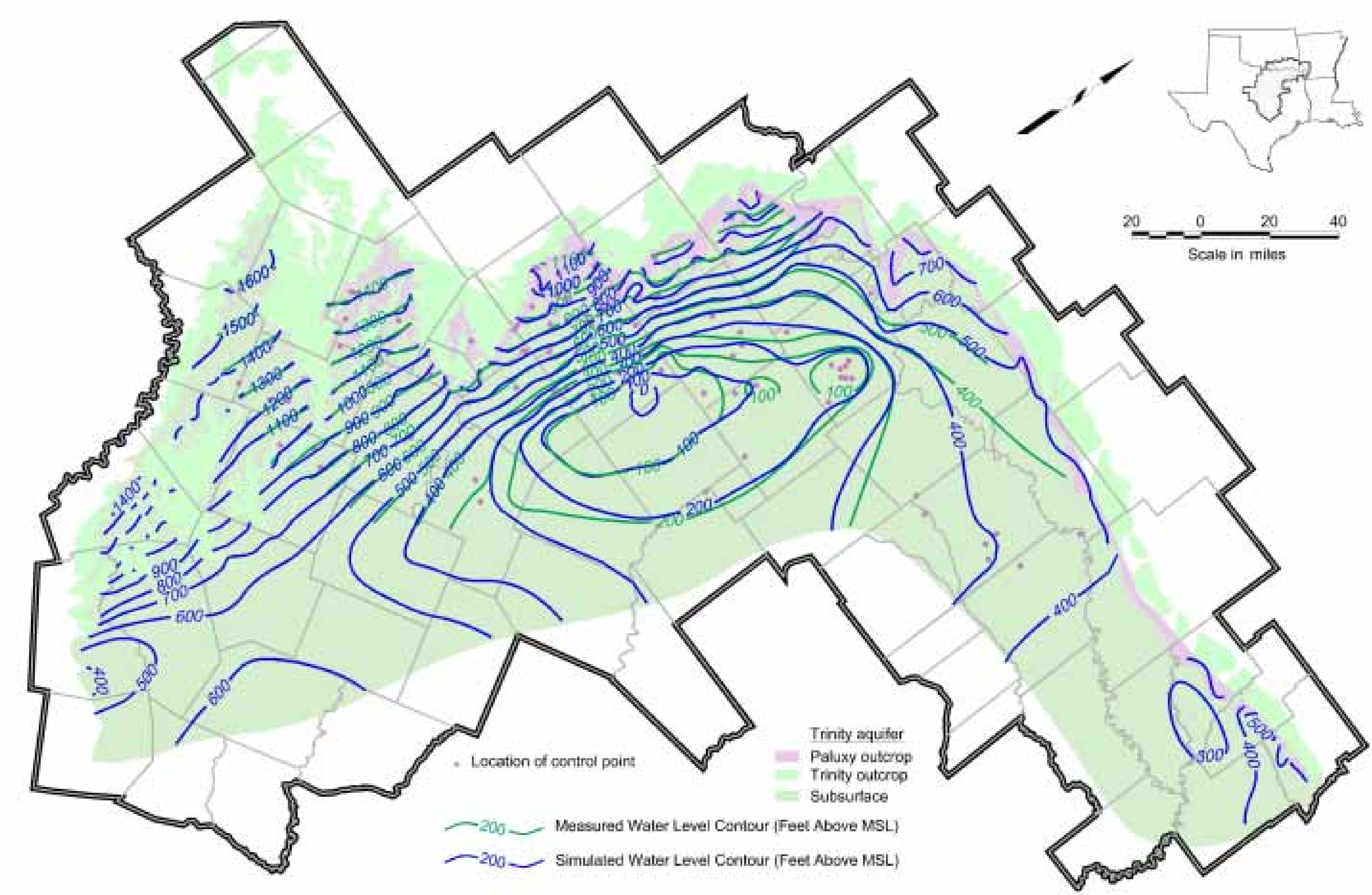



**Figure 9.3 Simulated vs. Measured Hydraulic Head, 1990 – Paluxy (Layer 3)**

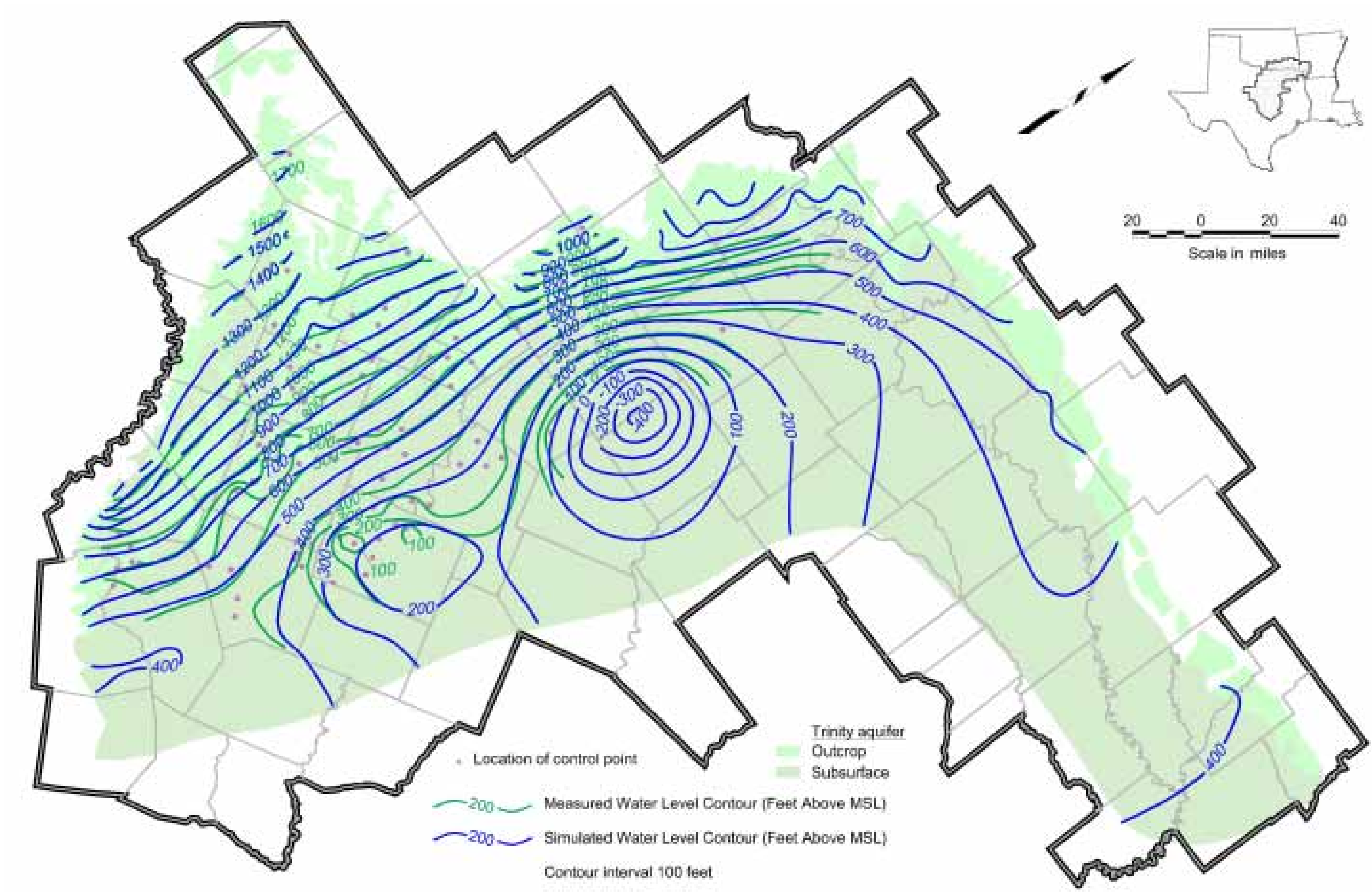



**Figure 9.4 Simulated vs. Measured Hydraulic Head, 1990 – Hensell (Layer 5)**

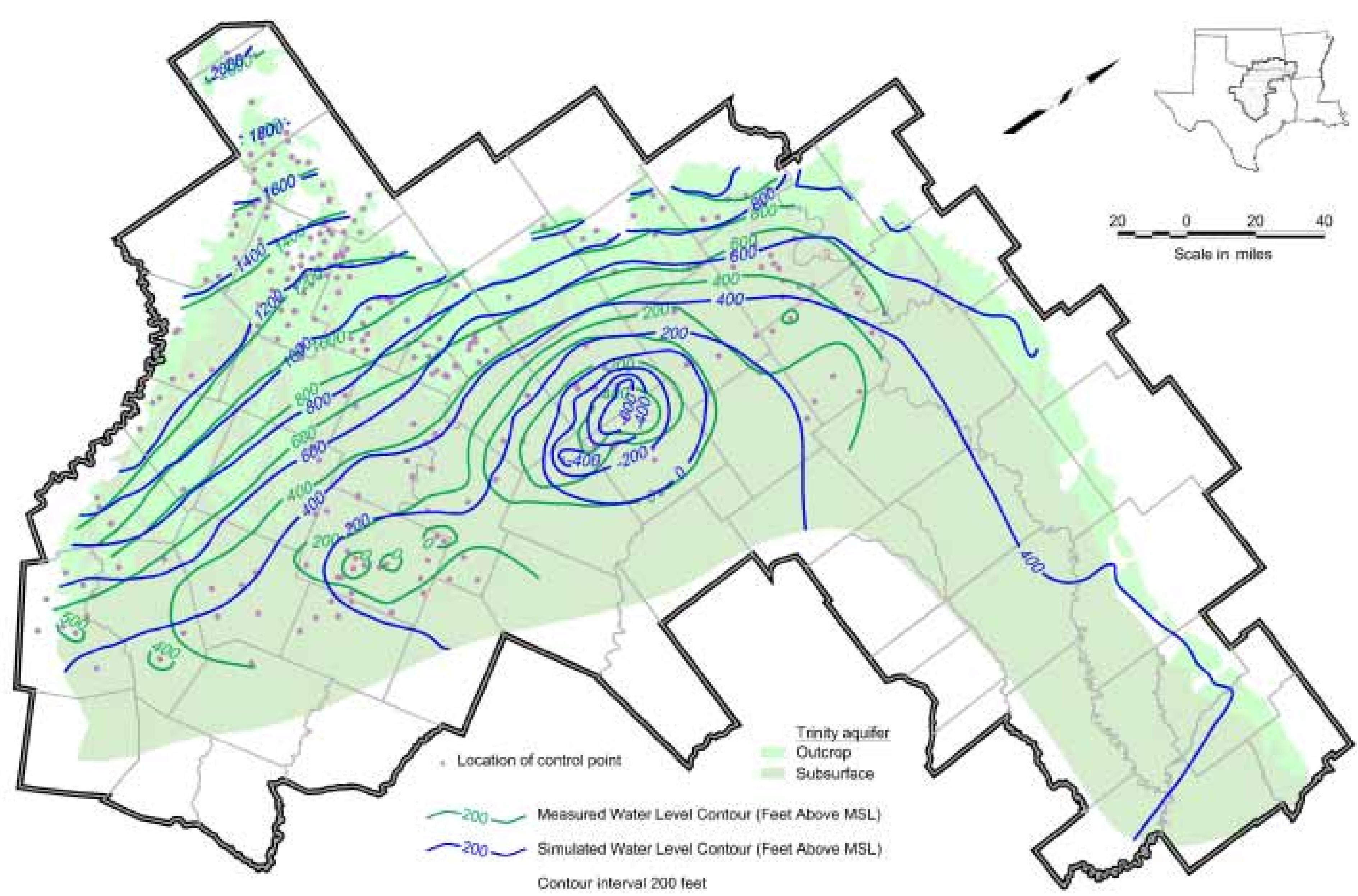



**Figure 9.5 Simulated vs. Measured Hydraulic Head, 1990 – Hosston (Layer 7)**

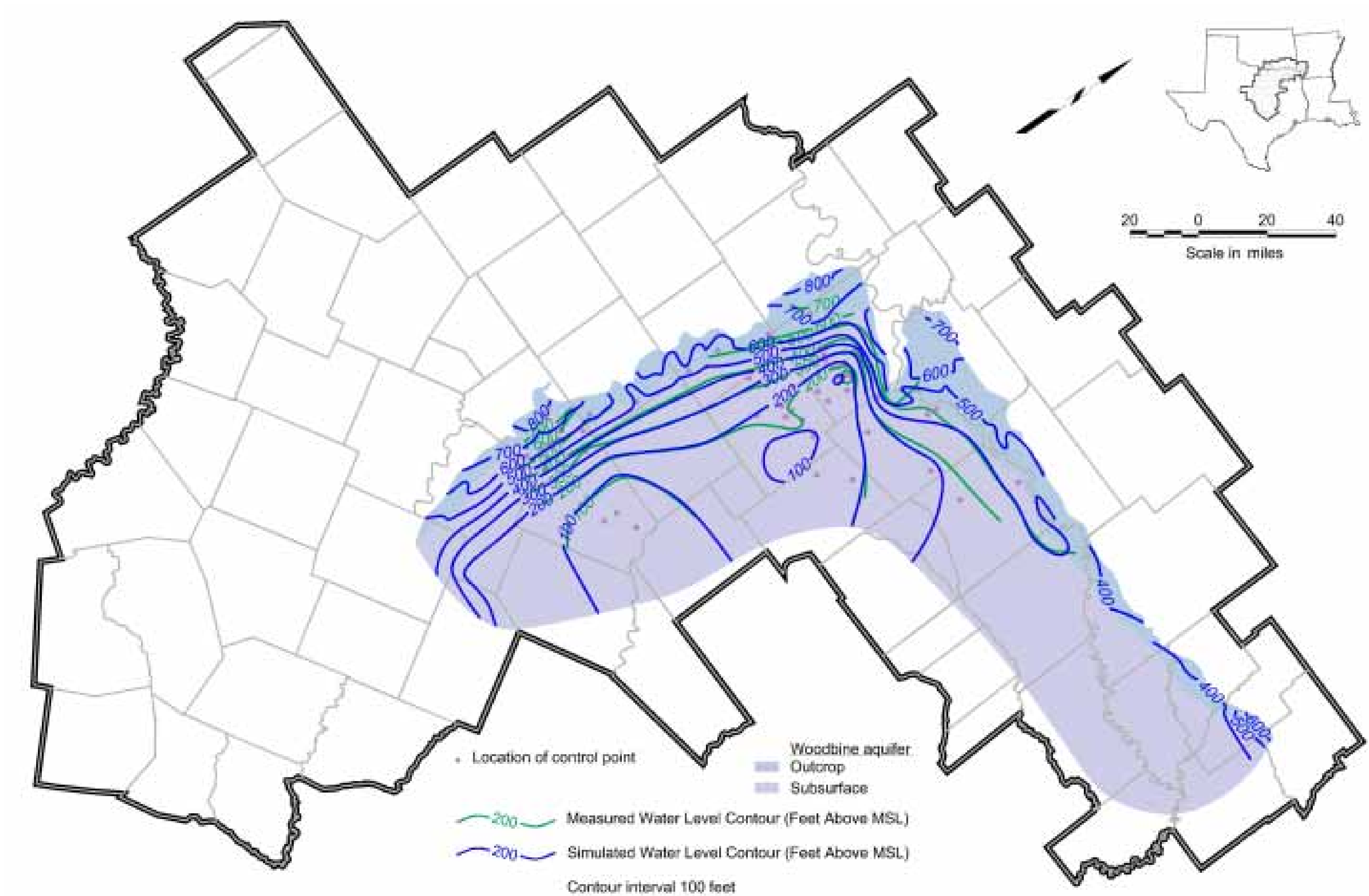



**Figure 9.6 Simulated vs. Measured Hydraulic Head, 2000 – Woodbine (Layer 1)**

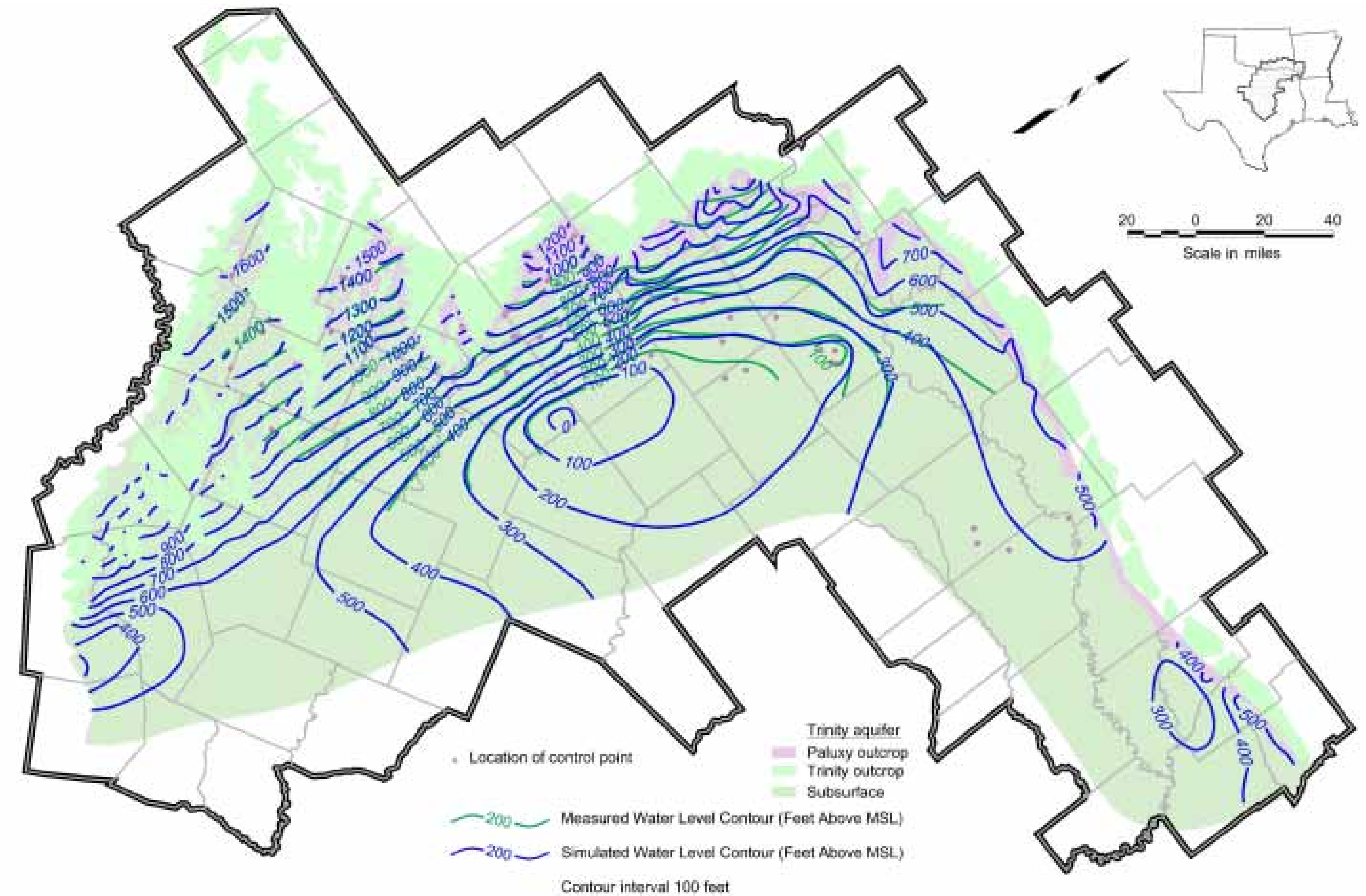



**Figure 9.7 Simulated vs. Measured Hydraulic Head, 2000 – Paluxy (Layer 3)**

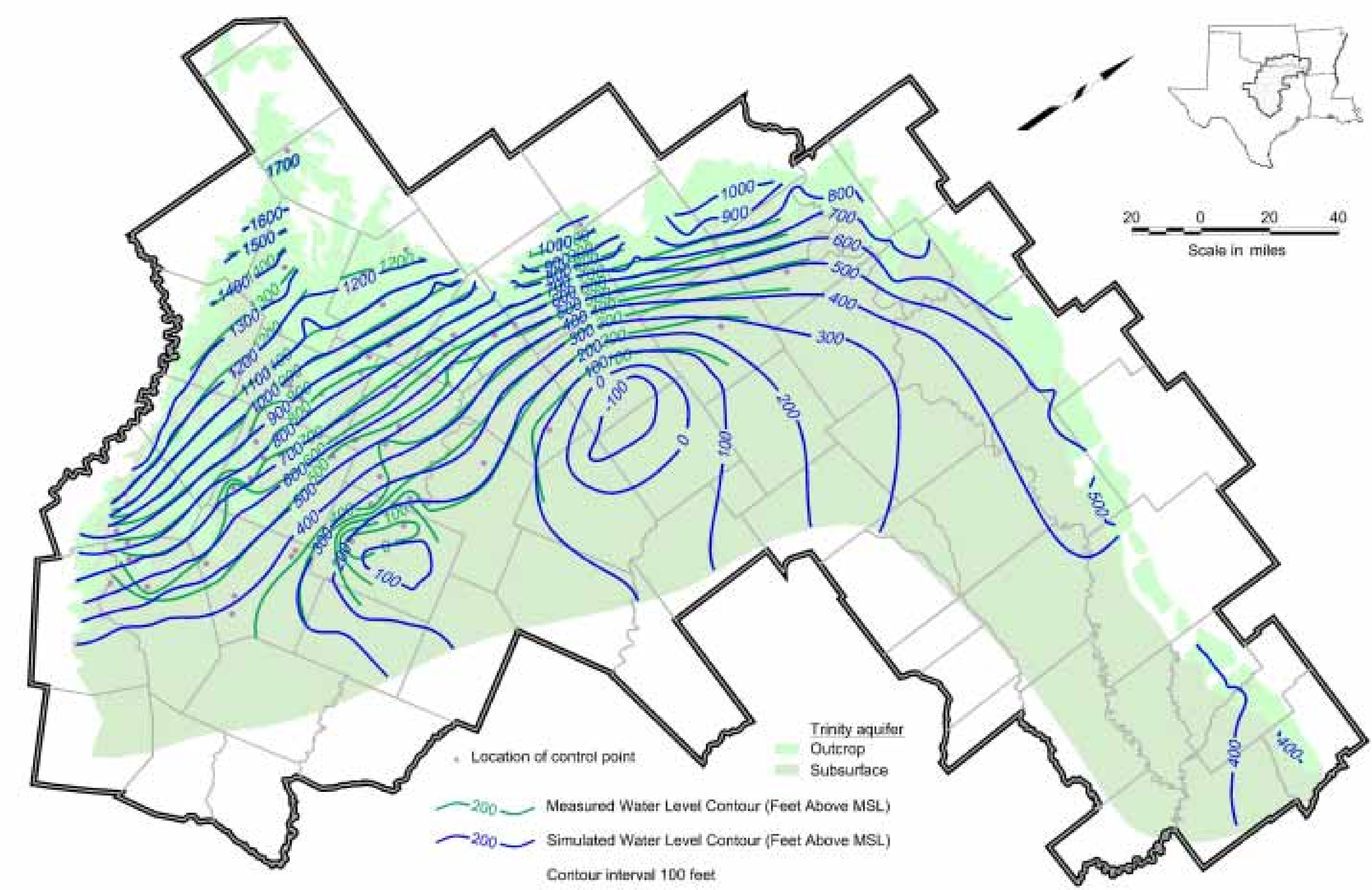



**Figure 9.8 Simulated vs. Measured Hydraulic Head, 2000 – Hensell (Layer 5)**

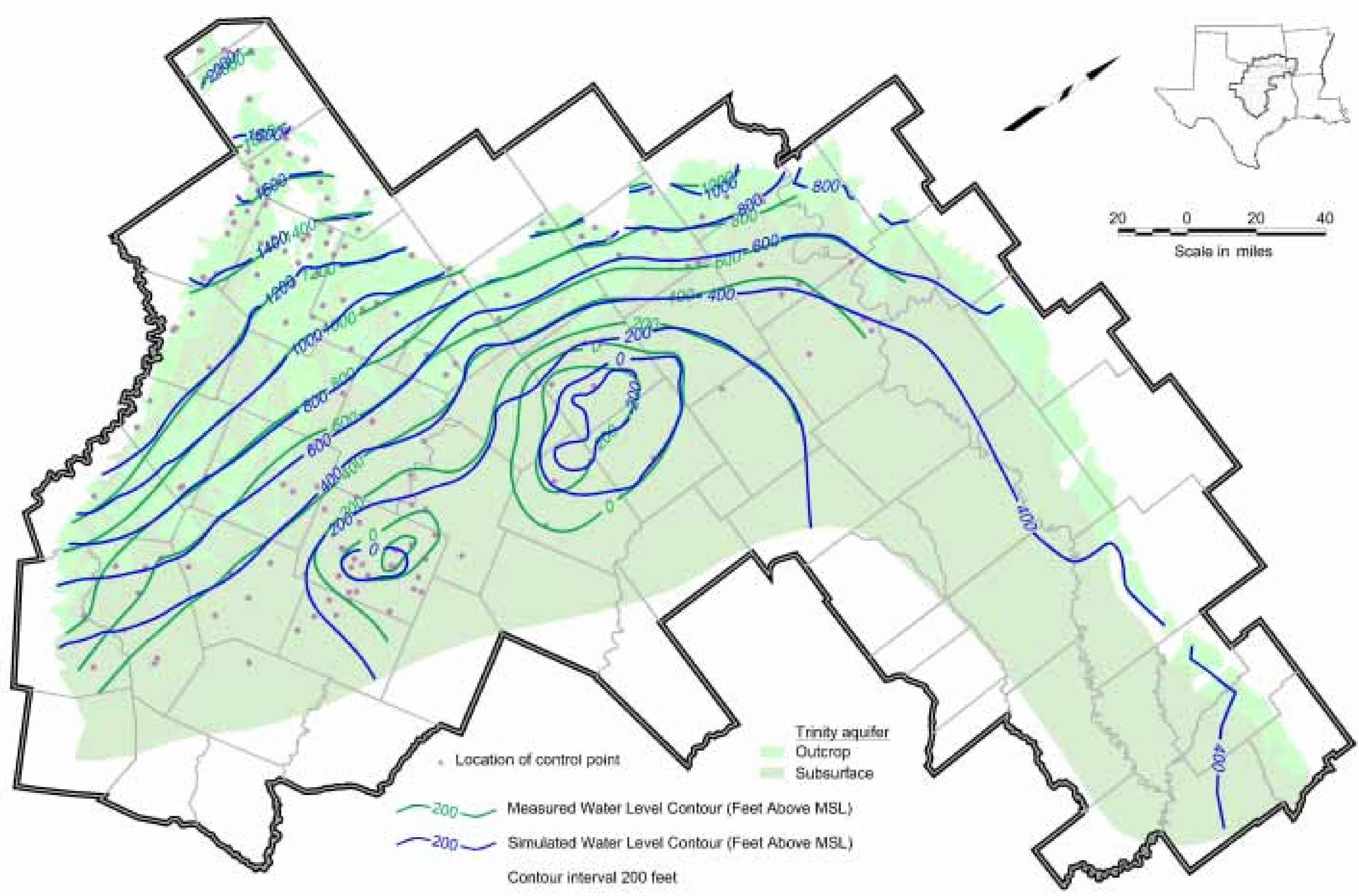



**Figure 9.9 Simulated vs. Measured Hydraulic Head, 2000 – Hosston (Layer 7)**

## Figure 9.10 Woodbine Historical vs. Simulated Water Level Hydrographs

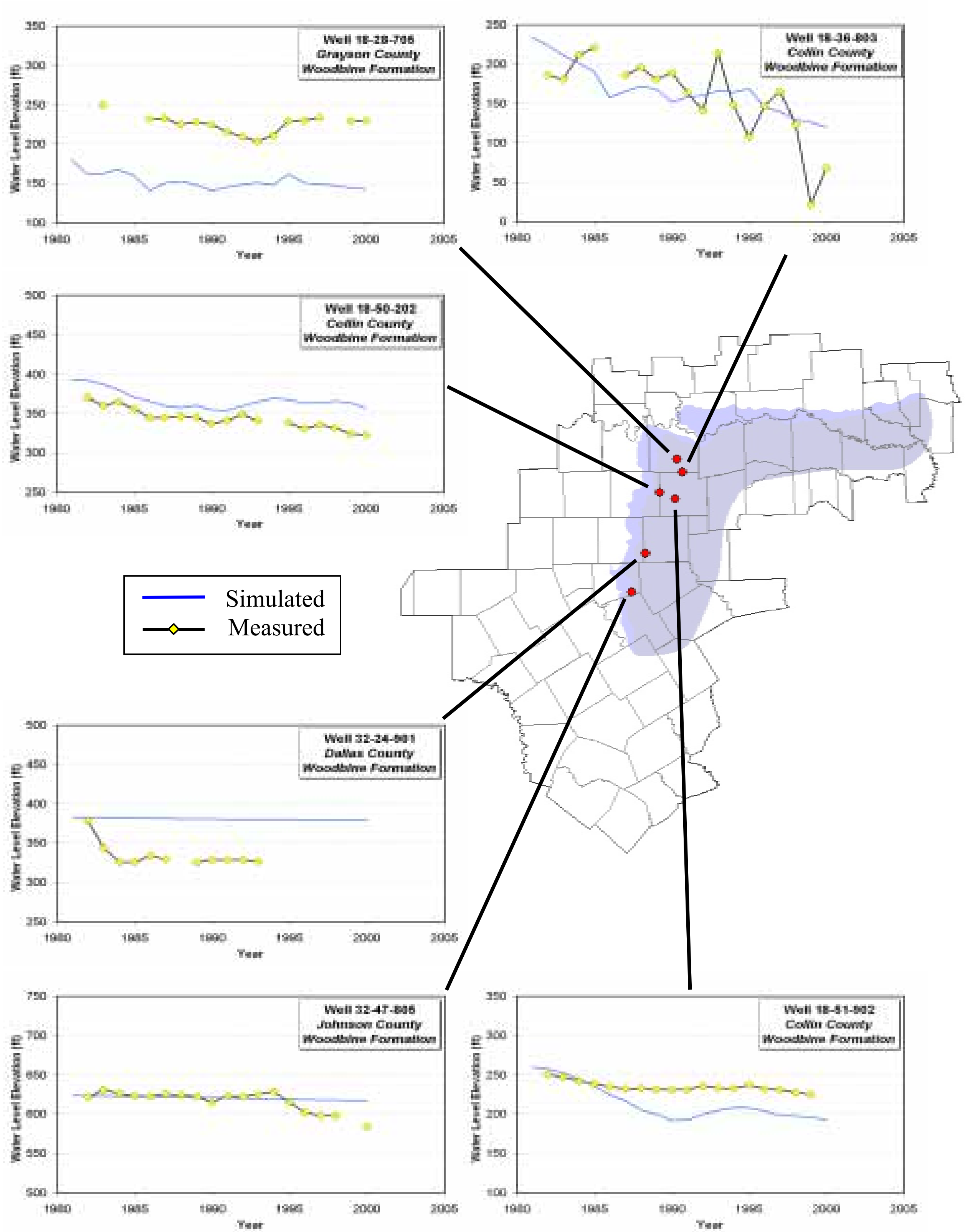


**Figure 9.11 Paluxy Historical vs. Simulated Water Level Hydrographs**

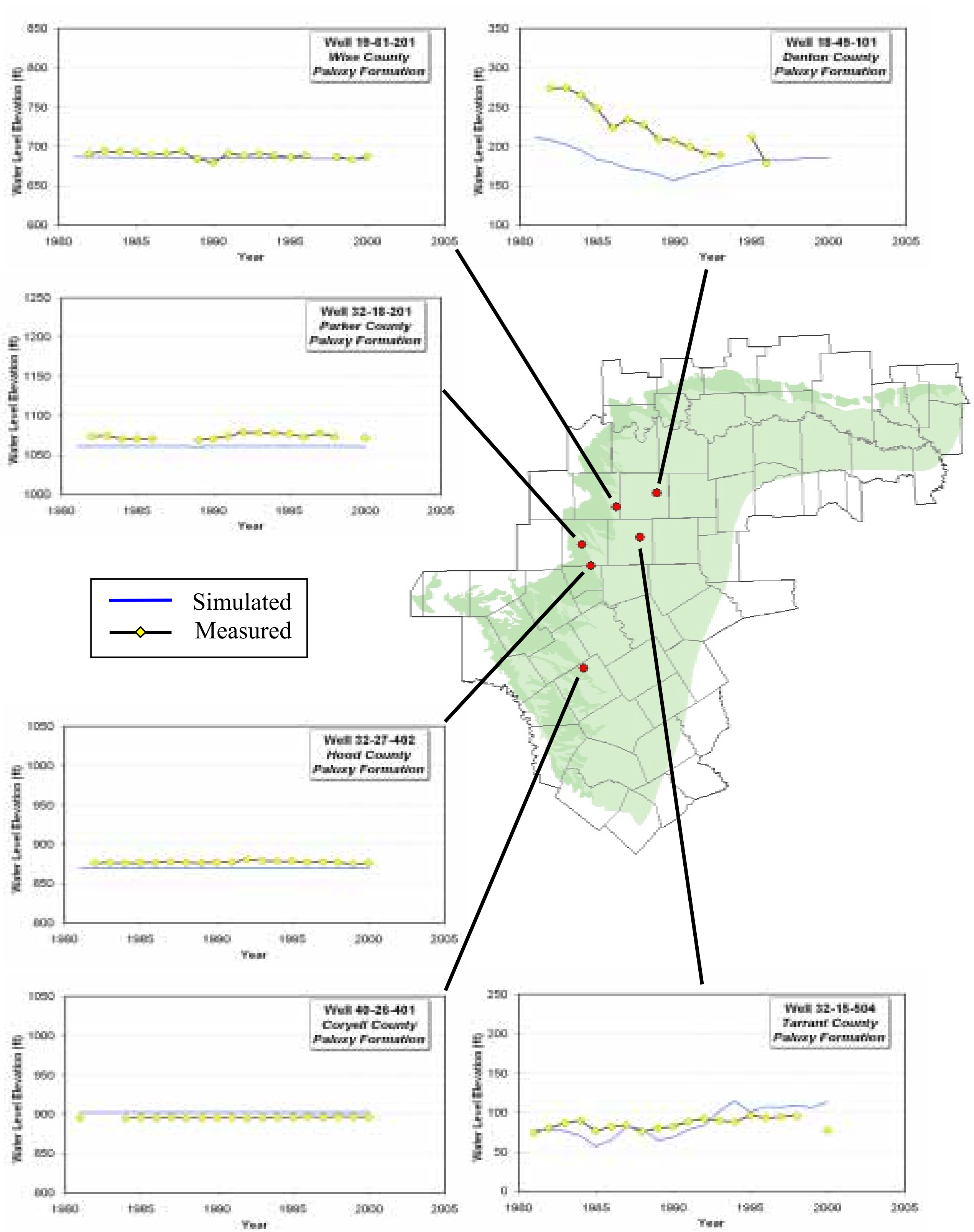


**Figure 9.12 Hensell Historical vs. Simulated Water Level Hydrographs**

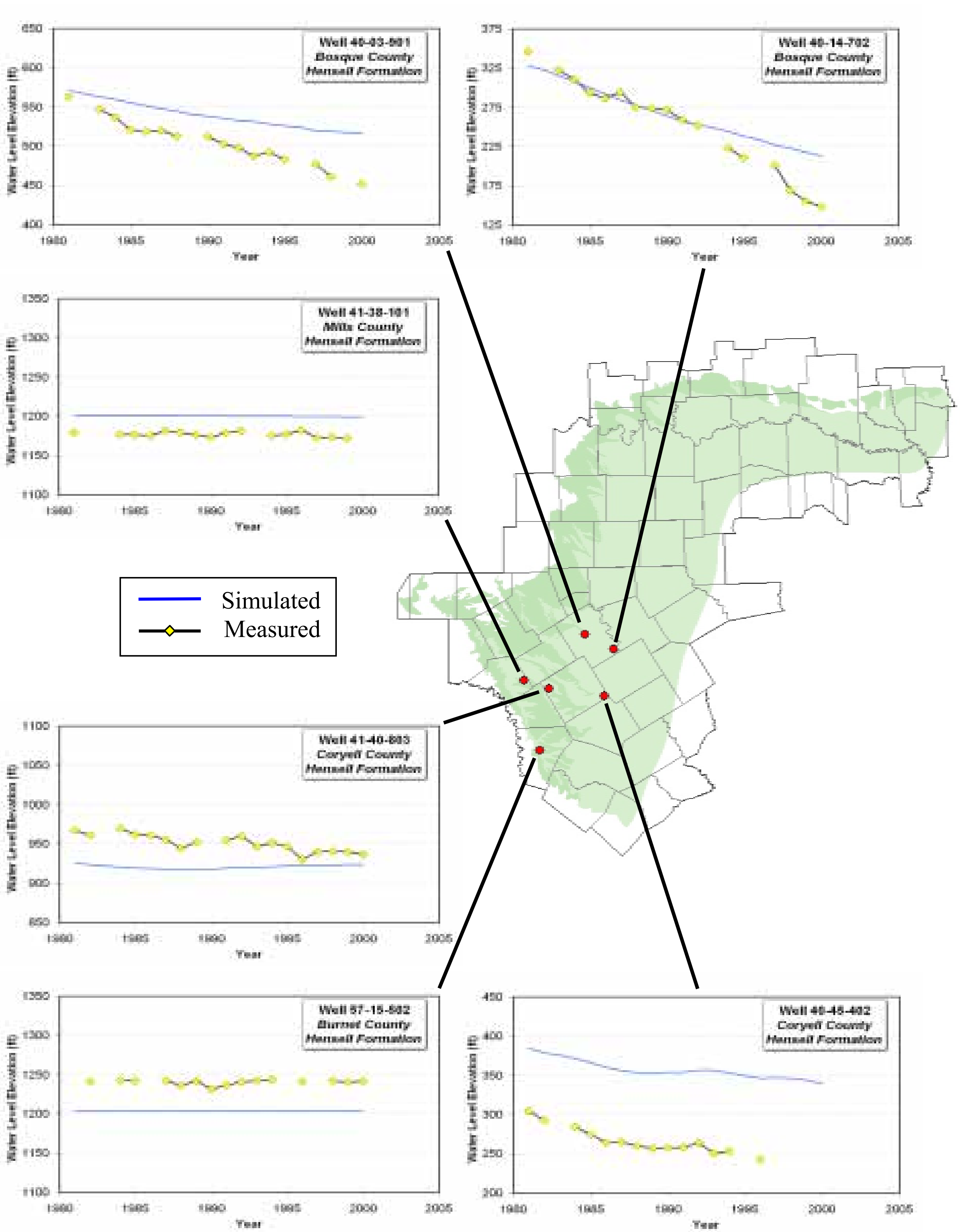
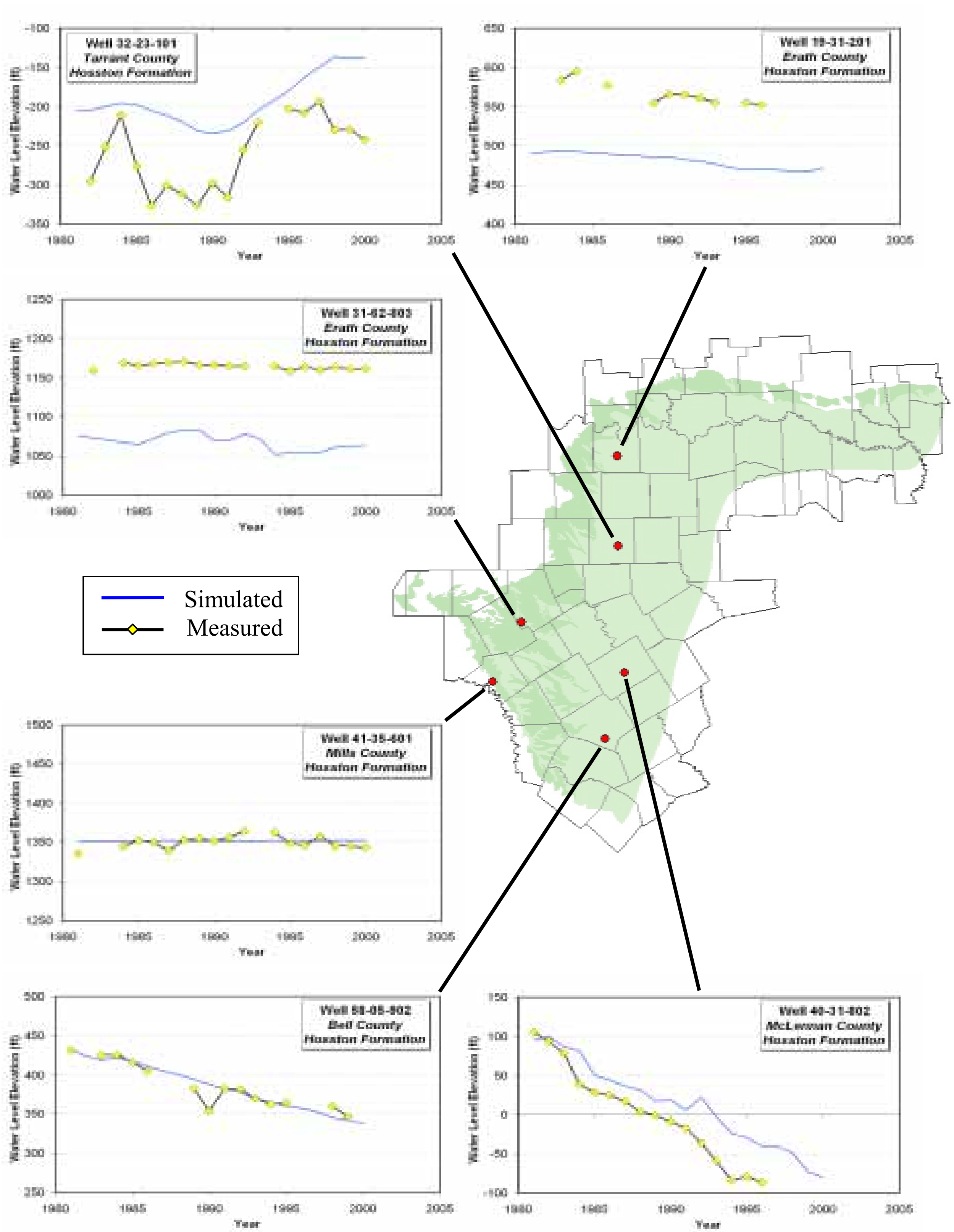


**Figure 9.13 Hosston/Trinity Historical vs. Simulated Water Level Hydrographs**



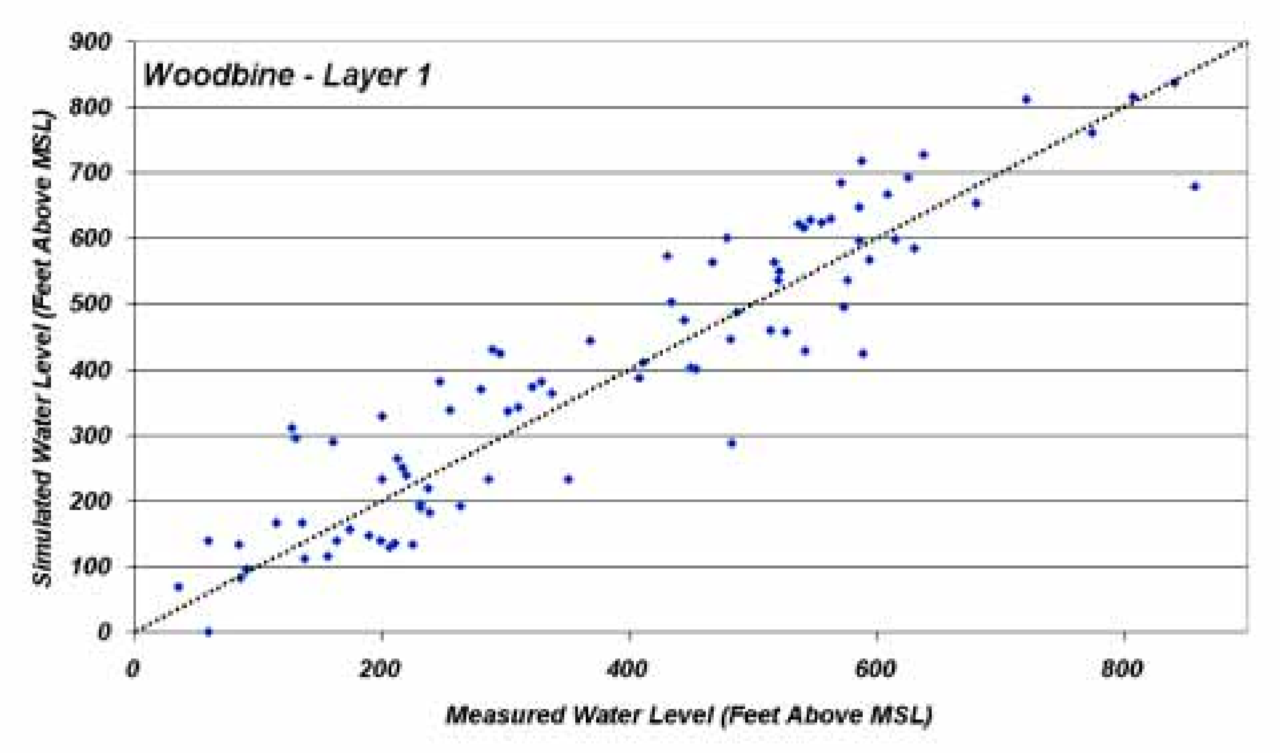



**Figure 9.14 Simulated vs. Measured Hydraulic Head Scatterplot, 1990 – Woodbine (Layer 1)**

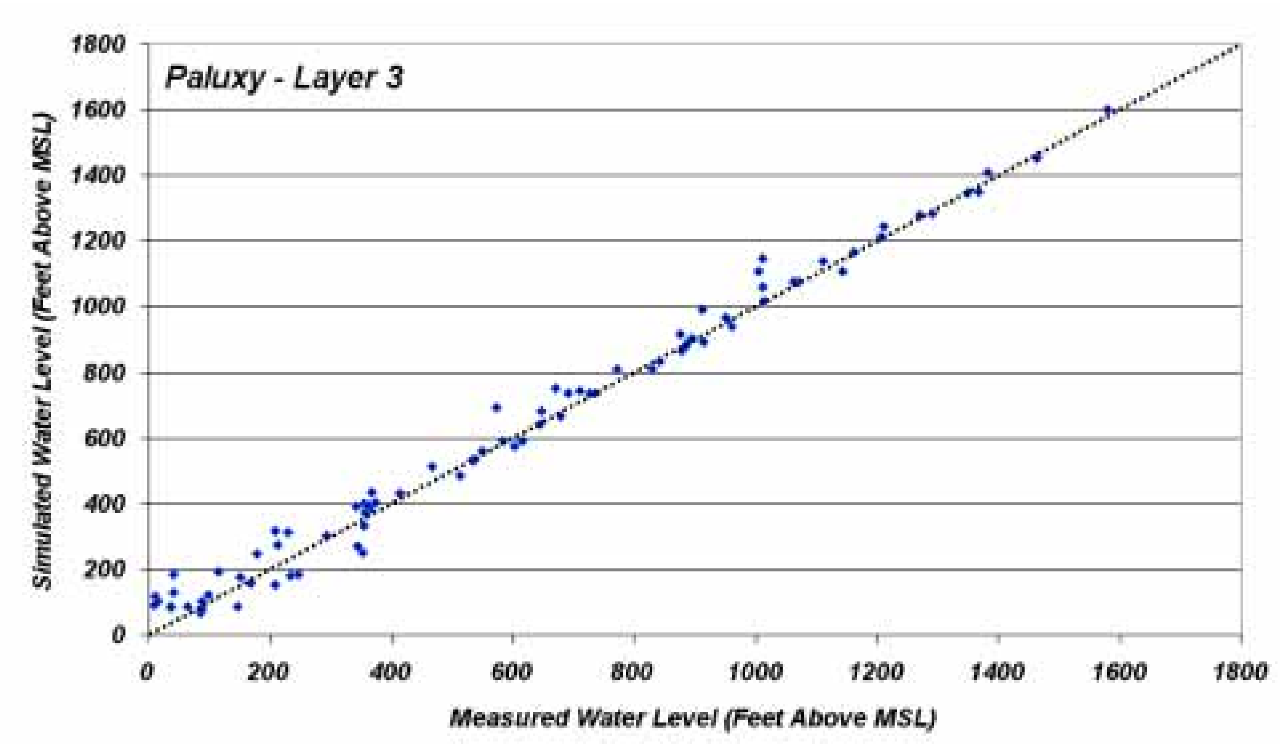



**Figure 9.15 Simulated vs. Measured Hydraulic Head Scatterplot, 1990 – Paluxy (Layer 3)**

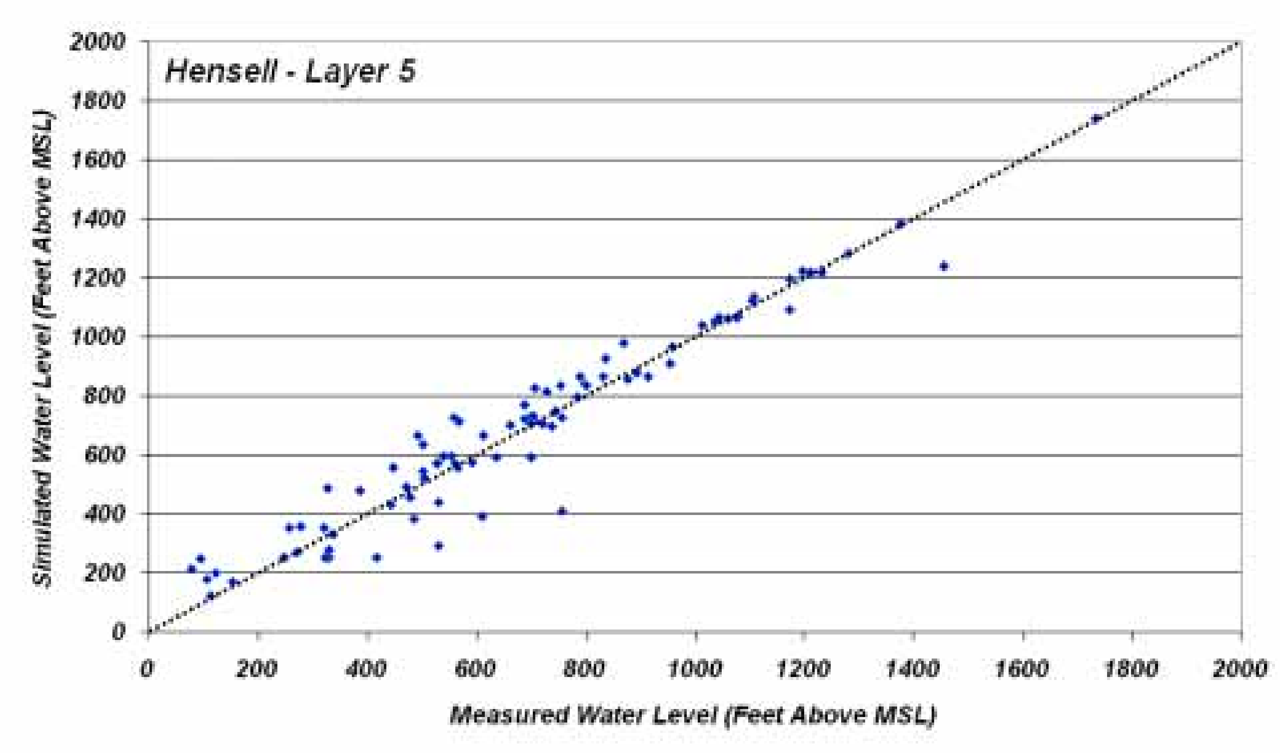



**Figure 9.16 Simulated vs. Measured Hydraulic Head Scatterplot, 1990 – Hensell (Layer 5)**

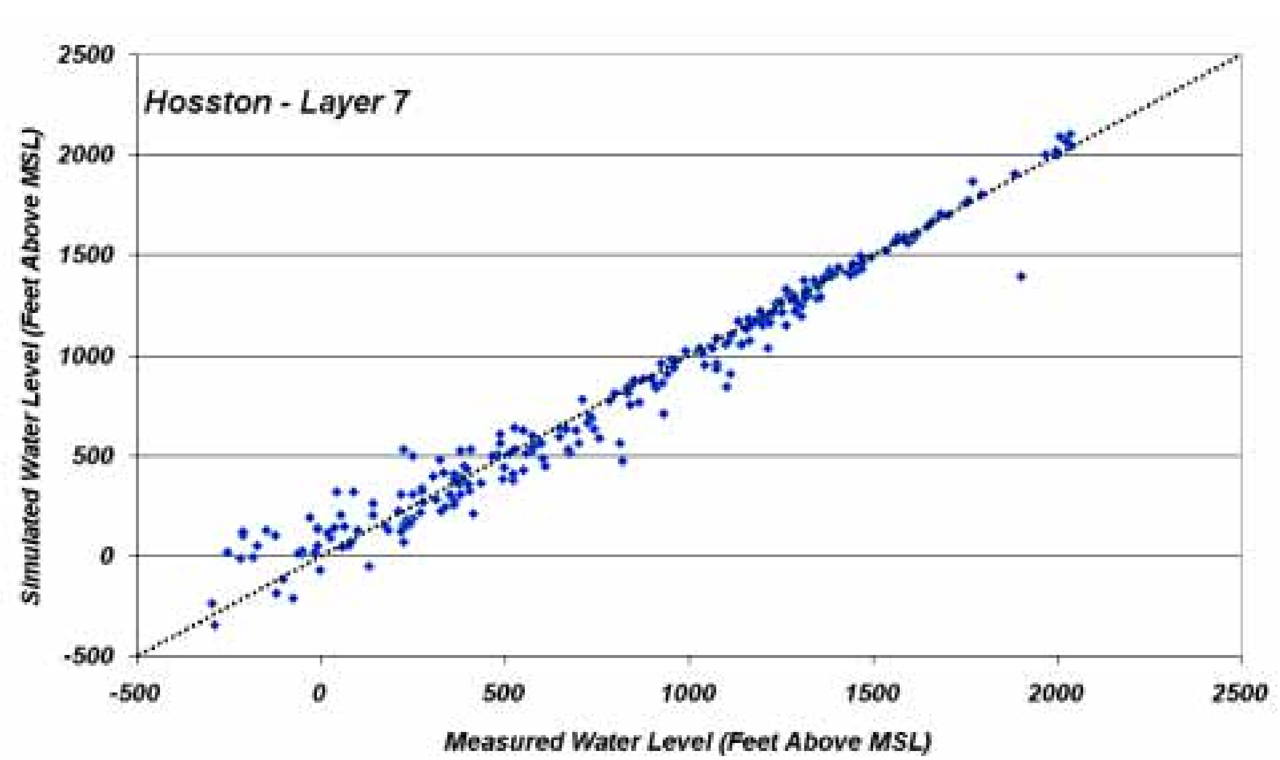



**Figure 9.17 Simulated vs. Measured Hydraulic Head Scatterplot, 1990 – Hosston (Layer 7)**

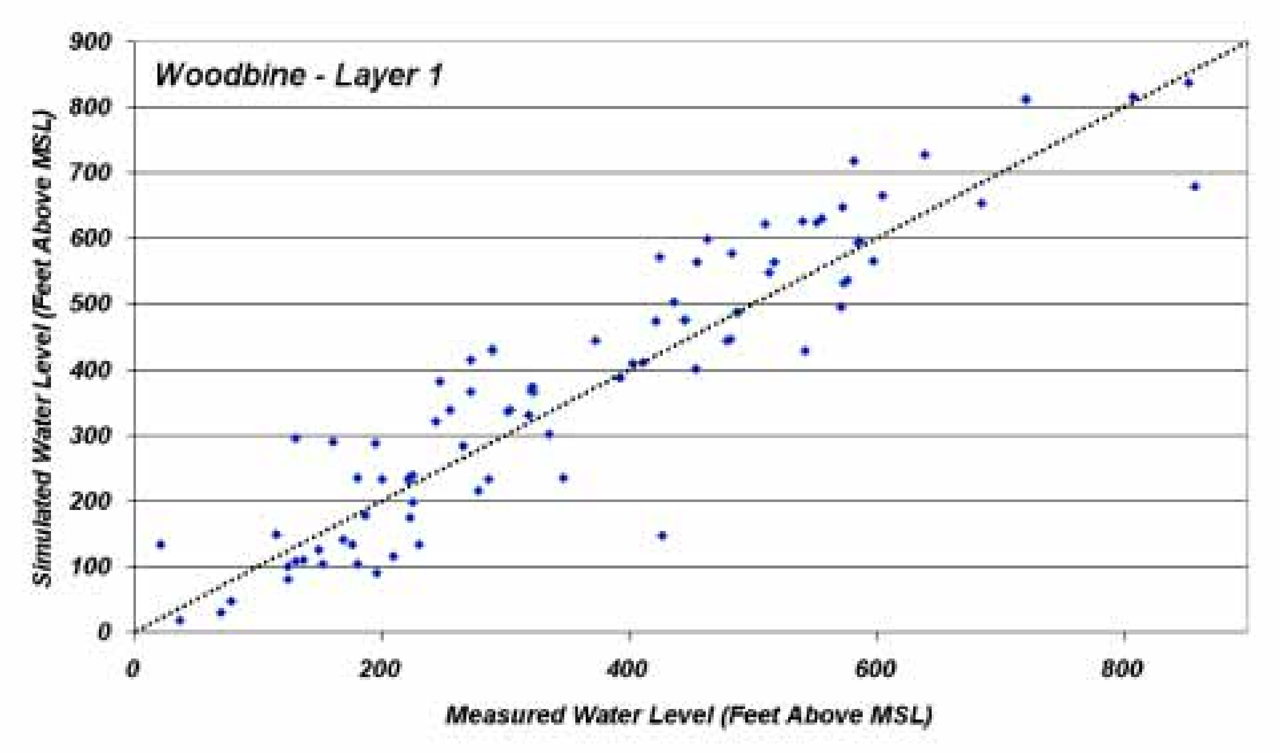



**Figure 9.18 Simulated vs. Measured Hydraulic Head Scatterplot, 2000 – Woodbine (Layer 1)**

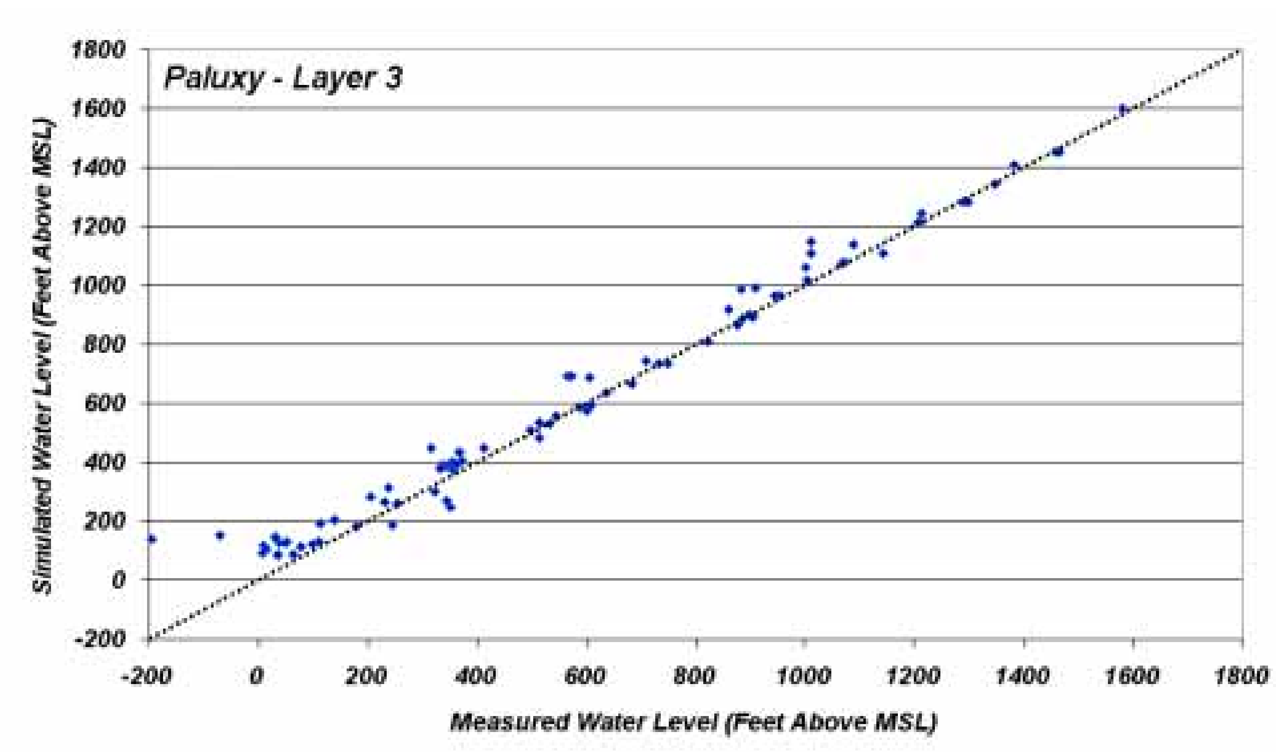



**Figure 9.19 Simulated vs. Measured Hydraulic Head Scatterplot, 2000 – Paluxy (Layer 3)**

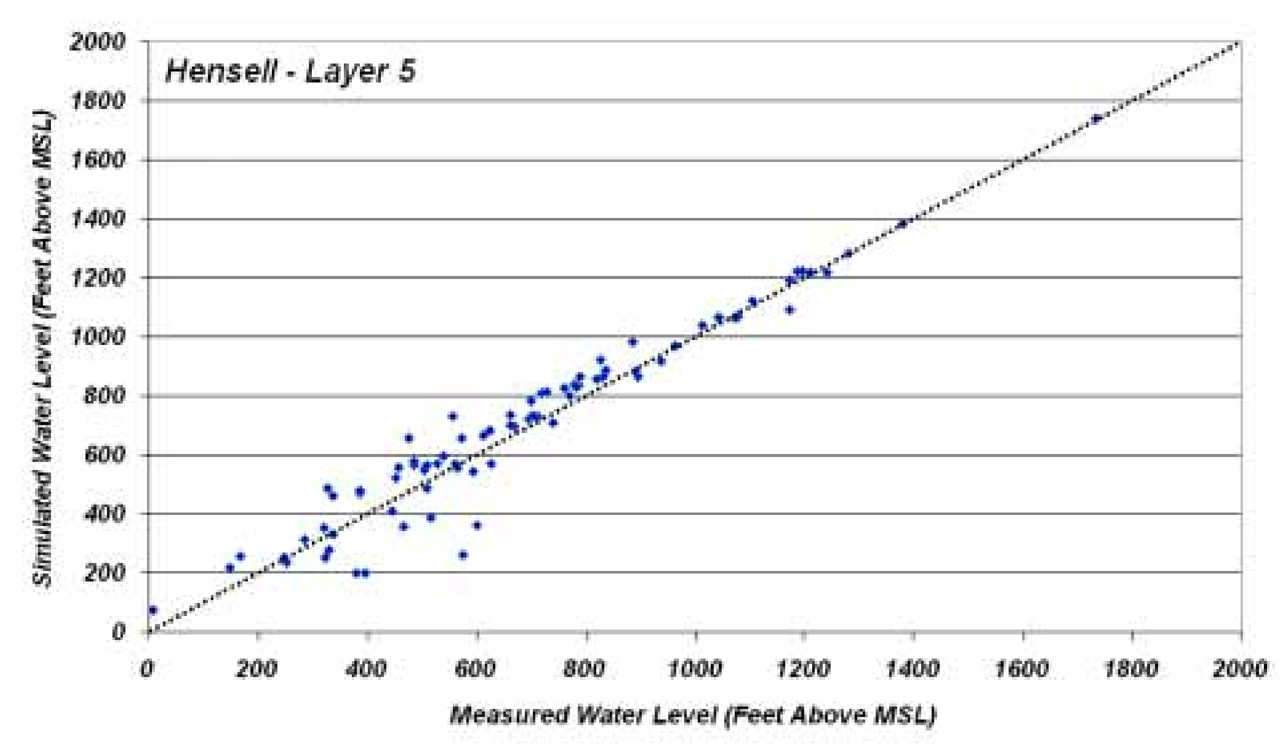



**Figure 9.20 Simulated vs. Measured Hydraulic Head Scatterplot, 2000 – Hensell (Layer 5)**

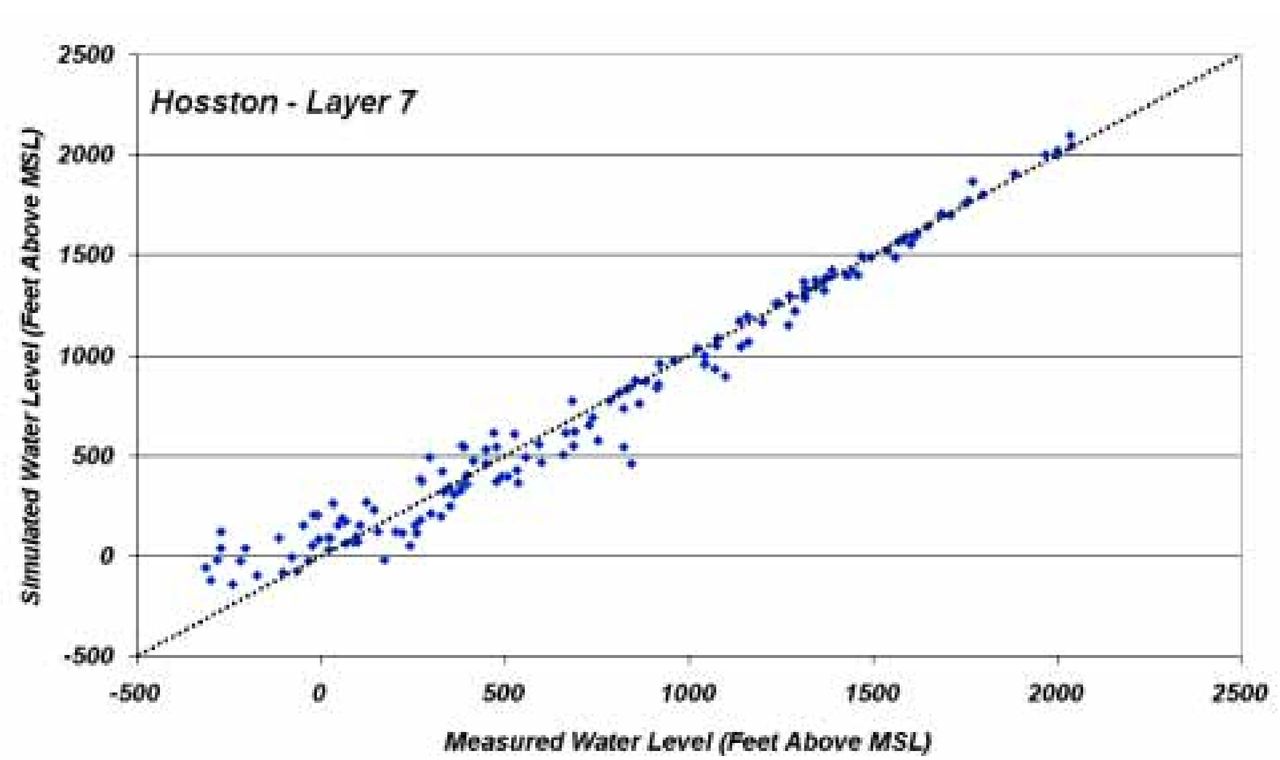



**Figure 9.21 Simulated vs. Measured Hydraulic Head Scatterplot, 2000 – Hosston (Layer 7)**

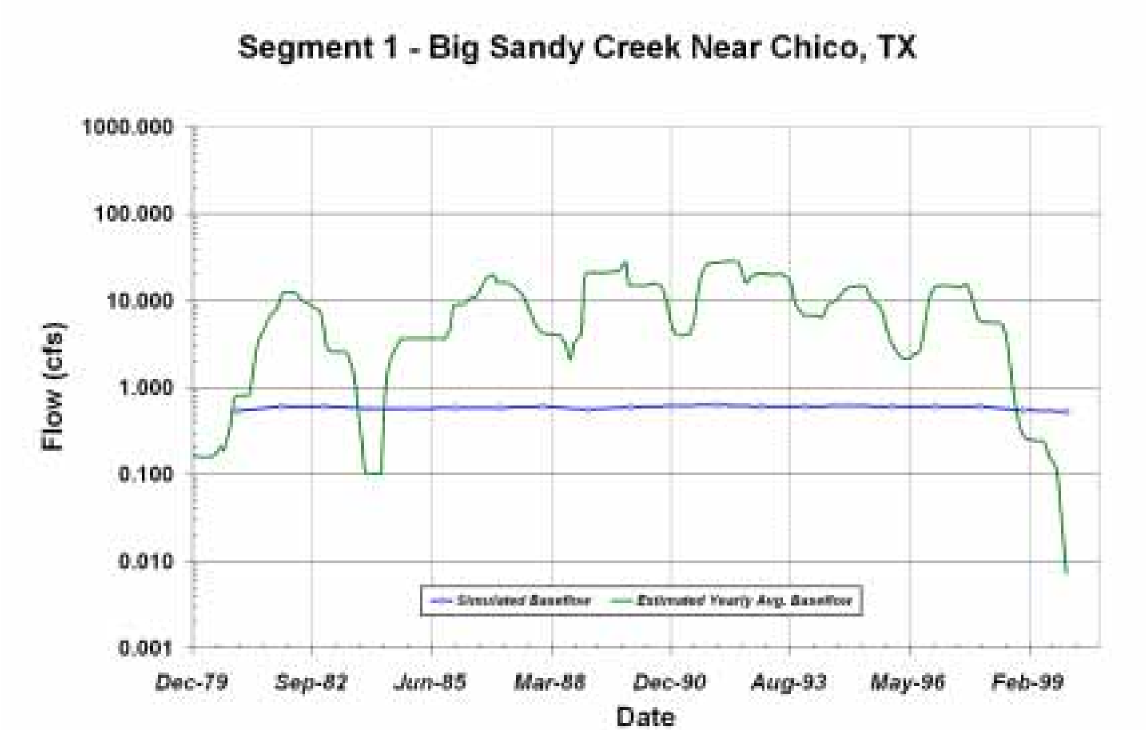



**Figure 9.22 Simulated vs. Estimated Baseflow of Stream Segment 1**


**Figure 9.23 Simulated vs. Estimated Baseflow of Stream Segment 2**

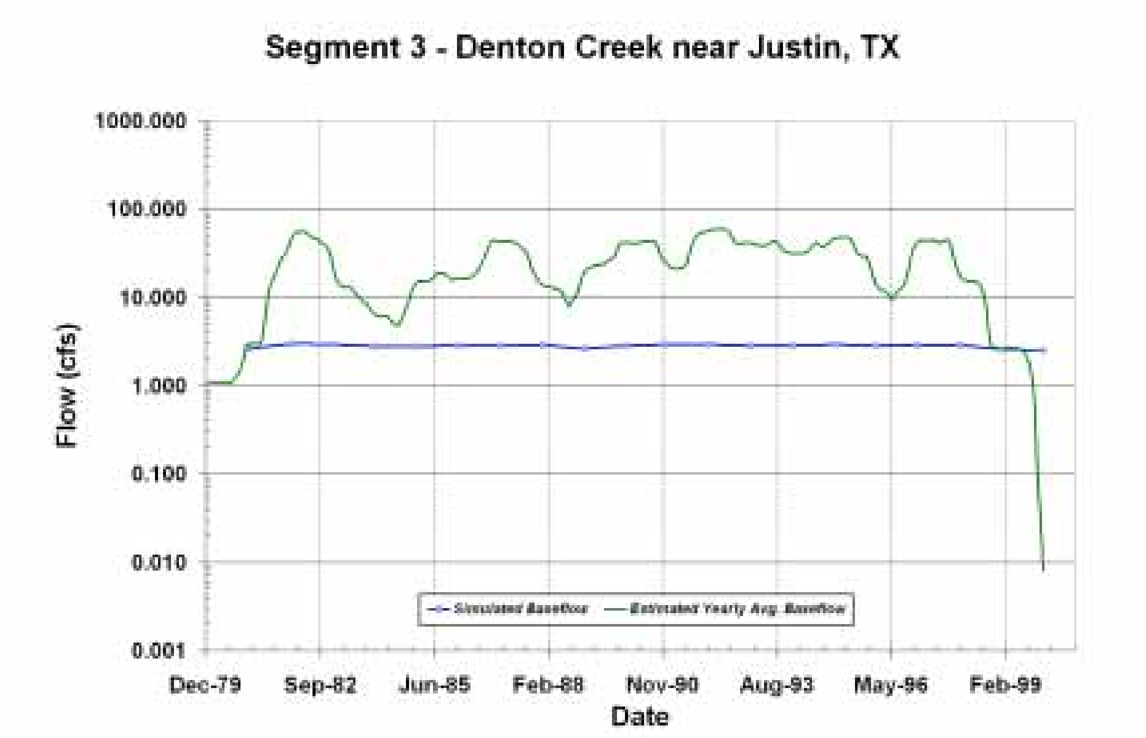



**Figure 9.24 Simulated vs. Estimated Baseflow of Stream Segment 3**

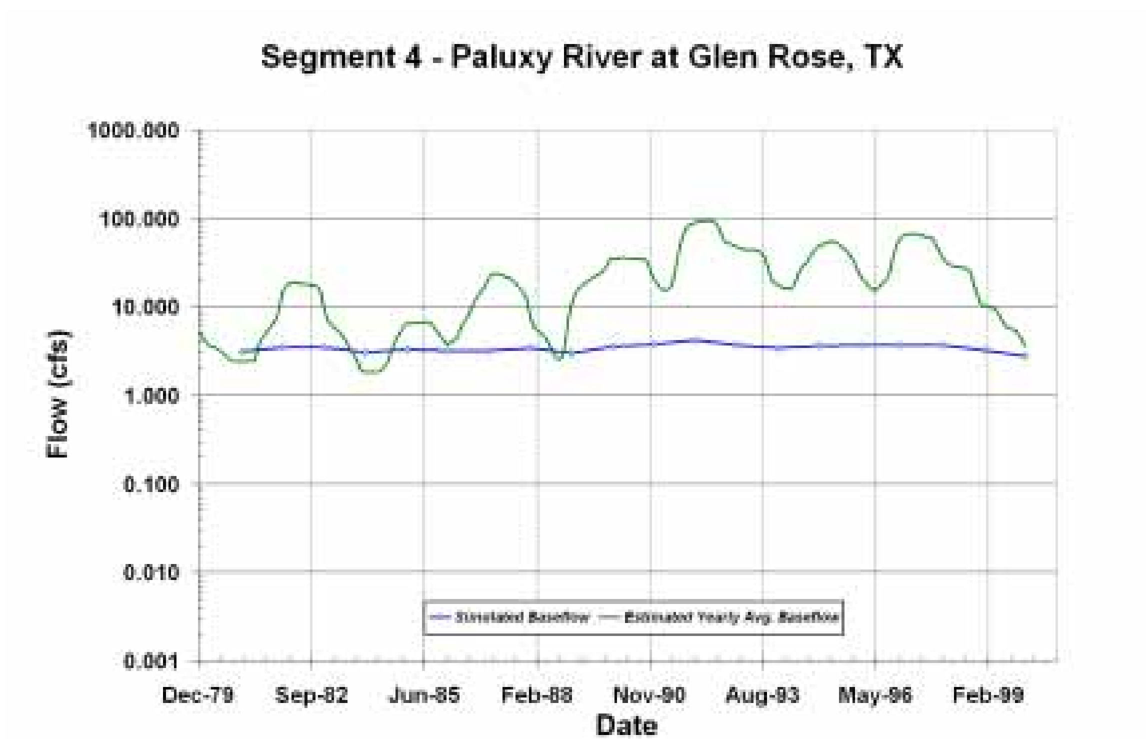



**Figure 9.25 Simulated vs. Estimated Baseflow of Stream Segment 4**

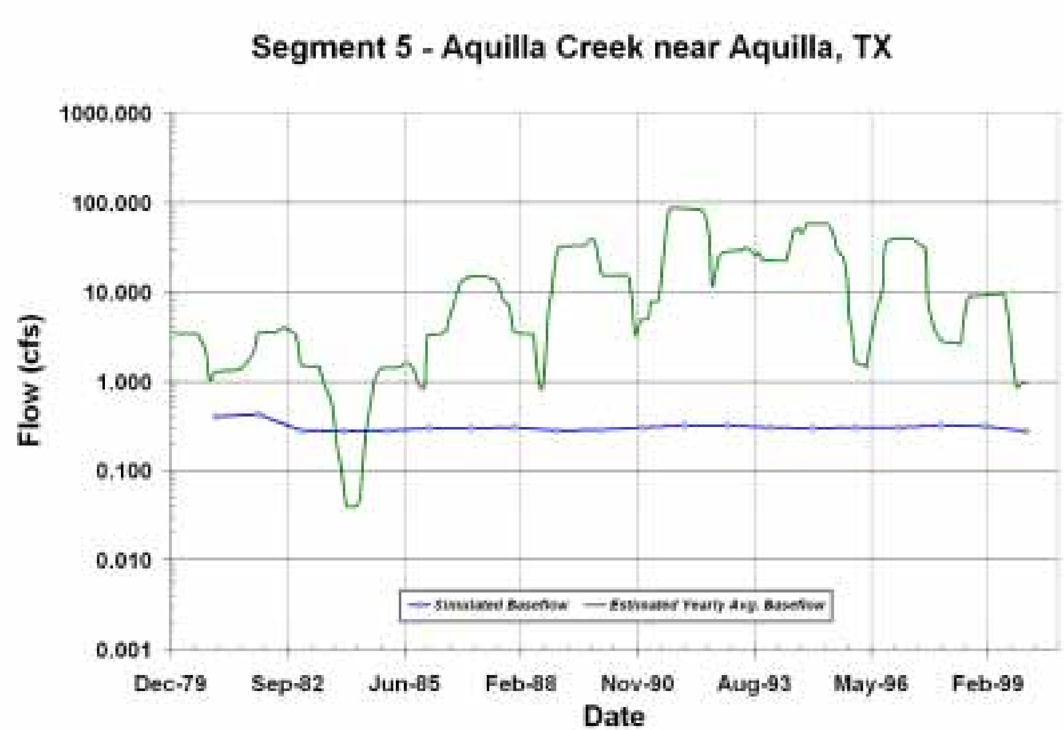



**Figure 9.26 Simulated vs. Estimated Baseflow of Stream Segment 5**

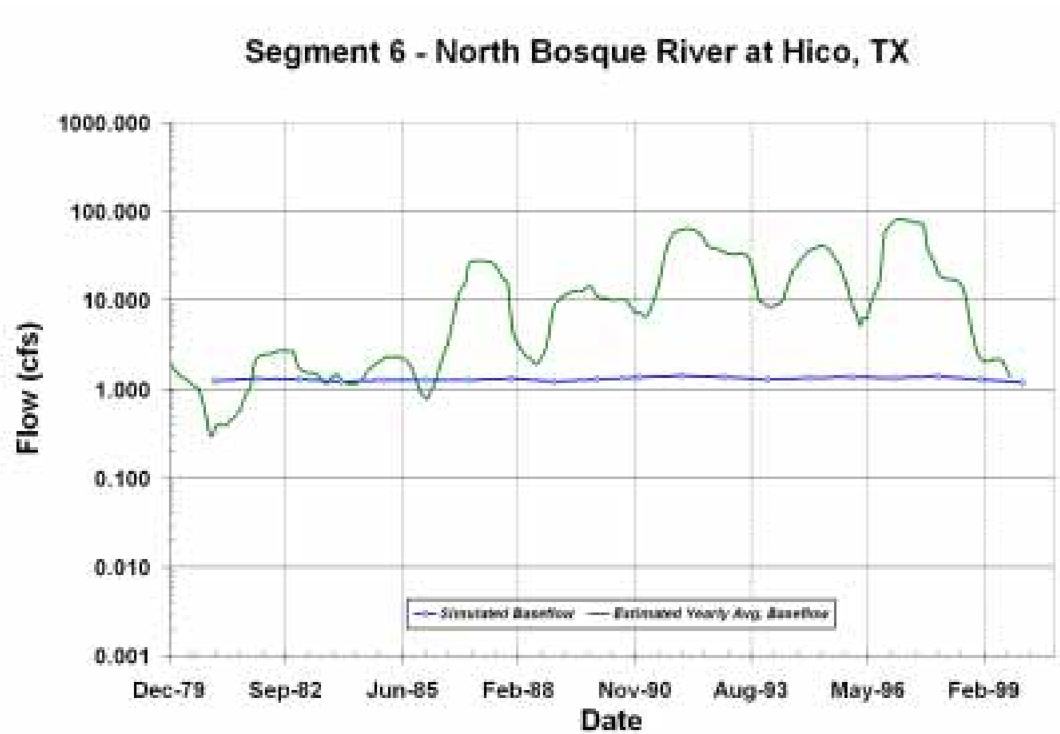



**Figure 9.27 Simulated vs. Estimated Baseflow of Stream Segment 6**

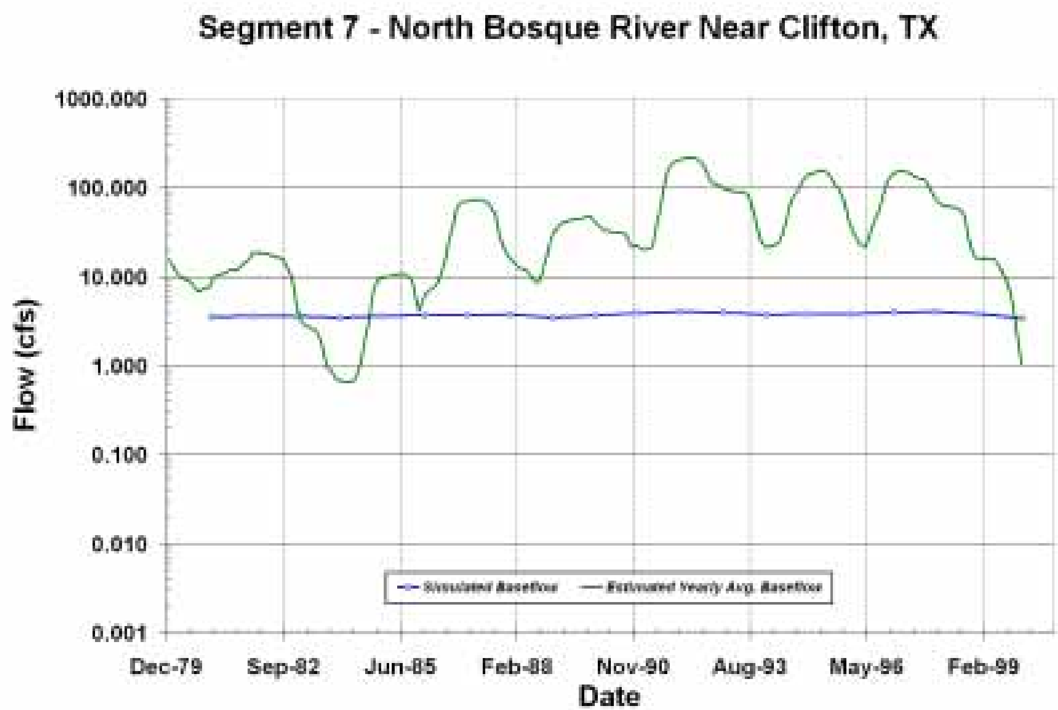



**Figure 9.28 Simulated vs. Estimated Baseflow of Stream Segment 7**

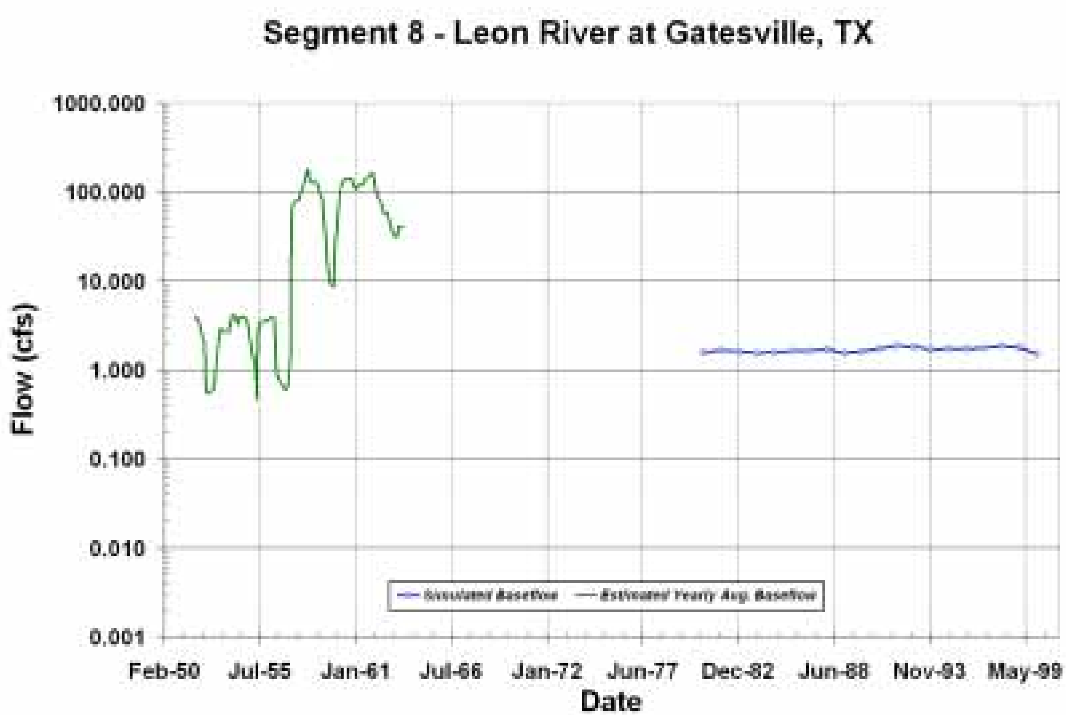



**Figure 9.29 Simulated vs. Estimated Baseflow of Stream Segment 8**

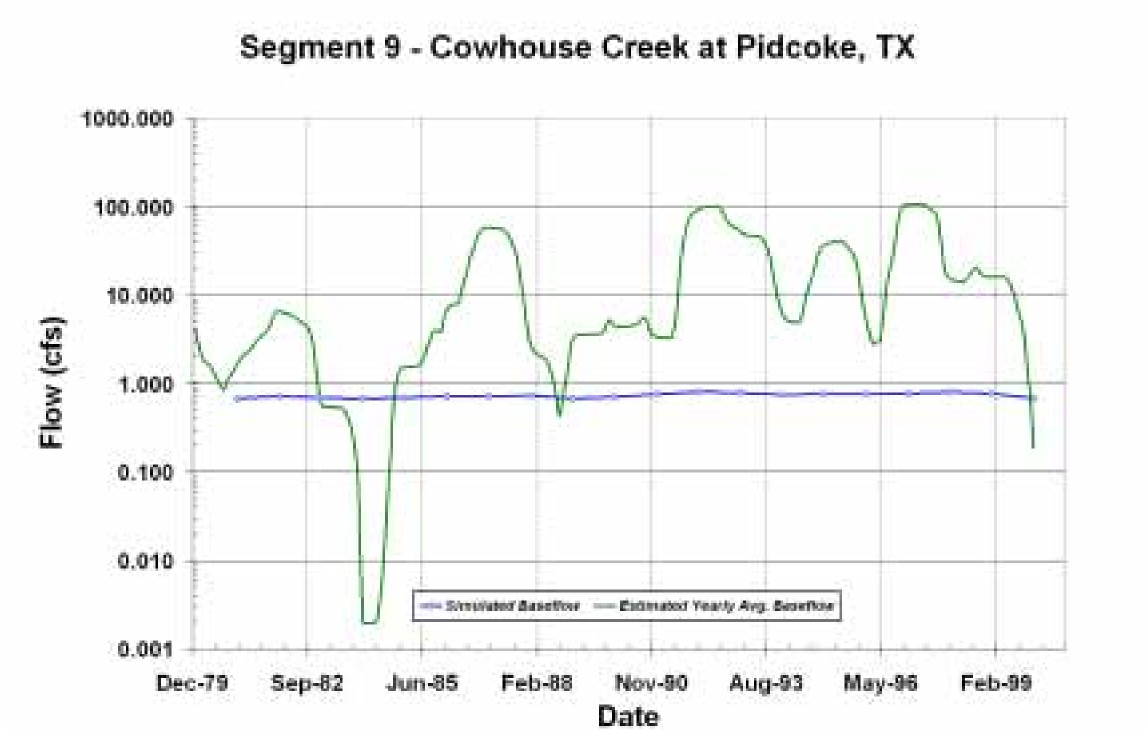



**Figure 9.30 Simulated vs. Estimated Baseflow of Stream Segment 9**

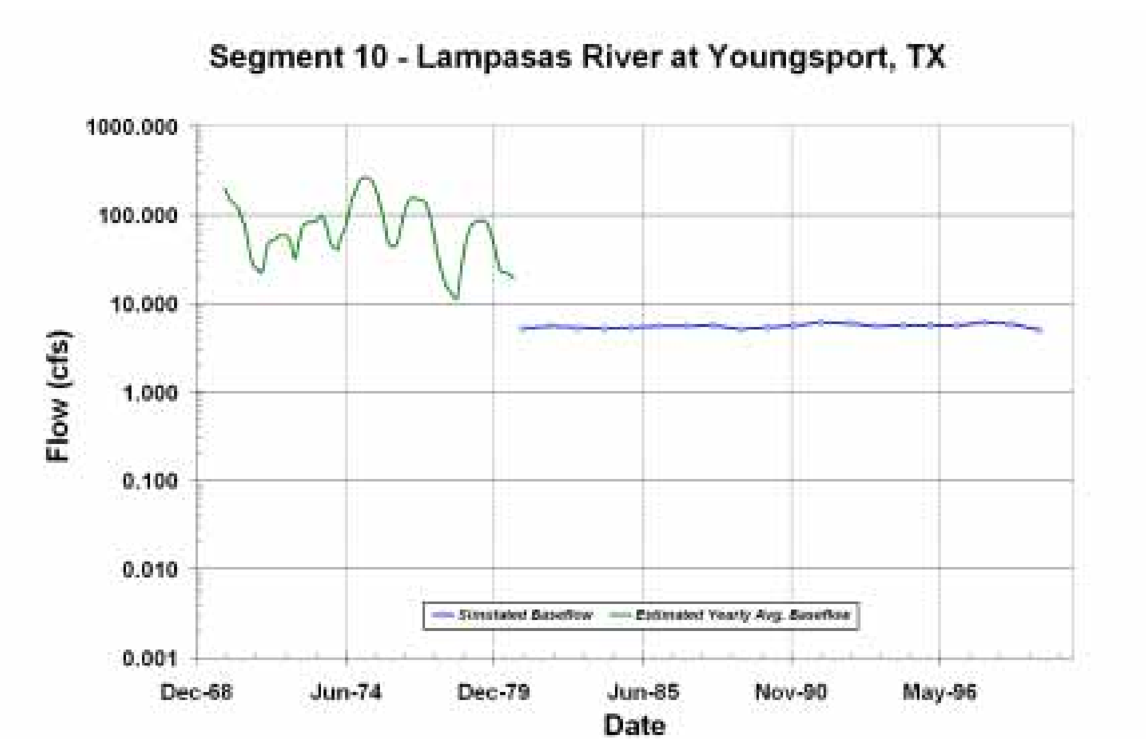



**Figure 9.31 Simulated vs. Estimated Baseflow of Stream Segment 10**

### 9.1.2 Water Budget

The calibrated and verified model was used to investigate the groundwater fluxes and relationships between inflow and discharge mechanisms within the Trinity/Woodbine system during the interval between 1980 and 2000 (calibration period). Table 9.3 lists the water budget or the rate at which water enters, exits, or is transferred within the aquifer system at specific points in time including: 1) the beginning of the calibration period (1980), 2) the end of the year with the smallest reported average precipitation during the calibration period (1988), 3) the end of the calibration period (1990), and 4) the end of the verification period (2000).

In 1980, approximately 1.9 million acre-feet per year (ac-ft/yr) is exchanged within the aquifer system. About 166,000 ac-ft/yr is withdrawn from wells distributed across the model. The recharge applied to the model in 1980 was about 1.79 million ac-ft/yr. Extraction by evapotranspiration is approximately 1.67 million ac-ft/yr, which is about 93 percent of the applied recharge. Storage depletion and baseflow discharge to streams in the system is reported as 111,000 ac-ft/yr and 67,000 ac-ft/yr, respectively. Very little interaction was observed between Trinity/Woodbine units and overlying sediments, with a net flow of 22 ac-ft/yr into the aquifer system reported in 1980.

The amount of water transferred within the model totaled about 1.65 million ac-ft/yr at the end of 1988. Wells extracted approximately 211,000 ac-ft/yr, and a corresponding decrease in storage of about 293,000 ac-ft/yr was reported. Evapotranspiration diminished to about 1.37 million ac-ft/yr by 1988, but surpassed applied recharge at that time, which decreased to approximately 1.35 million ac-ft/yr during the same interval. A reduction in baseflow to streams was also reported at the end of 1988, showing a 25 percent decrease from 1980 volumes to about 50,000 ac-ft/yr. The recharge and baseflow rates declined because of the reduction in precipitation recorded during 1988.

Precipitation increased in the interval between 1980 and 1990, and as a result, the amount of water transferred in the model rose to approximately 2.01 million ac-ft/yr at the end of the calibration period. As seen in previous simulations, recharge and evapotranspiration accounted for majority of the water transferred, with an applied recharge of 1.87 million ac-ft/yr, of which 1.64 million ac-ft/yr was removed by evapotranspiration. The rate of storage depletion by 1990 decreased by 86 percent to about 42,000 ac-ft/yr in response to the increase in applied recharge.

At the end of the verification period (2000), the total amount of water transferred in the model dropped to approximately 1.57 million ac-ft/yr because of the decrease in precipitation recorded during 1999. The recharge applied to the model was about 1.27 million ac-ft/yr, the lowest rate of the 20-year calibration/verification interval. The minor lowering of outcrop water levels resulted from the decrease in recharge to the Trinity/Woodbine system. Consequently, a reduction in the amount of evapotranspiration removed from the model was also reported.

**Table 9.3 Water Budget for Calibrated / Verified Model**

| Year | Layer | Storage | Top | Bottom | Wells | Recharge | ET | Lakes | GHB | Streams |
|---|---|---|---|---|---|---|---|---|---|---|
| ***1980*** | 1 | 13,151 | 0 | 950 | -26,367 | 281,173 | -255,769 | 0 | 662 | -13,812 |
| | 2 | 3,342 | -950 | -3,698 | -5,506 | 604,184 | -570,599 | 0 | 0 | -26,768 |
| | 3 | 26,842 | 3,698 | -5,254 | -35,816 | 305,863 | -287,968 | 0 | -15 | -7,384 |
| | 4 | 10,561 | 5,254 | -17,192 | -6,161 | 177,210 | -155,501 | 0 | -346 | -13,823 |
| | 5 | 36,112 | 17,192 | -34,696 | -30,334 | 191,990 | -176,081 | 0 | 0 | -4,204 |
| | 6 | 9,798 | 34,696 | -44,312 | -182 | 0 | 0 | 0 | 0 | 0 |
| | 7 | 11,484 | 44,312 | 0 | -62,072 | 234,388 | -226,459 | 0 | -279 | -1,394 |
| | All | 111,285 | NA | NA | -166,434 | 1,794,814 | -1,672,381 | 0 | 22 | -67,385 |
| ***1988*** | 1 | 45,457 | 0 | 636 | -31,739 | 213,866 | -217,262 | 142 | 758 | -11,865 |
| | 2 | 39,724 | -636 | -4,309 | -6,641 | 453,400 | -467,195 | 1,502 | 0 | -15,837 |
| | 3 | 67,031 | 4,309 | -9,512 | -41,523 | 231,466 | -245,436 | 38 | -12 | -6,381 |
| | 4 | 28,775 | 9,512 | -23,401 | -6,718 | 131,327 | -128,961 | 114 | -329 | -10,317 |
| | 5 | 57,991 | 23,401 | -42,669 | -29,606 | 144,557 | -149,827 | 2 | 0 | -3,868 |
| | 6 | 6,962 | 42,669 | -49,502 | -128 | 0 | 0 | 0 | 0 | 0 |
| | 7 | 46,791 | 49,502 | 0 | -94,469 | 177,052 | -177,344 | 42 | -325 | -1,261 |
| | All | 292,709 | NA | NA | -210,821 | 1,351,657 | -1,386,030 | 1,839 | 93 | -49,529 |

Note: Values are in acre-feet per year. For the "Storage" field, positive values indicate water lost from storage. For all other fields positive numbers indicate water entering the aquifer system or layer while negative numbers indicate water leaving the aquifer system or layer. The "Top" and "Bottom" fields indicate interformational leakage into (+) or out of (-) the top and bottom of each layer, respectively. The "ET" field denotes water removed from the model due to near-surface processes (evaporation, transpiration, springs/seeps, and surface/groundwater interaction not specifically modeled in the GAM), while the "GHB" field indicates water entering or leaving the system through interaction with sediments overlying the Woodbine.

**Table 9.3 Water Budget for Calibrated / Verified Model (Continued)**

| Year | Layer | Storage | Top | | Wells | Recharge | | Lakes | GHB | Streams |
|---|---|---|---|---|---|---|---|---|---|---|
| ***1990*** | 1 | -1,024 | 0 | 627 | -32,507 | 294,486 | -249,794 | 142 | 767 | -12,704 |
| | 2 | -17,049 | -627 | -4,333 | -8,396 | 619,849 | -573,267 | 1,496 | 0 | -17,670 |
| | 3 | 11,755 | 4,333 | -9,651 | -40,974 | 322,369 | -280,980 | 37 | -12 | -6,898 |
| | 4 | 6,821 | 9,651 | -23,352 | -7,414 | 183,172 | -156,994 | 113 | -328 | -11,667 |
| | 5 | 24,076 | 23,352 | -43,515 | -29,047 | 200,117 | -170,765 | 2 | 0 | -4,241 |
| | 6 | 5,985 | 43,515 | -49,376 | -124 | 0 | 0 | 0 | 0 | 0 |
| | 7 | 11,510 | 49,376 | 0 | -101,842 | 247,629 | -205,109 | 42 | -307 | -1,311 |
| | All | 42,077 | NA | NA | -220,299 | 1,867,618 | -1,636,910 | 1,833 | 120 | -54,491 |
| ***2000*** | 1 | 42,385 | 0 | 408 | -28,193 | 197,333 | -201,795 | 148 | 782 | -11,073 |
| | 2 | 46,452 | -408 | -4,454 | -7,594 | 424,569 | -444,276 | 1,503 | 0 | -15,793 |
| | 3 | 64,775 | 4,454 | -10,496 | -39,812 | 217,741 | -230,324 | 38 | -11 | -6,387 |
| | 4 | 33,884 | 10,496 | -22,743 | -6,643 | 116,325 | -121,017 | 113 | -330 | -10,085 |
| | 5 | 55,599 | 22,743 | -43,789 | -29,016 | 139,980 | -141,866 | 2 | 0 | -3,673 |
| | 6 | 3,638 | 43,789 | -47,338 | -89 | 0 | 0 | 0 | 0 | 0 |
| | 7 | 38,317 | 47,338 | 0 | -84,546 | 171,669 | -171,294 | 34 | -291 | -1,239 |
| | All | 285,028 | NA | NA | -195,889 | 1,267,621 | -1,310,575 | 1,838 | 150 | -48,251 |

Note: Values are in acre-feet per year. For the "Storage" field, positive values indicate water lost from storage. For all other fields positive numbers indicate water entering the aquifer system or layer while negative numbers indicate water leaving the aquifer system or layer. The "Top" and "Bottom" fields indicate interformational leakage into (+) or out of (-) the top and bottom of each layer, respectively. The "ET" field denotes water removed from the model due to near-surface processes (evaporation, transpiration, springs/seeps, and surface/groundwater interaction not specifically modeled in the GAM), while the "GHB" field indicates water entering or leaving the system through interaction with sediments overlying the Woodbine.

### 9.1.3 Sensitivity Analysis

The calibrated transient model was subjected to a sensitivity analysis through systematic changes to input parameters and subsequent investigation of the resulting changes in simulated water levels. The parameters that were analyzed were:

1) Horizontal Hydraulic Conductivity (Kh)
2) Pumpage
3) Specific Yield (Sy)
4) General Head Boundary Head (GHB Head)
5) Vertical Hydraulic Conductivity (Kv)
6) Storativity (S)
7) General Head Boundary Conductance (GHB Cond)
8) Evapotranspiration Rate (ET)
9) Horizontal Flow Boundary Conductance (HFB Cond)
10) Recharge Rate (Recharge)
11) Stream Conductance (Stream Cond)
12) Lake Conductance (Lake Cond)

Parameters 1 through 4 were increased and decreased by 10% and 20%. All other parameters were increased and decreased by 10%, 20% and an order of magnitude. The values reported in Figures 9.32 through 9.41 are the mean difference at the calibration points between the simulated water levels in the calibrated model and the simulated water levels in a model run with a parameter change. Figures 9.42 through 9.45 depict the changes in simulated water levels associated with individual wells resulting from modification of selected model parameters.

Parameters having the largest influence on the simulated water levels are horizontal and vertical hydraulic conductivities, storativity and pumpage. Layer 1 (Woodbine) also showed some sensitivity to GHB conductivity. For order of magnitude changes to model parameters, Layer 5 (Hensell) and Layer 7 (Hosston) were most sensitive to increases of Kv with an average increase in water levels greater than 80 feet. Layer 1 showed a slightly higher sensitivity to decreases in pumpage with a 60-foot increase in water levels whereas Layers 3 (Paluxy), 5, and 7 showed increases of less than 40 feet. Changes up to an order of magnitude to ET, HFB conductance, Sy, recharge, GHB head, stream conductance and lake conductance had little to no effect on the calibrated model water levels.

**Figure 9.32 Mean Water Level Differences for Sensitivity Runs – Woodbine (Layer 1)**

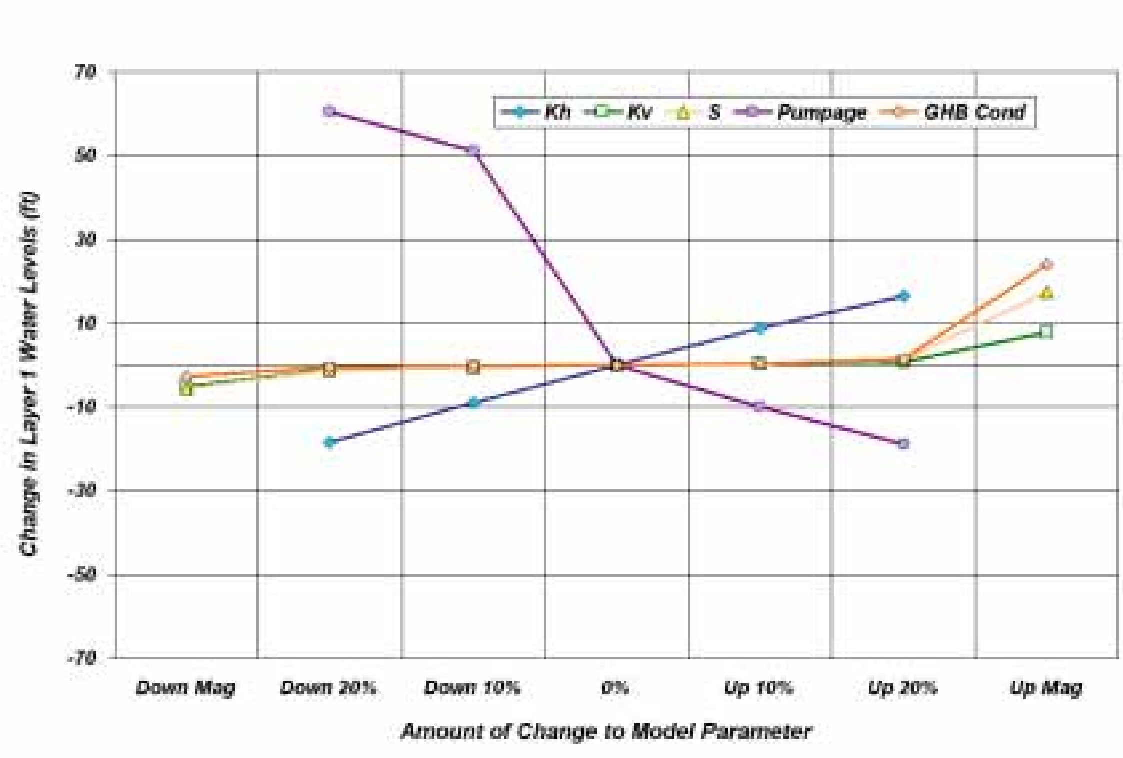



**Figure 9.33 Mean Water Level Differences for Sensitivity Runs – Paluxy (Layer 3)**

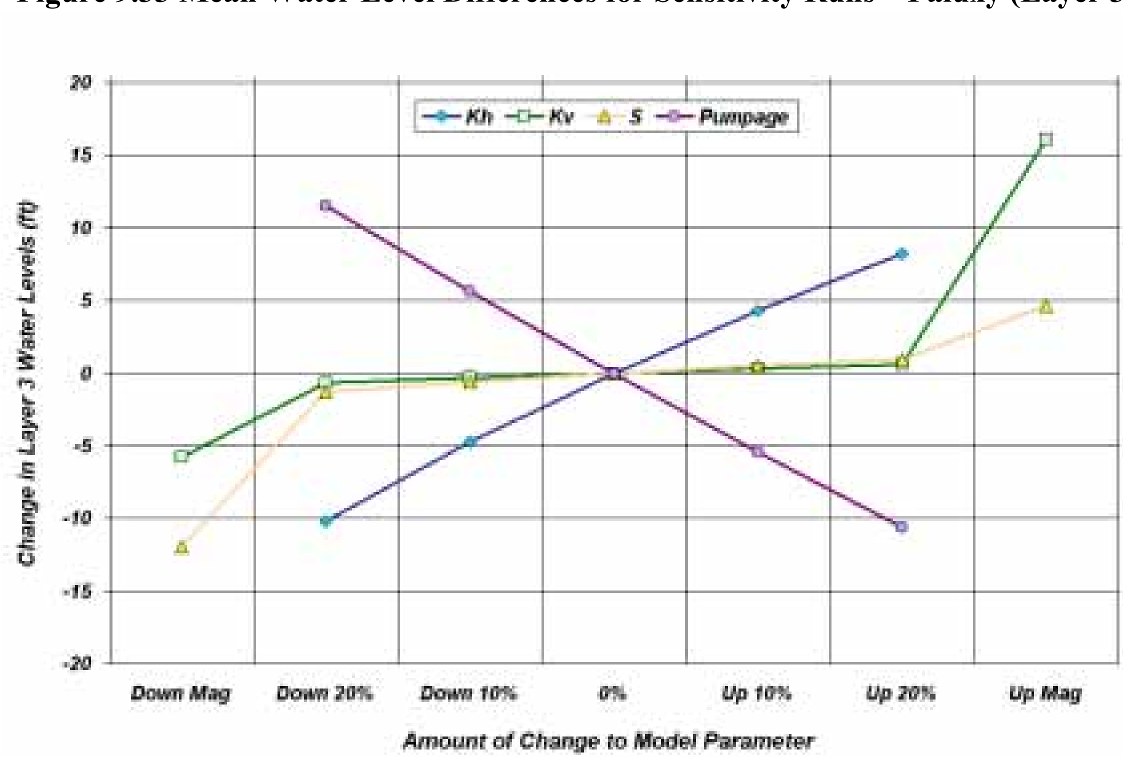


**Figure 9.34 Mean Water Level Differences for Sensitivity Runs – Hensell (Layer 5)**

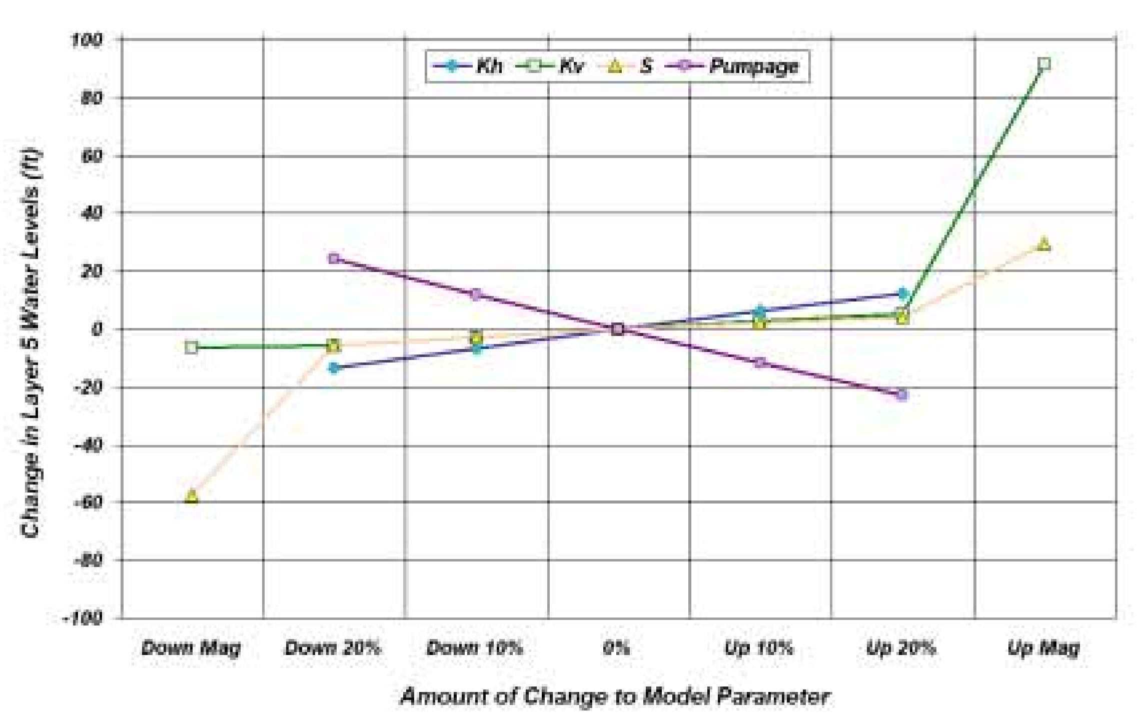



**Figure 9.35 Mean Water Level Differences for Sensitivity Runs – Hosston (Layer 7)**

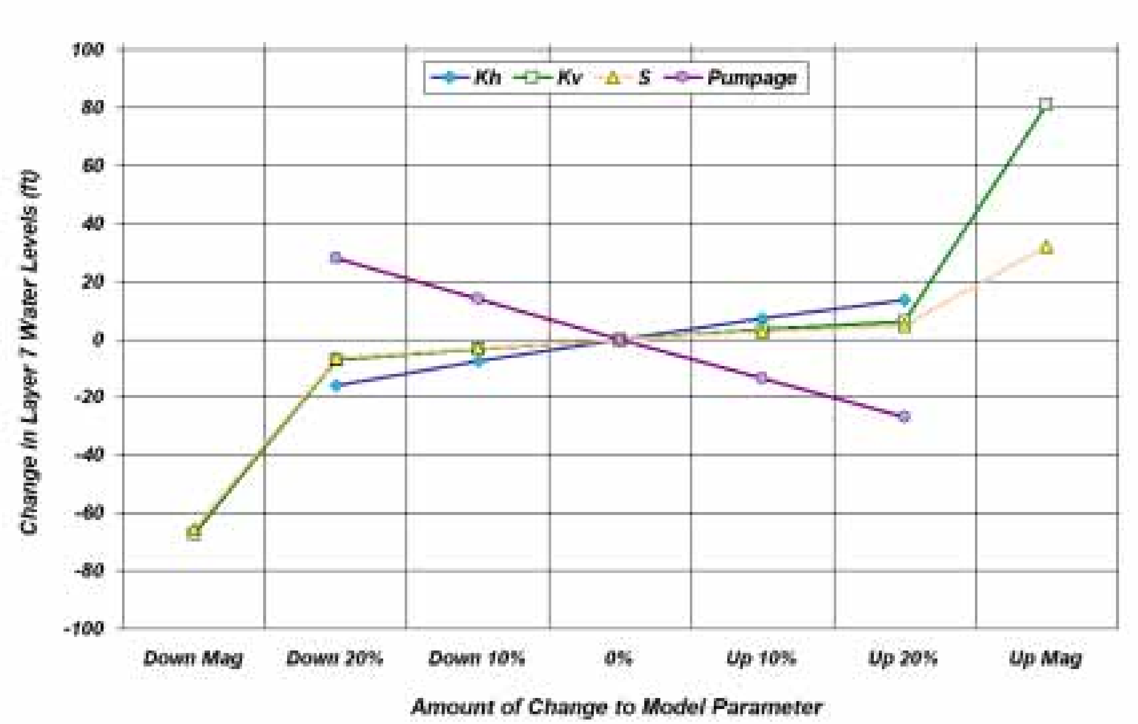


**Figure 9.36 Mean Water Level Differences for Sensitivity Runs – Whole Model**

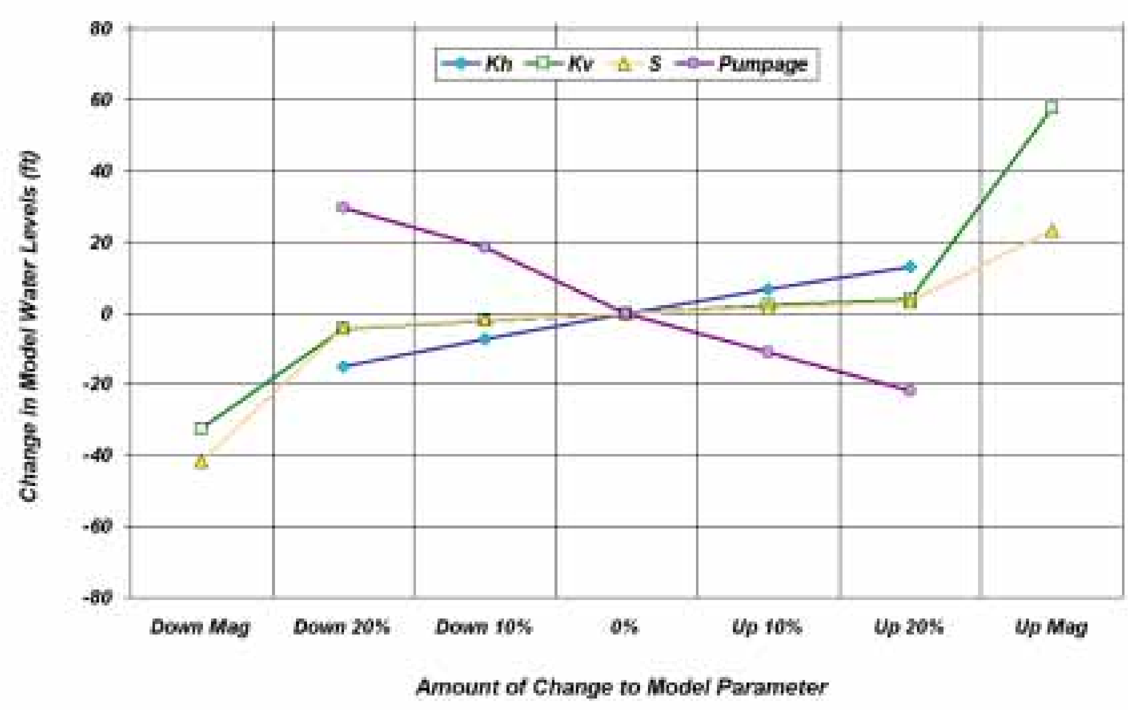



**Figure 9.37 Mean Water Level Differences for Sensitivity Runs – Woodbine (Layer 1)**

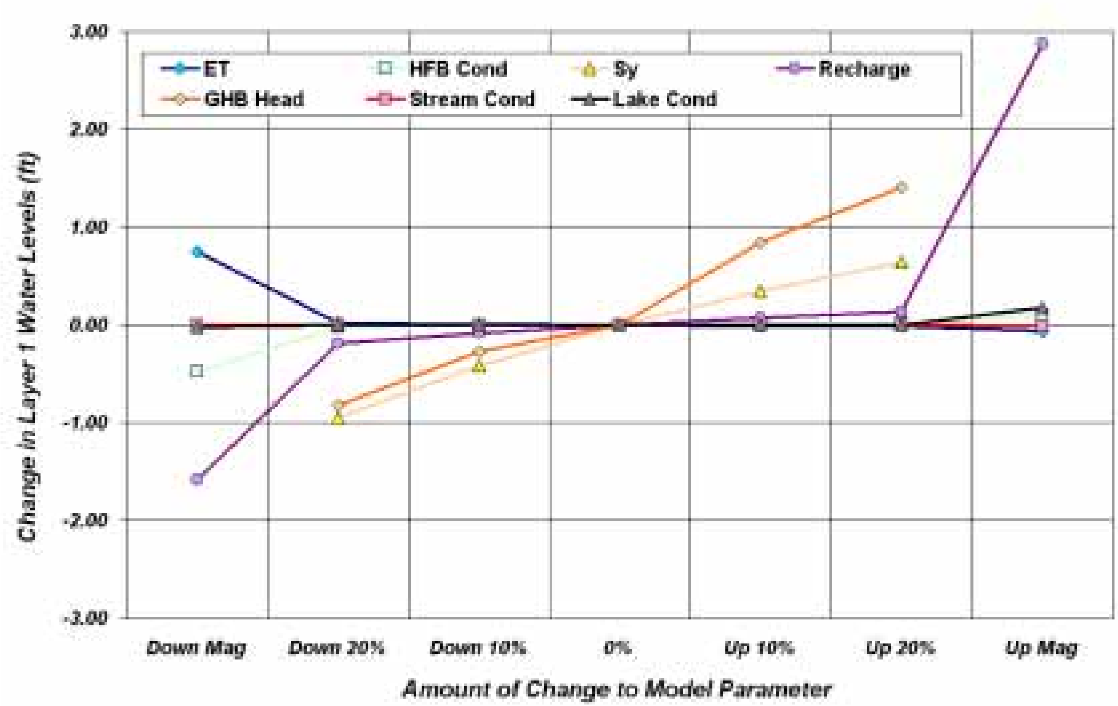


**Figure 9.38 Mean Water Level Differences for Sensitivity Runs – Paluxy (Layer 3)**

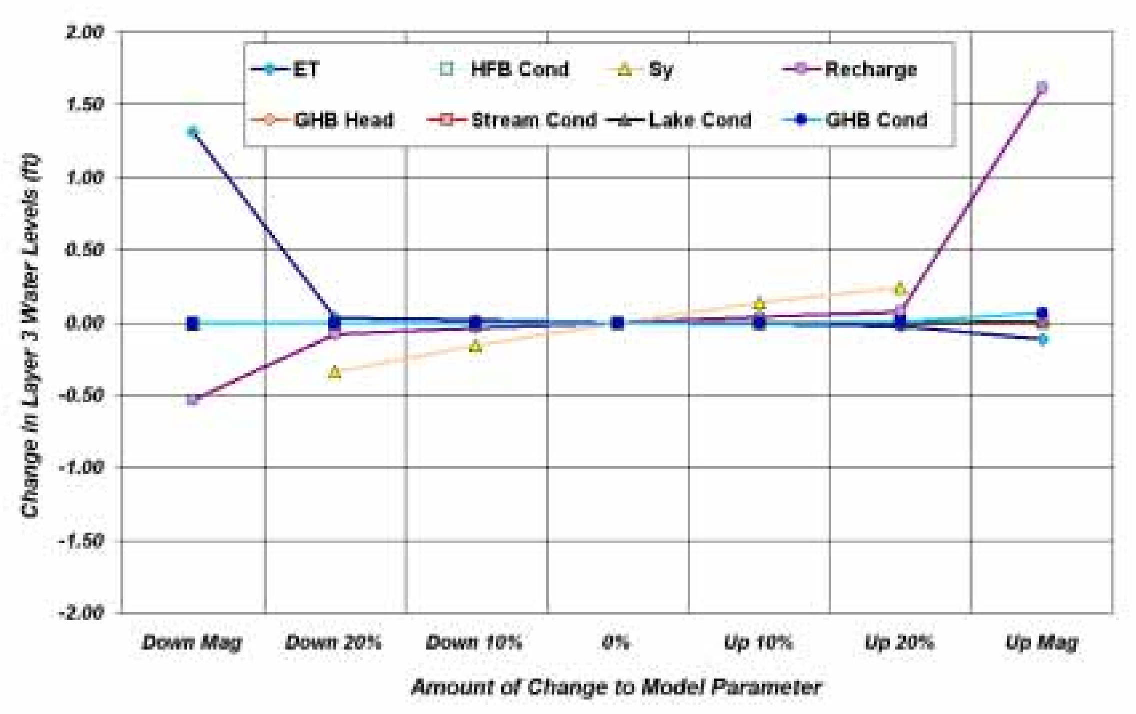



**Figure 9.39 Mean Water Level Differences for Sensitivity Runs – Hensell (Layer 5)**

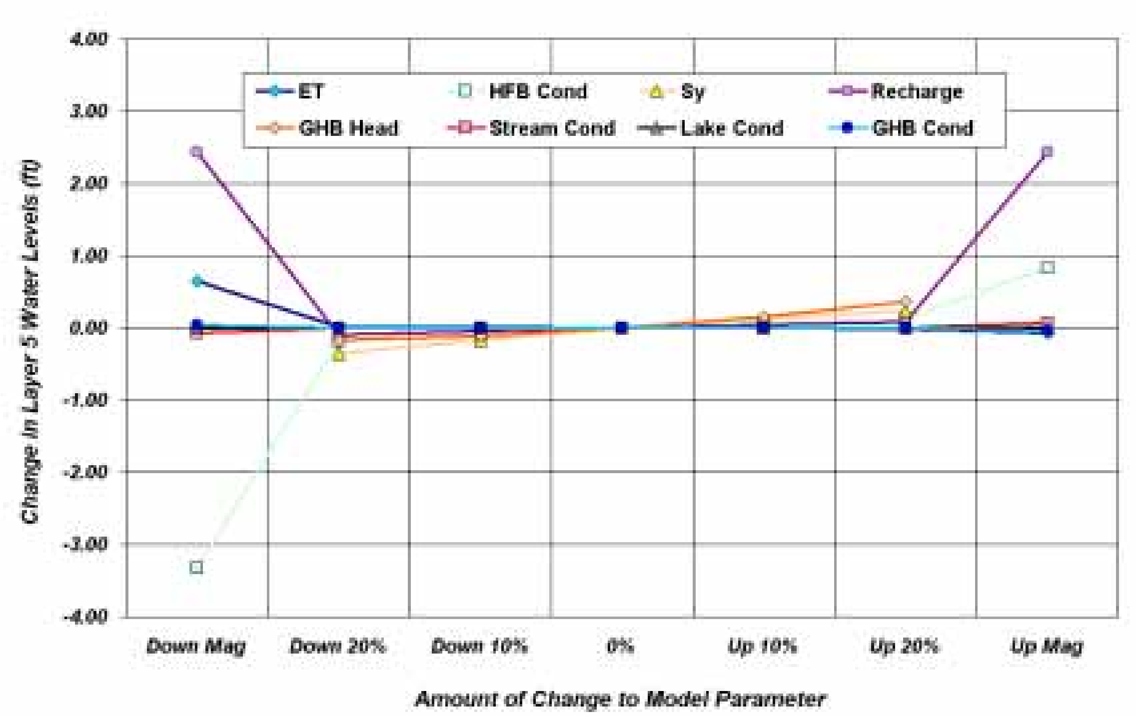


**Figure 9.40 Mean Water Level Differences for Sensitivity Runs – Hosston (Layer 7)**

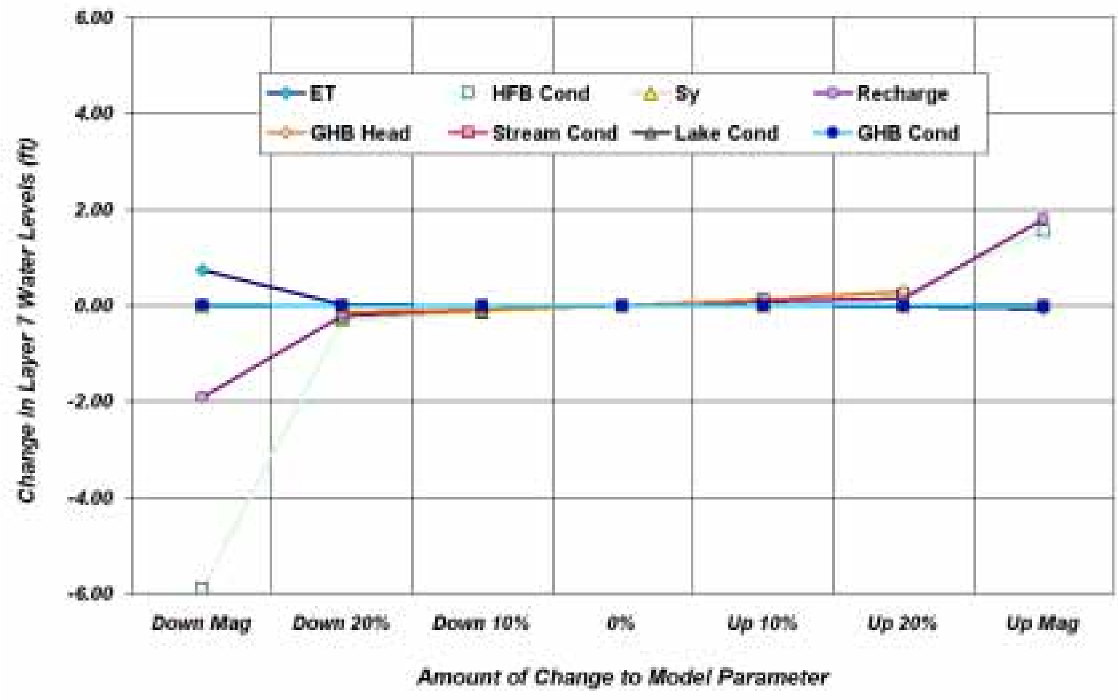



**Figure 9.41 Mean Water Level Differences for Sensitivity Runs – Whole Model**

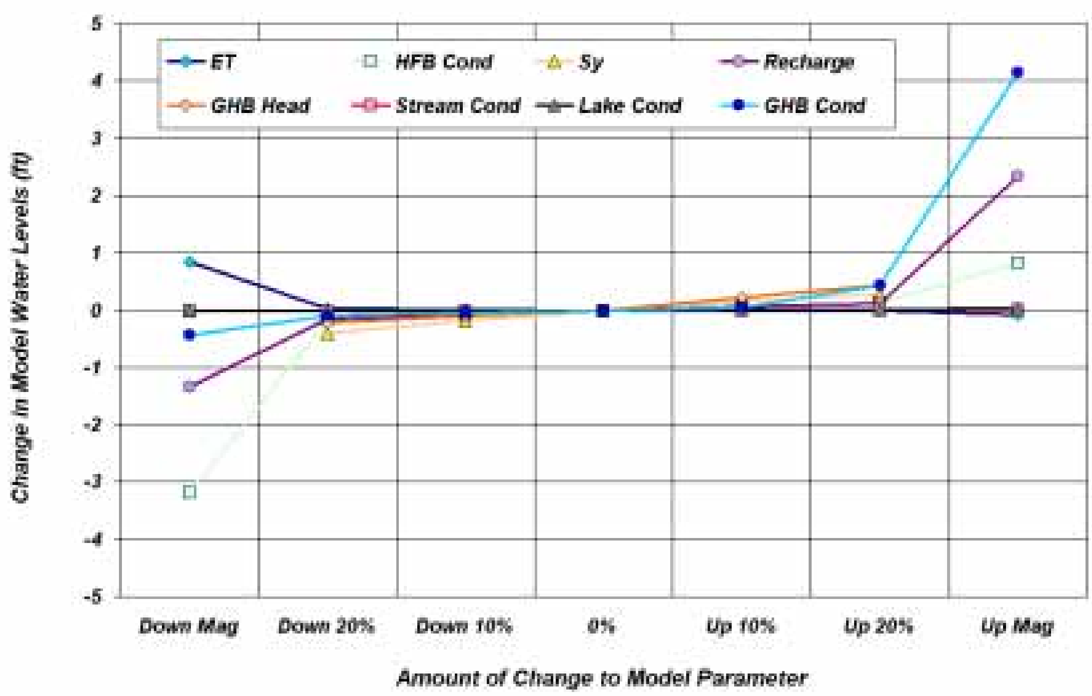
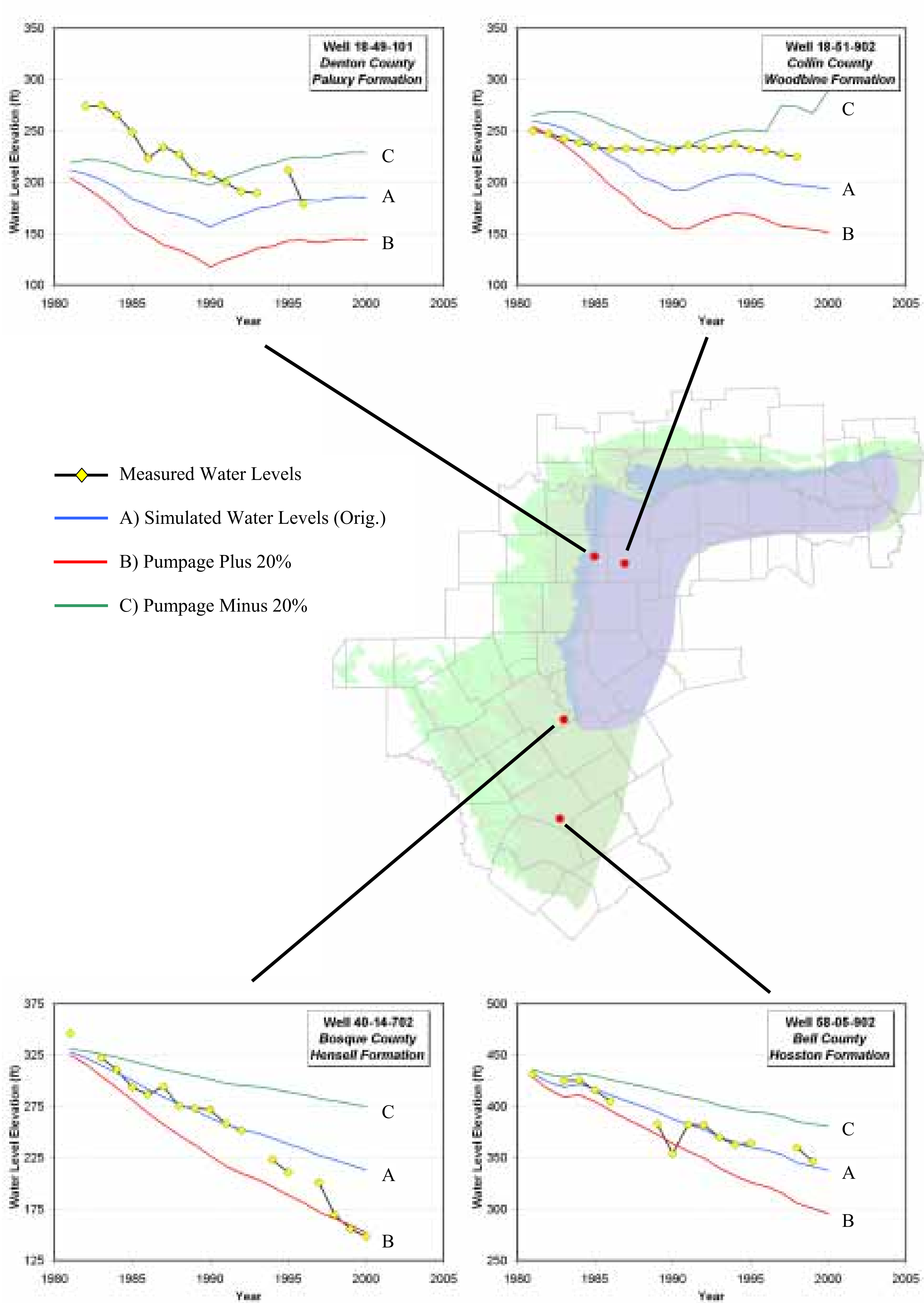


**Figure 9.42 Water Level Hydrographs for Pumpage Sensitivity Runs**



## Figure 9.43 Water Level Hydrographs for Horizontal Conductivity (Kh) Sensitivity Runs

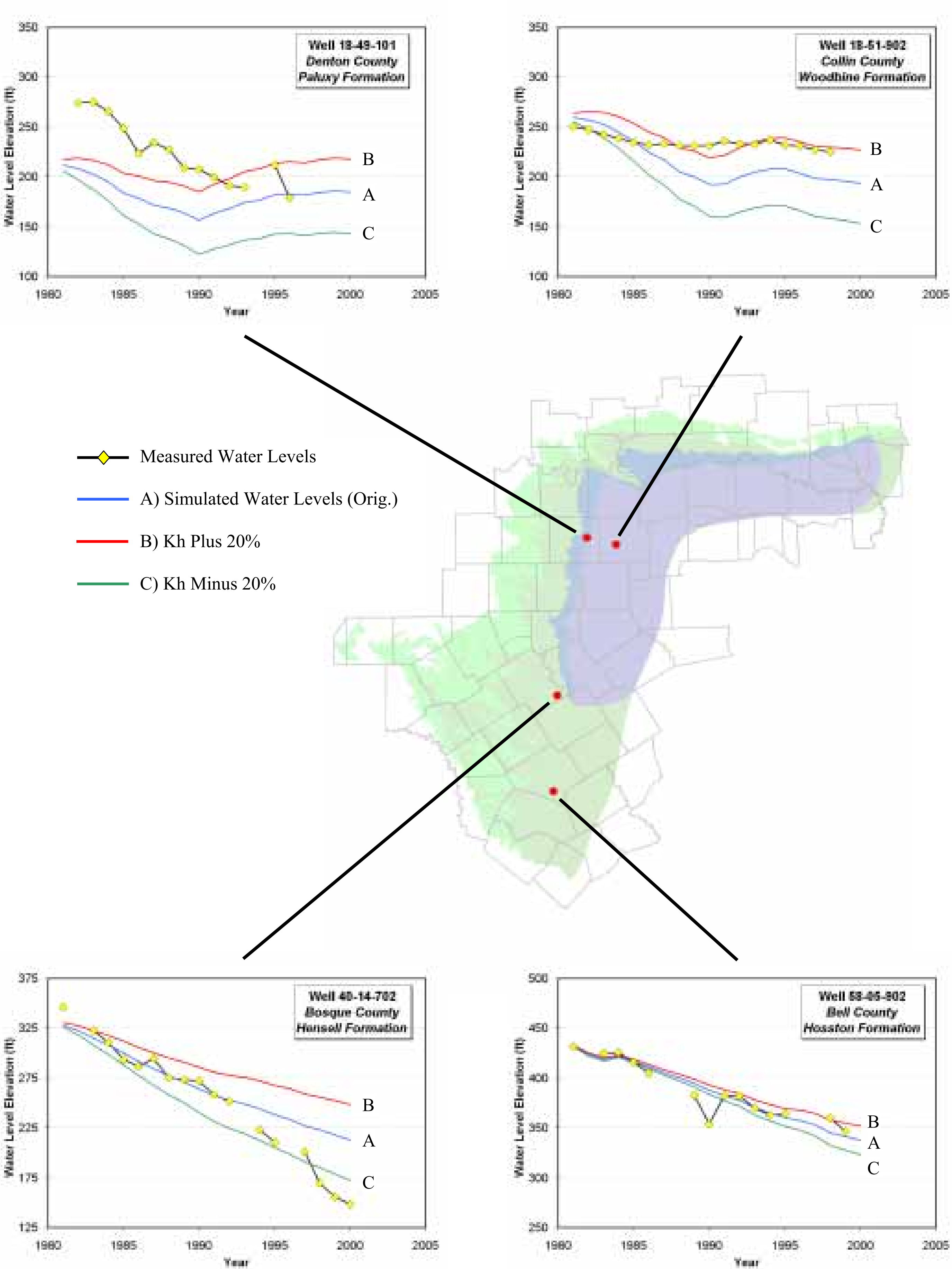


**Figure 9.44 Water Level Hydrographs for Vertical Conductivity (Kv) Sensitivity Runs**

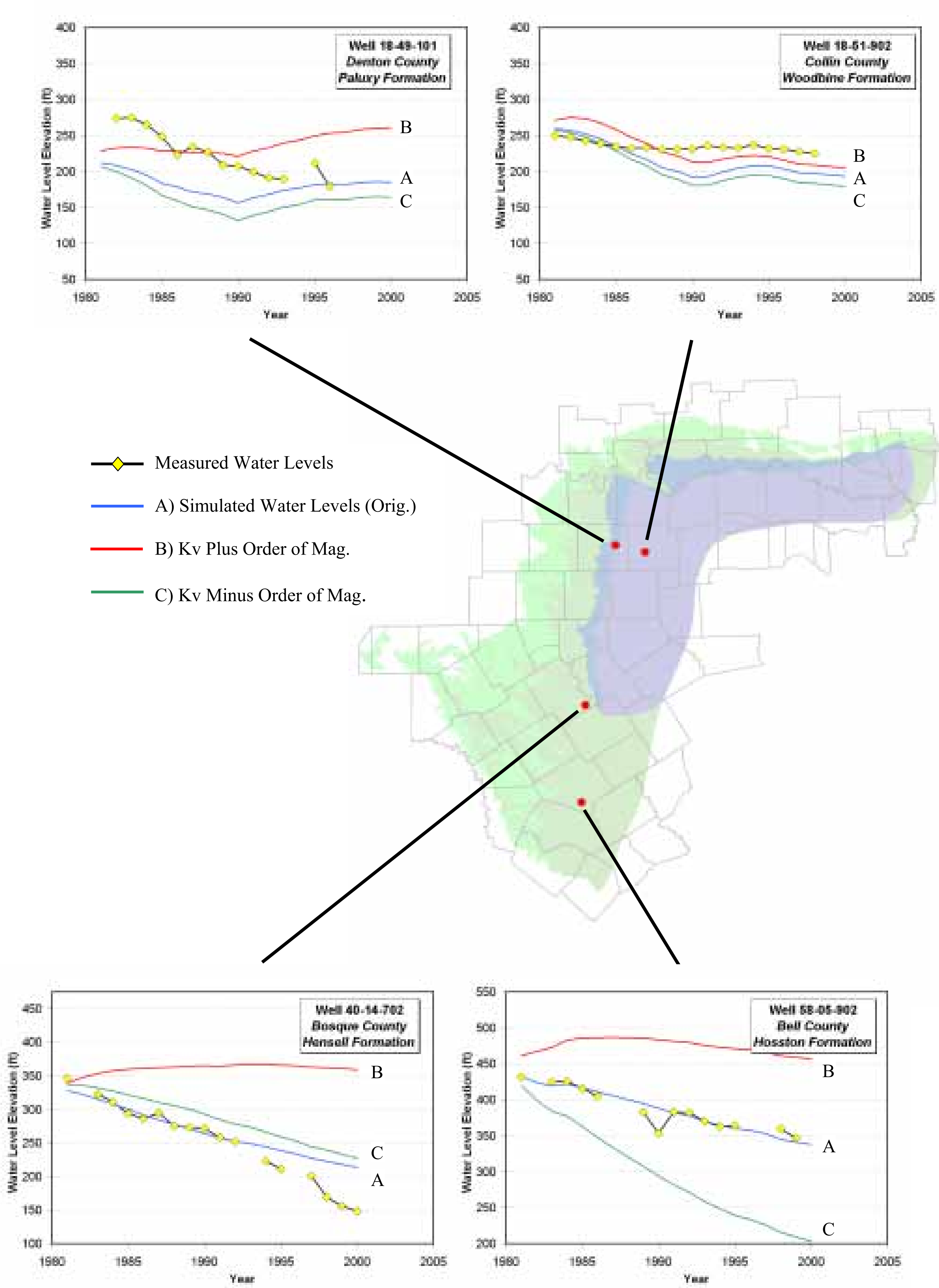
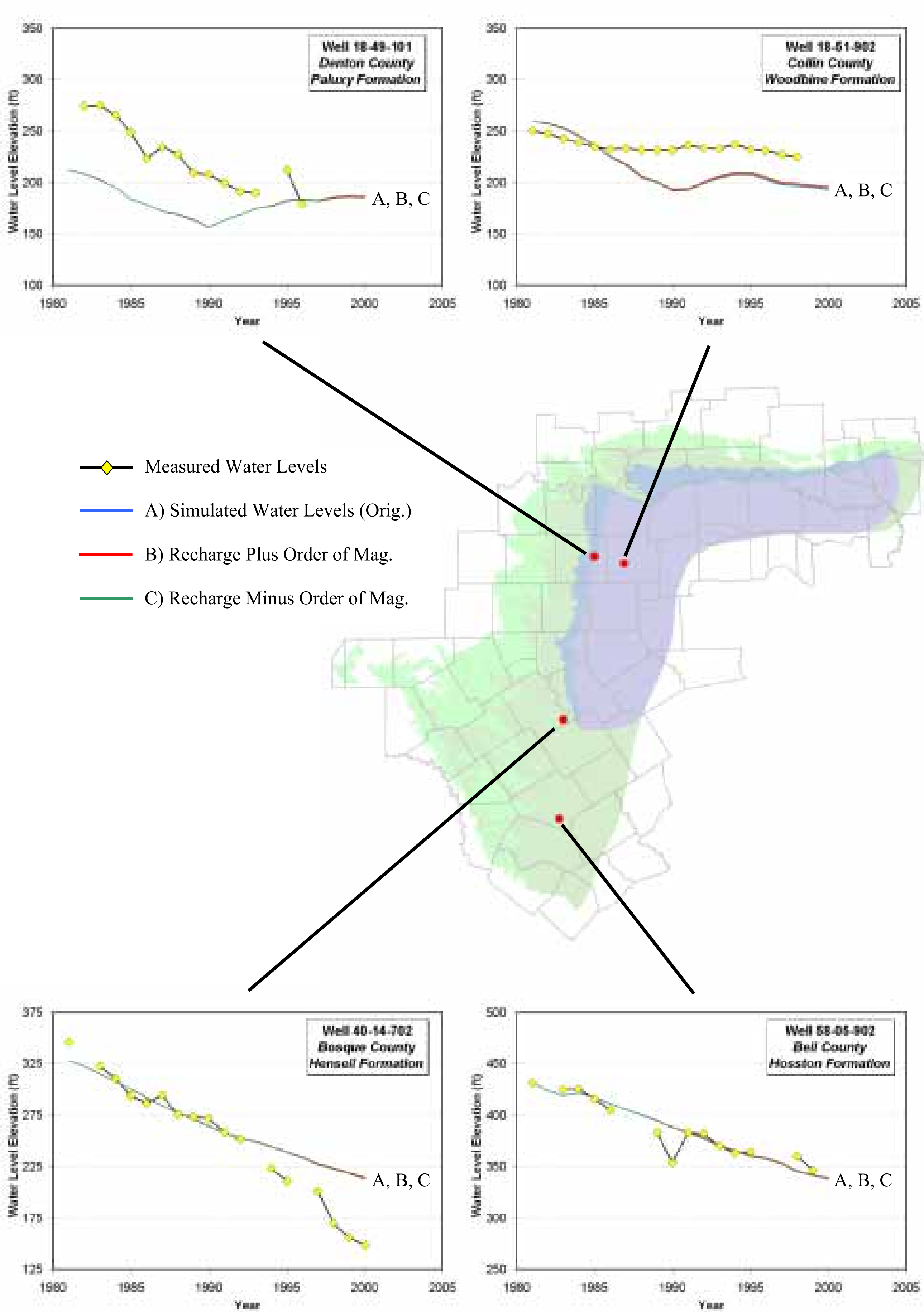


**Figure 9.45 Water Level Hydrographs for Recharge Sensitivity Runs**



# 10.0 PREDICTIVE SIMULATIONS

Future water level response in the outcrop, and artesian pressure declines/recovery in the downdip portions of the Trinity/Woodbine aquifers were evaluated using the calibrated and verified transient model. Regional pumpage in the predictive simulations was based on estimated groundwater demands provided by the appropriate Regional Water Planning Groups (RWPG). To assess the water level and artesian pressure response from average rainfall and drought-of-record conditions, as required by Senate Bill 1, six scenarios were simulated:

1) A 50-year predictive period from 2000-2050 (1/1/2000 to 12/31/2049) with average rainfall,
2) A 10-year predictive period from 2000-2010 (1/1/2000 to 12/31/2009) with a drought-of-record occurring from 2007-2010 (1/1/2007 to 12/31/2009),
3) A 20-year predictive period from 2000-2020 (1/1/2000 to 12/31/2019) with a drought-of-record occurring from 2017-2020 (1/1/2017 to 12/31/2019),
4) A 30-year predictive period from 2000-2030 (1/1/2000 to 12/31/2029) with a drought-of-record occurring from 2027-2030 (1/1/2027 to 12/31/2029),
5) A 40-year predictive period from 2000-2040 (1/1/2000 to 12/31/2039) with a drought-of-record occurring from 2037-2040 (1/1/2037 to 12/31/2039), and
6) A 50-year predictive period from 2000-2050 (1/1/2000 to 12/31/2049) with a drought-of-record occurring from 2047-2050 (1/1/2047 to 12/31/2049).

The following sections describe the development of drought-of-record conditions, the results of the predictive simulations, and the water budget for the predictive simulations.

## 10.1 Drought-of-Record

Rainfall records from the National Weather Service (NWS) and the Texas Water Development Board in the study area were used to develop precipitation characteristics and to evaluate the spatial and temporal variability across the Trinity/Woodbine Formations. The TWDB has classified numerous NWS and other participant precipitation stations into quads throughout the state and assembled complete rainfall records for thousands of stations from 1940 to 2000. For this study, more than 190 stations in 20 quads throughout 52 counties covering Texas and Oklahoma were used to construct a historical rainfall record from 1940 to 2000 (Figure 2.10).

The region is characterized by a spatial distribution of precipitation that decreases in vertical bands from east to west with a distinct gradient geographically parallel to the IH 35 corridor.

Average rainfall from 1960 to 2000 across the outcrop was 38 inches per year (in/yr) with an average maximum in the northeast of about 55 in/yr and an average low to the west of about 30 in/yr (Figure 2.11). The southern edge of the model area has seen historical annual lows of about 13 in/yr, while the eastern portion of the aquifer outcrop has received historic high annual rainfall of over 72 in/yr. The smallest amount of precipitation fell across the region in 1963, with an average of just under 23 in/yr. The trend of decreasing rainfall to the west is likely attributable to increasing topographic elevation and increasing distance from the Gulf of Mexico.

Analysis of 3-year moving averages and Palmer Drought Indexes shows that the most extreme, consecutive years of drought in the region occurred between 1954 and 1956. The consecutive periods of low rainfall are evident in the hyetographs of Quads 410, 509, 709, and 710.

## 10.2 Predicted Water Level Response

Water table response in the outcrop and artesian pressure response were predicted in each of the six scenarios described above. Water level changes (drawdown) were calculated by subtracting the future predicted water levels from the calibrated water levels at the end of 1999 from the water levels at the end of each decadal simulation period. Throughout much of the modeled Trinity/Woodbine aquifer system, water levels rose due to a planned reduction in pumpage assumed by the Regional Water Planning Groups and the TWDB (Figure 4.73 and Tables 4.22 and 4.23).

As discussed in detail in Section 9.1.3, water level responses are most sensitive to pumpage and horizontal hydraulic conductivity. All other aquifer parameters including storage, specific yield, recharge, vertical conductivity, boundary conductance, lake conductance, and stream conductance had minor effects when varied plus or minus 20 percent. Storage, vertical conductivity, and general head boundary conductance had effects greater than 10 feet in some layers when varied by an order of magnitude. Considering the small impact of recharge and evapotranspiration in the sensitivity analyses, it was expected that drought-of record conditions would not have a dramatic affect on water levels. With few exceptions, the drought-of-record water levels in the Woodbine, Paluxy, Hensell, and Hosston for all five drought-of-record scenarios were less than two feet lower than the water levels simulated during average rainfall conditions. Most of the model domain showed less than one-half foot of difference between average rainfall and drought-of-record conditions.

In each of the three areas that showed water level differences between average rainfall and drought-of-record greater than two feet, none were greater than 10 feet. The areas exhibiting between two and 10 feet of difference between average rainfall and drought-of-record conditions were located in Bell County, Lampasas County, and in Choctaw County, Oklahoma. As expected, difference between average rainfall conditions and drought-of-record conditions was greatest on or very near the outcrop. The predictive simulations showed that differences between drought-of-record and average rainfall water levels in downdip portions of the aquifer system were significantly less than one foot.

It should also be noted that the pumpage estimates used in the drought-of-record scenarios and the average rainfall scenario were identical, as required in the GAM contract specifications. In actual drought conditions, pumpage would likely increase due to increased water usage. No estimates of the increased usage (and subsequent pumpage) during drought-of-record conditions are provided in this report. Therefore, given the model's sensitivity to variations in pumpage, aquifer users should expect that water levels will decline below average rainfall levels during drought conditions if usage increases above the pumpage estimates used in these predictive simulations.

As shown in Table 4.22 and 4.23, groundwater use estimates by the RWPGs and the TWDB show a significant decrease in groundwater pumpage in the major pumpage centers of Sherman-Dennison, Dallas Fort Worth, Waco, and Austin beginning in 2010. Lamar County is the only use area showing a significant increase in pumpage (from the Woodbine) over the year 2000 pumpage levels. As a result, most pumpage centers and rural areas show significant water level rises during the 50-year predictive period. A summary of notable water level responses from each aquifer is provided below.

### 10.2.1 Woodbine (Layer 1)

Figures 10.1 through 10.21 present the Woodbine water level, saturated thickness, and drawdown results for the predictive model runs. It should be noted that, because little change in the saturated thickness was observed throughout all of the predictive simulations, only the conditions simulated in 2010 (average recharge conditions) are provided herein. Western and Central Lamar County show maximum water level declines in 2050 of over 300 feet due to the increased pumpage over 2000 pumpage amounts. Recoveries of over 100 feet in 2050 due to decreases in pumpage were simulated in Grayson, Ellis, Dallas, Kaufman, Navarro, and Henderson Counties. Most of the maximum predicted water level rises and declines occur by 2010 and continue up through 2050.

### 10.2.2 Paluxy (Layer 3)

Figures 10.22 through 10.42 present the Paluxy water level, saturated thickness, and drawdown results for the predictive model runs. It should be noted that, because little change in the saturated thickness was observed throughout all of the predictive simulations, only the conditions simulated in 2010 (average recharge conditions) are provided herein. Water levels in the Paluxy at the major pumping centers along the IH-35 corridor generally increase from 50 to 100 feet due to a significant decrease in pumpage from 2000 amounts. Dallas County was the only area that showed drawdown, which was over 200 feet in 2010 but decreased to less than 100 feet by 2050. Although pumpage from the Paluxy decreased overall in Dallas County, the location of pumpage was spatially redistributed and centered in a small area resulting in a decrease in water levels in a small portion of central Dallas County. The model results predict continued drawdown over the next 50 years in the far downdip portion of the Paluxy. Analysis of the water budget for that region indicates a net downward flux from the Paluxy that persists during and after the general reduction in model pumpage during the predictive period. The continued drawdown resulting from this flux is a consequence of the thinning of the Paluxy sands and the presence of the Balcones Fault Zone in southern areas. In general, the Paluxy is a thin, poorly-transmissive unit in these areas and tends to exhibit large changes in artesian pressure in response to relatively small fluxes through the unit. The poor transmissivity of the Paluxy coupled with the negative hydrologic boundary presented by the Balcones Fault Zone in the south restricts the movement of water in the downdip direction. As a result, water level drawdown and/or recovery in this area due to stresses in other parts of the aquifer system occurs at a much slower rate. In other words, the continuation of drawdown in the model through 2050 is a delayed reequilibration of the Paluxy water levels to the drawdown that occurred in the system prior to the predictive period.

### 10.2.3 Hensell (Layer 5)

Figures 10.43 through 10.63 present the Hensell water level, saturated thickness, and drawdown results for the predictive model runs. It should be noted that, because little change in the saturated thickness was observed throughout all of the predictive simulations, only the conditions simulated in 2010 (average recharge conditions) are provided herein. There are currently three significant pumping centers in the Hensell located in Tarrant, McLennan, and Williamson Counties. The predictive simulations showed that pumping centers in Tarrant and McLennan Counties had water level recoveries of over 300 feet, and over 100 feet of recovery in Williamson County in 2050. Much of the recovery occurs by 2010 due to the pumpage reduction estimates. There was also about 150 feet of recovery in the counties in between these three pumping centers. Eight Hensell cells dried during the predictive simulations. Located on the periphery of the model in Burnet, Lampasas, and Howard Counties, the drying of these cells reflects the interaction between pumpage, aquifer properties, and the local structural gradient.

### 10.2.4 Hosston (Layer 7)

Figures 10.64 through 10.84 present the Hosston water level, saturated thickness, and drawdown results for the predictive model runs. It should be noted that, because little change in the saturated thickness was observed throughout all of the predictive simulations, only the conditions simulated in 2010 (average recharge conditions) are provided herein. As was the case in each of the other aquifers, the Hosston showed significant water level recovery in each of the predictive simulations. The areas of maximum recovery are centered in Tarrant and McLennan Counties, with over 400 feet of water level rise predicted by 2050. Much of the predicted recovery occurs by 2010. Approximately 35 Hosston cells dried in the model during the 50-year predictive simulations. Most were located in Eastland and Comanche Counties, and are reflective of the relatively heavy pumpage distributed throughout that area. Two cells also dried in the outcrop portion of the Hosston in Pike County, Oklahoma. The cause of this drying is the interaction between the drawdown induced by pumpage, the properties of the aquifer, and the relatively small saturated thickness of those cells.

## 10.3 Predictive Simulation Water Budget

Table 10.1 shows the water budget in 10-year increments for each predictive simulation with average recharge. In each of the 10-year increments, the total flow through the model was about 1.86 million acre-feet per year (ac-ft/yr). Of that total, the major inflow components are recharge and storage, at about 1.8 million ac-ft/yr and 45,000 ac-ft/yr respectively. The major outflow components are evapotranspiration, pumpage from wells, discharge to streams, at about 1.65 million ac-ft/yr, 126,000 ac-ft/yr, and 51,000 ac-ft/yr, respectively. While storage, leakage from lakes, and discharge to streams all have both inflow and outflow components, the net gain/loss is provided in Table 10.1. The proportional distribution of each of these flow components remains relatively constant in each of the 10-year incremental simulations.

Table 10.2 shows the water budget at the end of each drought-of-record predictive simulation. In each of the 10-year increments, the total flow through the model was about 0.95 million ac-ft/yr. Of that total, the major inflow components are recharge and storage at about 894,000 ac-ft/yr and 217,000 ac-ft/yr, respectively. The major outflow components are evapotranspiration, pumpage from wells and discharge to streams at about 950,000 ac-ft/yr, 126,000 ac-ft/yr, and 37,000 ac-ft/yr, respectively. While storage, leakage from lakes, and discharge to streams all have both inflow and outflow components, the net gain/loss is provided in Table 10.2. The proportional distribution of each of these flow components remains relatively constant in each of the 10-year incremental simulations.

When comparing the average rainfall conditions to the drought-of-record conditions the following differences are noted. In drought-of-record conditions, evapotranspiration is about six percent greater than recharge, while in average rainfall conditions, recharge is approximately nine percent more than evapotranspiration. This difference is mainly accounted for in the model by a change in storage and a slight reduction in discharge to streams.

**Table 10.1 Water Budget for Predictive Model with Average Recharge**

| Year | Layer | Storage | Top | Bottom | Wells | Recharge | ET | Lakes | GHB | Streams |
|---|---|---|---|---|---|---|---|---|---|---|
| ***2010*** | 1 | 5,655 | - | 344 | -18,858 | 281,173 | -256,676 | 61 | 781 | -12,485 |
| | 2 | 1,618 | -344 | -4,761 | -781 | 604,184 | -584,912 | 489 | 0 | -15,485 |
| | 3 | 13,482 | 4,761 | -8,466 | -23,881 | 305,863 | -285,013 | 19 | -10 | -6,772 |
| | 4 | 2,579 | 8,466 | -18,415 | -736 | 177,210 | -157,413 | 62 | -331 | -11,420 |
| | 5 | 21,408 | 18,415 | -35,752 | -18,760 | 191,990 | -173,301 | 1 | 0 | -4,017 |
| | 6 | -2,853 | 35,752 | -32,879 | -21 | 0 | 0 | 0 | 0 | 0 |
| | 7 | 6,220 | 32,879 | - | -63,720 | 234,388 | -208,099 | 18 | -391 | -1,302 |
| | All | 48,107 | - | - | -126,755 | 1,794,814 | -1,665,416 | 649 | 49 | -51,480 |
| ***2020*** | 1 | 5,667 | - | 261 | -19,143 | 281,173 | -256,359 | 64 | 780 | -12,448 |
| | 2 | 1,529 | -261 | -4,821 | -824 | 604,184 | -584,807 | 489 | 0 | -15,481 |
| | 3 | 11,471 | 4,821 | -6,809 | -23,727 | 305,863 | -284,872 | 19 | -10 | -6,774 |
| | 4 | 1,591 | 6,809 | -15,641 | -794 | 177,210 | -157,483 | 62 | -331 | -11,422 |
| | 5 | 20,384 | 15,641 | -32,476 | -18,631 | 191,990 | -172,923 | 1 | 0 | -4,003 |
| | 6 | -1,689 | 32,476 | -30,765 | -22 | 0 | 0 | 0 | 0 | 0 |
| | 7 | 7,367 | 30,765 | - | -63,050 | 234,388 | -207,760 | 18 | -426 | -1,310 |
| | All | 46,318 | - | - | -126,188 | 1,794,814 | -1,664,204 | 653 | 13 | -51,437 |
| ***2030*** | 1 | 5,919 | - | 206 | -19,581 | 281,173 | -256,171 | 66 | 791 | -12,409 |
| | 2 | 1,377 | -206 | -4,769 | -927 | 604,184 | -584,663 | 489 | 0 | -15,478 |
| | 3 | 9,748 | 4,769 | -5,850 | -22,823 | 305,863 | -284,960 | 19 | -9 | -6,775 |
| | 4 | 1,060 | 5,850 | -13,982 | -954 | 177,210 | -157,492 | 62 | -331 | -11,421 |
| | 5 | 19,931 | 13,982 | -30,812 | -18,467 | 191,990 | -172,646 | 1 | 0 | -3,997 |
| | 6 | -979 | 30,812 | -29,810 | -23 | 0 | 0 | 0 | 0 | 0 |
| | 7 | 7,857 | 29,810 | - | -62,592 | 234,388 | -207,714 | 18 | -459 | -1,316 |
| | All | 44,913 | - | - | -125,364 | 1,794,814 | -1,663,647 | 655 | -9 | -51,395 |

**Table 10.1 Water Budget for Predictive Model with Average Recharge - Continued**

| Year | Layer | Storage | Top | Bottom | Wells | Recharge | ET | Lakes | GHB | Streams |
|---|---|---|---|---|---|---|---|---|---|---|
| ***2040*** | 1 | 6,141 | - | 164 | -20,149 | 281,173 | -255,827 | 68 | 803 | -12,378 |
| | 2 | 1,238 | -164 | -4,671 | -988 | 604,184 | -584,606 | 489 | 0 | -15,476 |
| | 3 | 9,468 | 4,671 | -5,196 | -23,259 | 305,863 | -284,801 | 19 | -9 | -6,774 |
| | 4 | 844 | 5,196 | -13,052 | -990 | 177,210 | -157,519 | 62 | -331 | -11,419 |
| | 5 | 19,791 | 13,052 | -29,856 | -18,597 | 191,990 | -172,400 | 1 | 0 | -3,999 |
| | 6 | -414 | 29,856 | -29,418 | -24 | 0 | 0 | 0 | 0 | 0 |
| | 7 | 7,772 | 29,418 | - | -62,220 | 234,312 | -207,512 | 18 | -477 | -1,319 |
| | All | 44,837 | - | - | -126,225 | 1,794,738 | -1,662,668 | 657 | -14 | -51,365 |
| ***2050*** | 1 | 6,034 | - | 133 | -20,254 | 281,173 | -255,623 | 69 | 815 | -12,353 |
| | 2 | 1,059 | -133 | -4,565 | -1,030 | 604,184 | -584,526 | 489 | 0 | -15,474 |
| | 3 | 8,893 | 4,565 | -4,770 | -23,084 | 305,863 | -284,725 | 19 | -9 | -6,772 |
| | 4 | 712 | 4,770 | -12,486 | -957 | 177,210 | -157,561 | 62 | -331 | -11,417 |
| | 5 | 19,604 | 12,486 | -29,196 | -18,678 | 191,990 | -172,229 | 1 | 0 | -3,996 |
| | 6 | -83 | 29,196 | -29,087 | -26 | 0 | 0 | 0 | 0 | 0 |
| | 7 | 7,704 | 29,087 | - | -61,904 | 234,312 | -207,408 | 18 | -495 | -1,321 |
| | All | 43,918 | - | - | -125,932 | 1,794,738 | -1,662,078 | 658 | -20 | -51,333 |

Note: Values are in acre-feet per year. For the "Storage" field, positive values indicate water lost from storage. For all other fields positive numbers indicate water entering the aquifer system or layer while negative numbers indicate water leaving the aquifer system or layer. The "Top" and "Bottom" fields indicate interformational leakage into (+) or out of (-) the top and bottom of each layer, respectively. The "ET" field denotes water removed from the model due to near-surface processes (evaporation, transpiration, springs/seeps, and surface/groundwater interaction not specifically modeled in the GAM), while the "GHB" field indicates water entering or leaving the system through interaction with sediments overlying the Woodbine.

**Table 10.2 Water Budget for Predictive Model with Drought of Record**

| Year | Layer | Storage | Top | Bottom | Wells | Recharge | ET | Lakes | GHB | Streams |
|---|---|---|---|---|---|---|---|---|---|---|
| ***2010*** | 1 | 33,565 | - | 346 | -18,858 | 141,104 | -149,162 | 63 | 781 | -7,846 |
| | 2 | 34,594 | -346 | -4,752 | -781 | 305,709 | -324,334 | 503 | 0 | -10,594 |
| | 3 | 41,940 | 4,752 | -8,448 | -23,881 | 151,787 | -160,989 | 19 | -10 | -5,191 |
| | 4 | 26,954 | 8,448 | -18,391 | -736 | 90,217 | -97,118 | 63 | -328 | -9,108 |
| | 5 | 46,237 | 18,391 | -35,671 | -18,760 | 93,912 | -100,904 | 1 | 0 | -3,226 |
| | 6 | -2,774 | 35,671 | -32,877 | -21 | 0 | 0 | 0 | 0 | 0 |
| | 7 | 38,924 | 32,877 | - | -63,720 | 110,862 | -117,545 | 18 | -391 | -1,039 |
| | All | 219,437 | - | - | -126,755 | 893,600 | -950,052 | 668 | 52 | -37,005 |
| ***2020*** | 1 | 33,634 | - | 262 | -19,143 | 141,104 | -148,907 | 66 | 781 | -7,804 |
| | 2 | 34,458 | -262 | -4,811 | -824 | 305,709 | -324,176 | 503 | 0 | -10,596 |
| | 3 | 39,909 | 4,811 | -6,791 | -23,727 | 151,787 | -160,822 | 19 | -10 | -5,197 |
| | 4 | 25,910 | 6,791 | -15,616 | -794 | 90,217 | -97,129 | 63 | -328 | -9,113 |
| | 5 | 45,247 | 15,616 | -32,394 | -18,631 | 93,912 | -100,564 | 1 | 0 | -3,207 |
| | 6 | -1,609 | 32,394 | -30,763 | -22 | 0 | 0 | 0 | 0 | 0 |
| | 7 | 40,035 | 30,763 | - | -63,050 | 110,862 | -117,170 | 18 | -426 | -1,047 |
| | All | 217,569 | - | - | -126,188 | 893,600 | -948,767 | 671 | 16 | -36,964 |
| ***2030*** | 1 | 33,912 | - | 207 | -19,581 | 141,104 | -148,749 | 68 | 791 | -7,760 |
| | 2 | 34,294 | -207 | -4,759 | -927 | 305,709 | -324,018 | 503 | 0 | -10,595 |
| | 3 | 38,175 | 4,759 | -5,832 | -22,823 | 151,787 | -160,897 | 19 | -9 | -5,199 |
| | 4 | 25,359 | 5,832 | -13,958 | -954 | 90,217 | -97,116 | 63 | -329 | -9,114 |
| | 5 | 44,823 | 13,958 | -30,730 | -18,467 | 93,912 | -100,320 | 1 | 0 | -3,197 |
| | 6 | -899 | 30,730 | -29,807 | -23 | 0 | 0 | 0 | 0 | 0 |
| | 7 | 40,451 | 29,807 | - | -62,491 | 110,817 | -117,104 | 18 | -459 | -1,053 |
| | All | 216,100 | - | - | -125,263 | 893,554 | -948,202 | 673 | -6 | -36,918 |

**Table 10.2 Water Budget for Predictive Model with Drought of Record - Continued**

| Year | Layer | Storage | Top | Bottom | Wells | Recharge | ET | Lakes | GHB | Streams |
|---|---|---|---|---|---|---|---|---|---|---|
| ***2040*** | 1 | 34,188 | - | 165 | -20,149 | 141,104 | -148,461 | 70 | 803 | -7,727 |
| | 2 | 34,132 | -165 | -4,663 | -988 | 305,709 | -323,934 | 503 | 0 | -10,593 |
| | 3 | 37,897 | 4,663 | -5,178 | -23,259 | 151,787 | -160,741 | 19 | -9 | -5,199 |
| | 4 | 25,135 | 5,178 | -13,028 | -990 | 90,217 | -97,133 | 63 | -329 | -9,113 |
| | 5 | 44,706 | 13,028 | -29,773 | -18,597 | 93,912 | -100,101 | 1 | 0 | -3,196 |
| | 6 | -333 | 29,773 | -29,415 | -24 | 0 | 0 | 0 | 0 | 0 |
| | 7 | 40,437 | 29,415 | - | -62,220 | 110,817 | -116,950 | 18 | -477 | -1,056 |
| | All | 216,150 | - | - | -126,225 | 893,554 | -947,320 | 675 | -11 | -36,884 |
| ***2050*** | 1 | 34,100 | - | 134 | -20,254 | 141,104 | -148,277 | 71 | 815 | -7,700 |
| | 2 | 33,956 | -134 | -4,557 | -1,030 | 305,709 | -323,856 | 503 | 0 | -10,591 |
| | 3 | 37,314 | 4,557 | -4,752 | -23,084 | 151,787 | -160,656 | 19 | -9 | -5,197 |
| | 4 | 24,998 | 4,752 | -12,462 | -957 | 90,217 | -97,169 | 63 | -329 | -9,111 |
| | 5 | 44,549 | 12,462 | -29,112 | -18,678 | 93,912 | -99,961 | 1 | 0 | -3,191 |
| | 6 | -3 | 29,112 | -29,083 | -26 | 0 | 0 | 0 | 0 | 0 |
| | 7 | 40,510 | 29,083 | - | -61,904 | 110,628 | -116,798 | 18 | -494 | -1,057 |
| | All | 215,380 | - | - | -125,932 | 893,366 | -946,719 | 676 | -17 | -36,848 |

Note: Values are in acre-feet per year. For the "Storage" field, positive values indicate water lost from storage. For all other fields positive numbers indicate water entering the aquifer system or layer while negative numbers indicate water leaving the aquifer system or layer. The "Top" and "Bottom" fields indicate interformational leakage into (+) or out of (-) the top and bottom of each layer, respectively. The "ET" field denotes water removed from the model due to near-surface processes (evaporation, transpiration, springs/seeps, and surface/groundwater interaction not specifically modeled in the GAM), while the "GHB" field indicates water entering or leaving the system through interaction with sediments overlying the Woodbine.

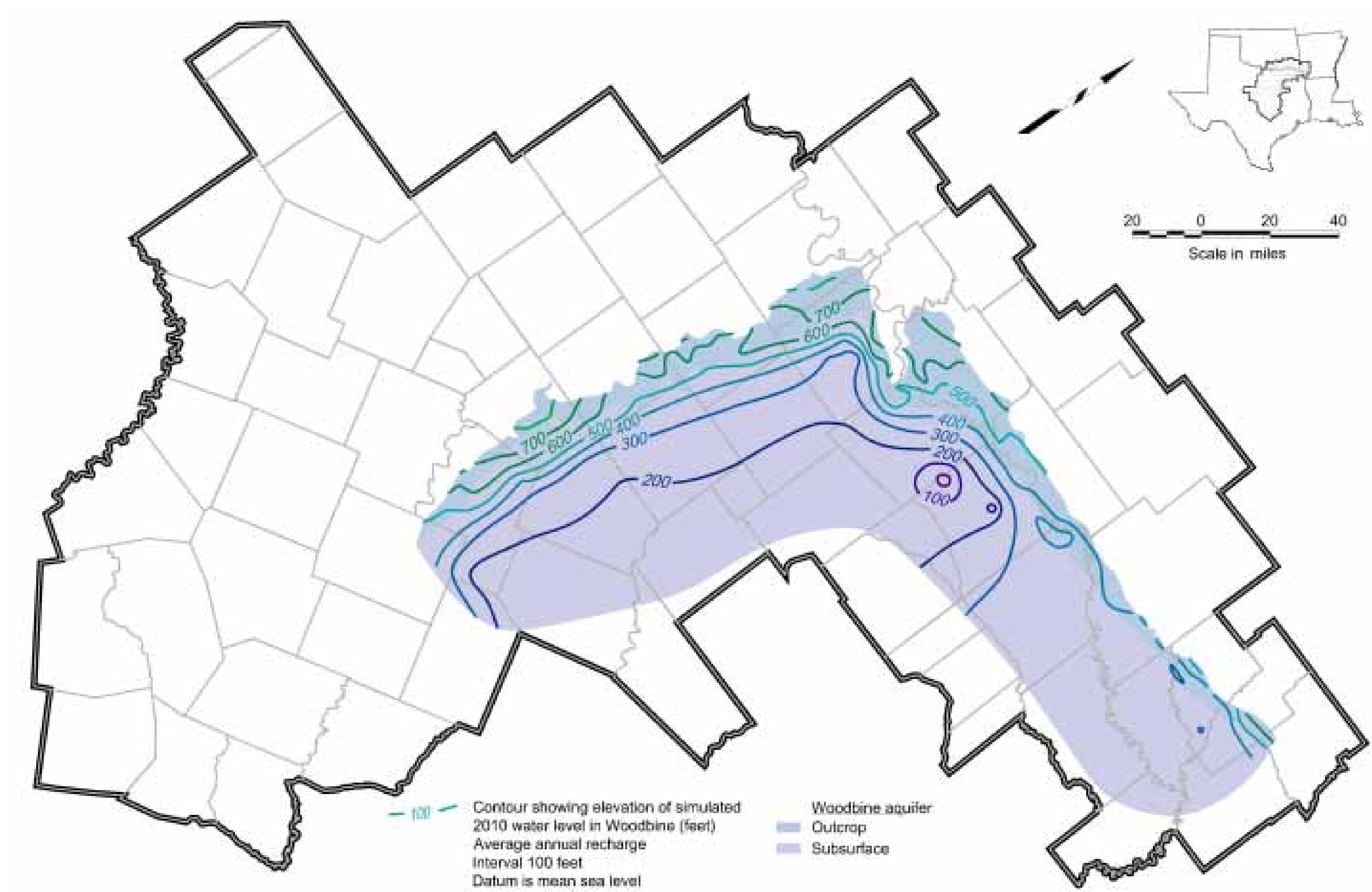



**Figure 10.1 Simulated 2010 Water Levels for Layer 1 (Woodbine) Assuming Average Annual Recharge**

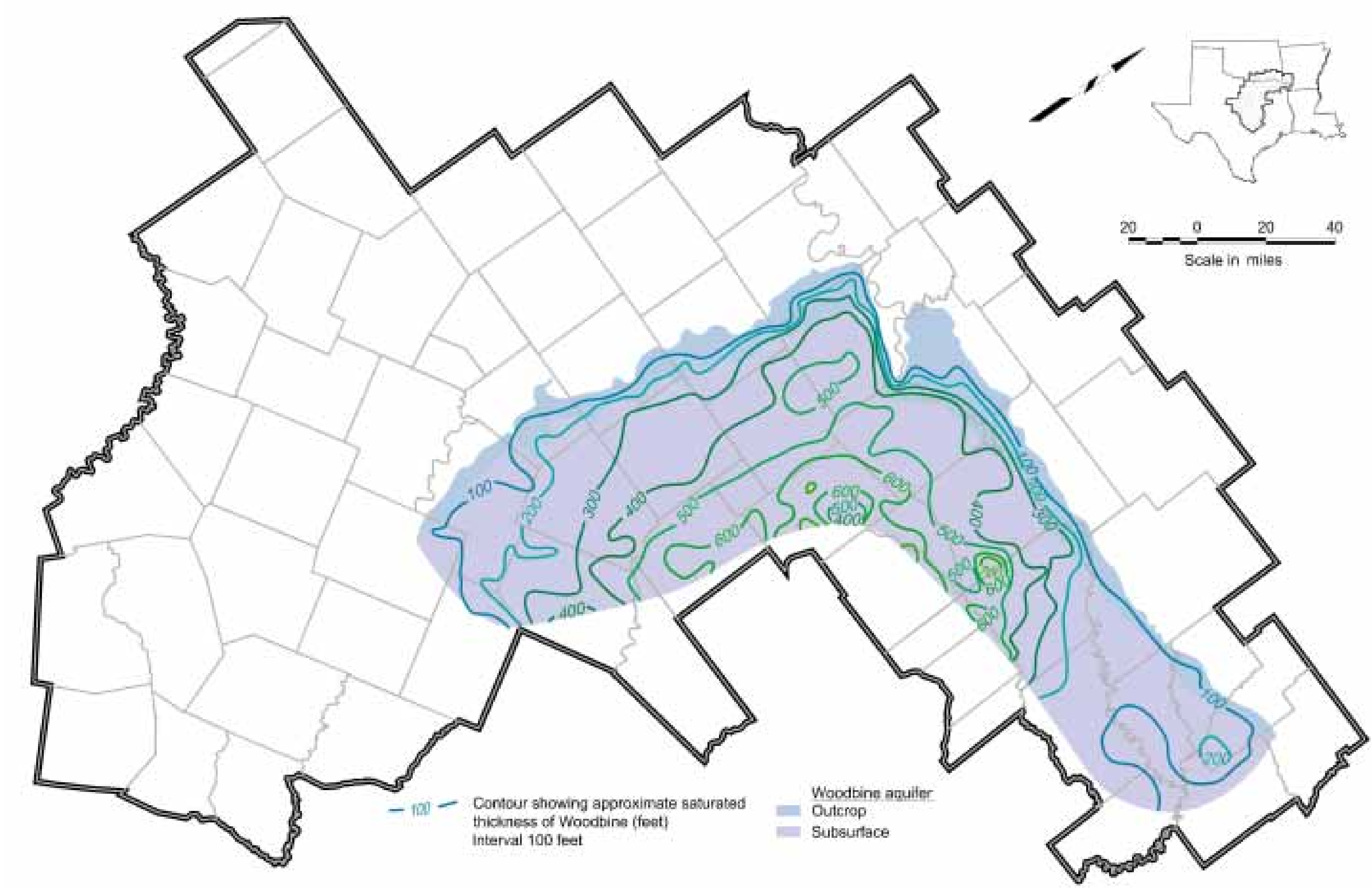



**Figure 10.2 Simulated 2010 Saturated Thickness for Layer 1 (Woodbine) Assuming Average Annual Recharge**

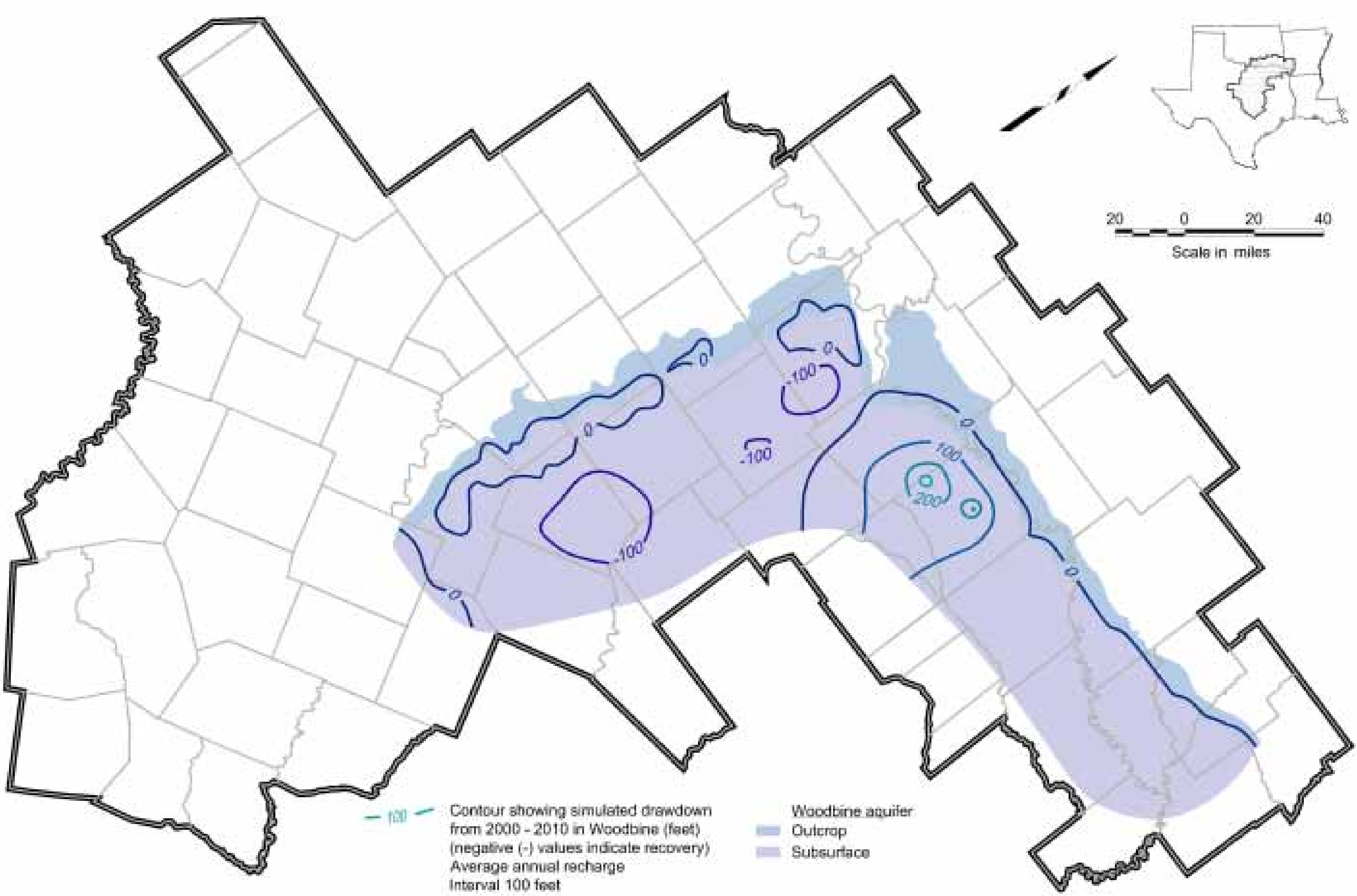



**Figure 10.3 Simulated Water Level Change From 2000 to 2010 for Layer 1 (Woodbine) Assuming Average Annual Recharge**

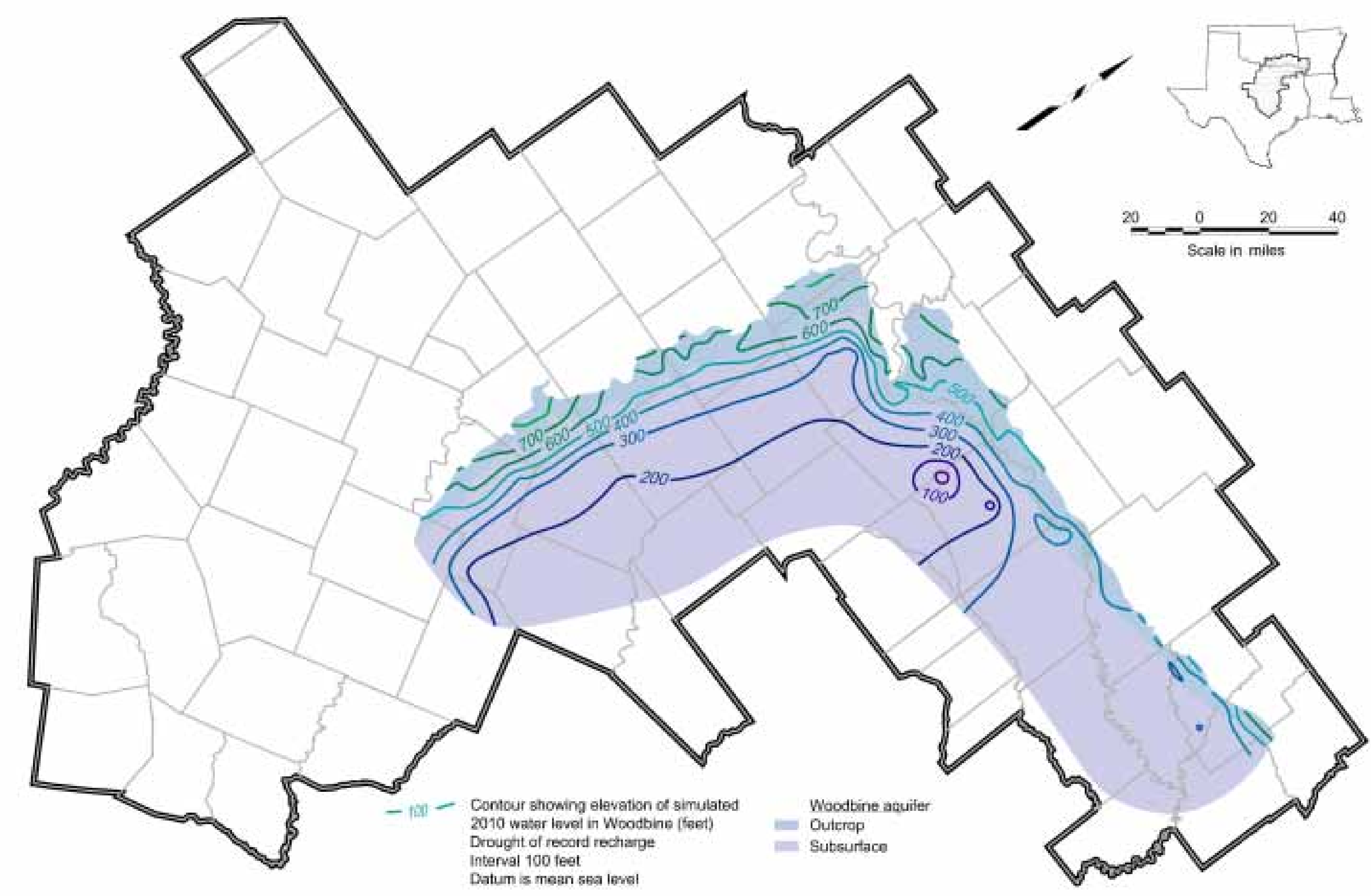



**Figure 10.4 Simulated 2010 Water Levels for Layer 1 (Woodbine) Assuming Drought of Record Recharge Distribution**

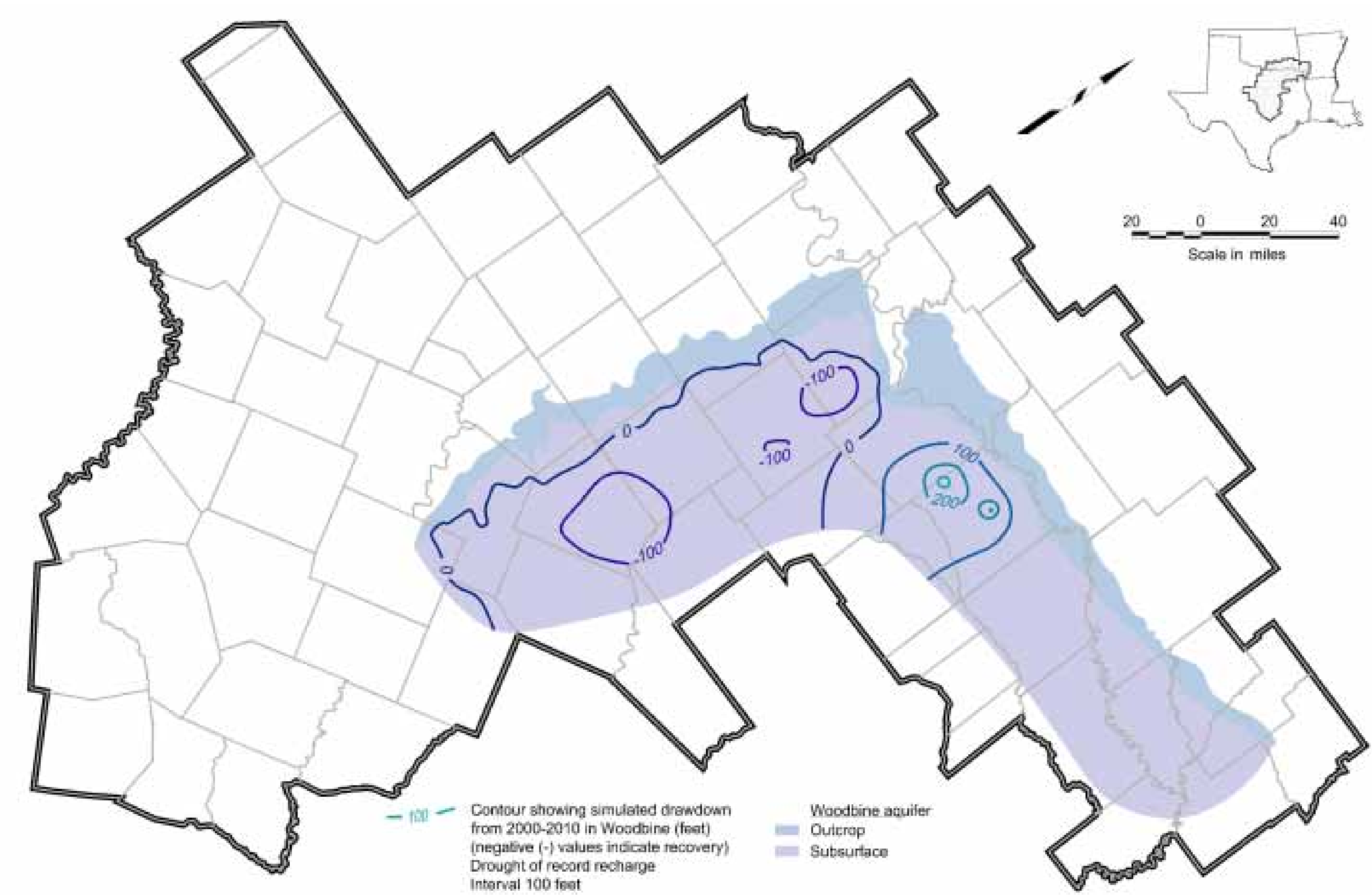



**Figure 10.5 Simulated Water Level Change From 2000 to 2010 for Layer 1 (Woodbine) Assuming Drought of Record Recharge Distribution**

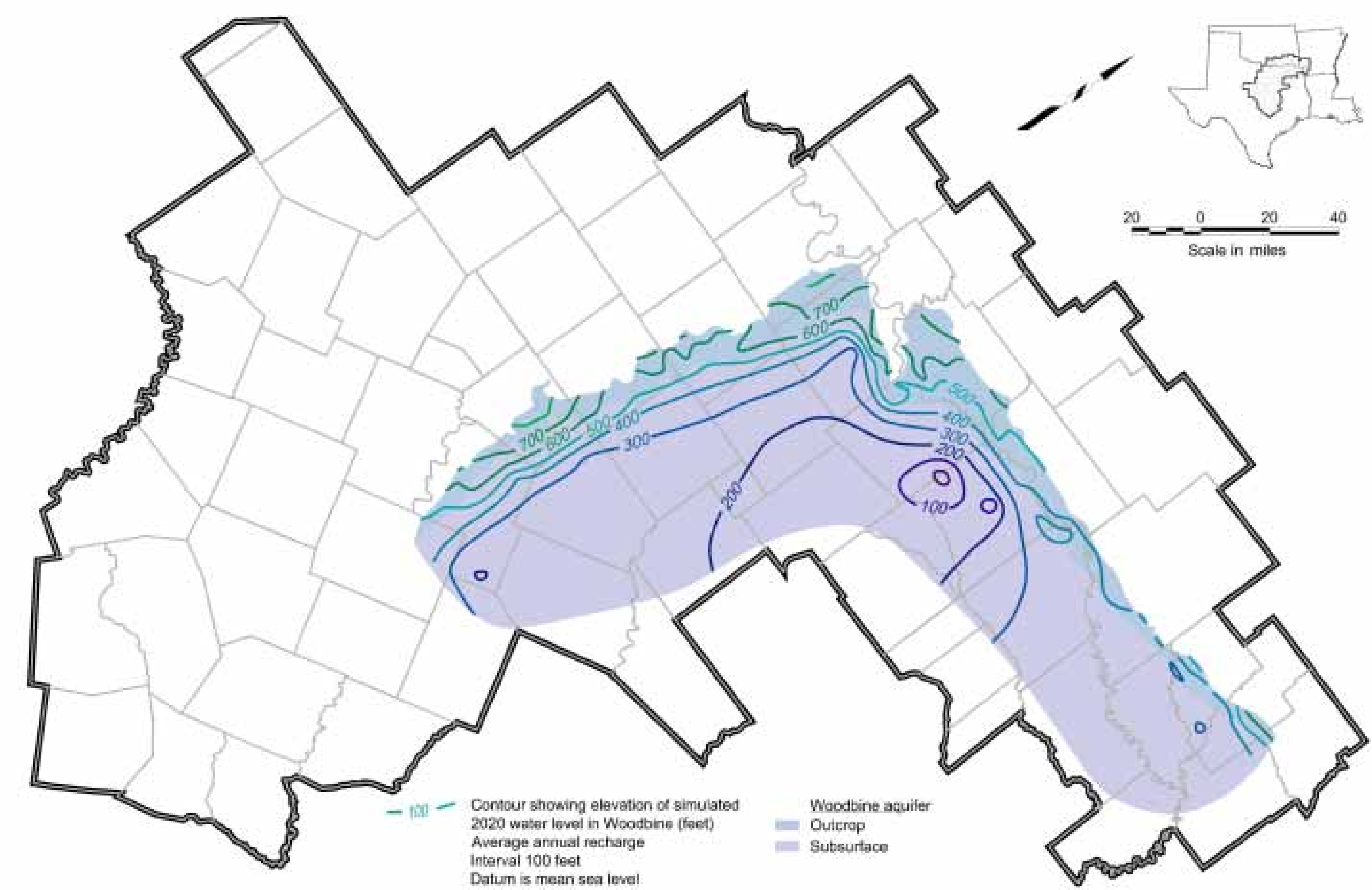



**Figure 10.6 Simulated 2020 Water Levels for Layer 1 (Woodbine) Assuming Average Annual Recharge**

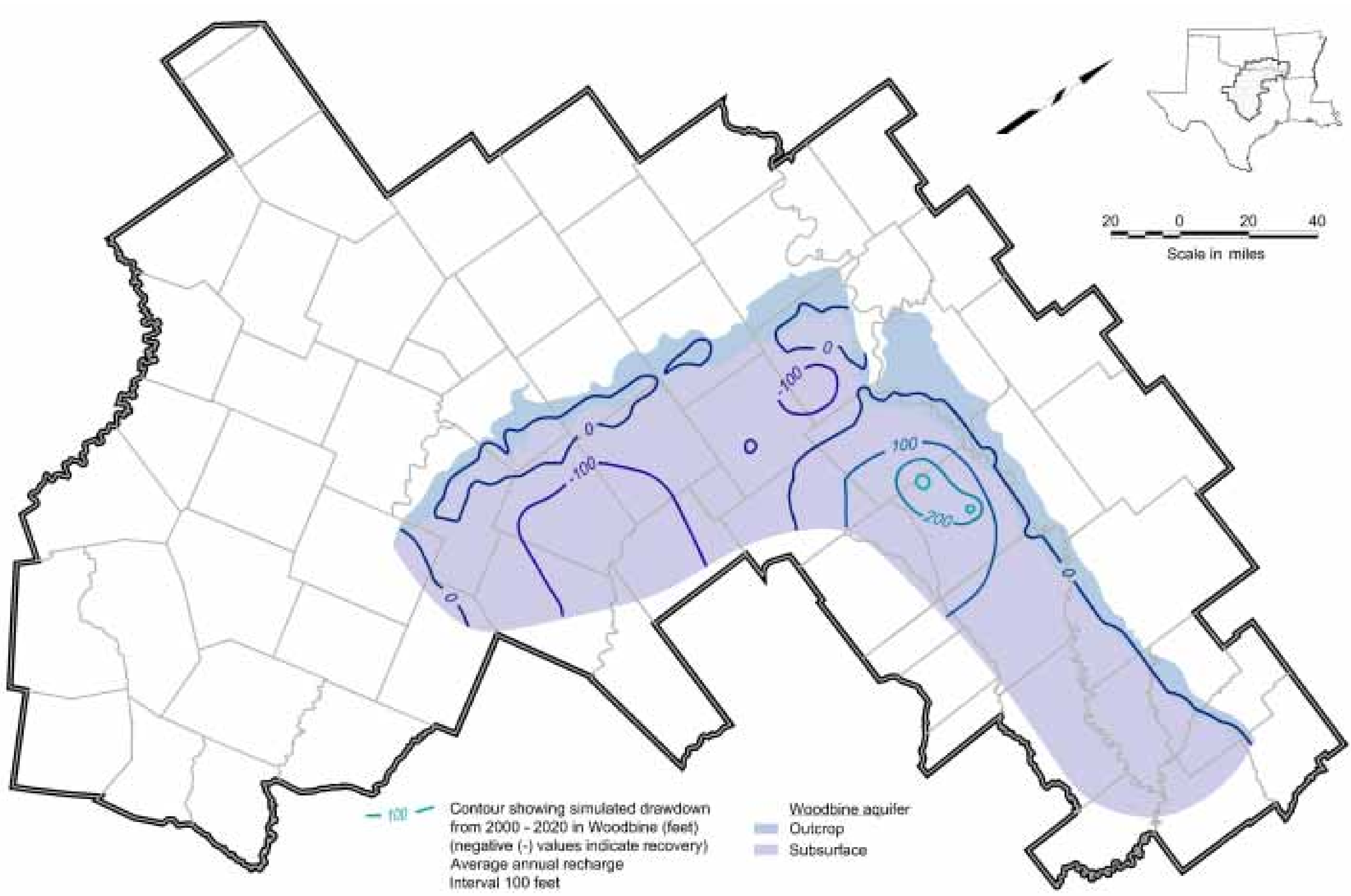



**Figure 10.7 Simulated Water Level Change From 2000 to 2020 for Layer 1 (Woodbine) Assuming Average Annual Recharge**

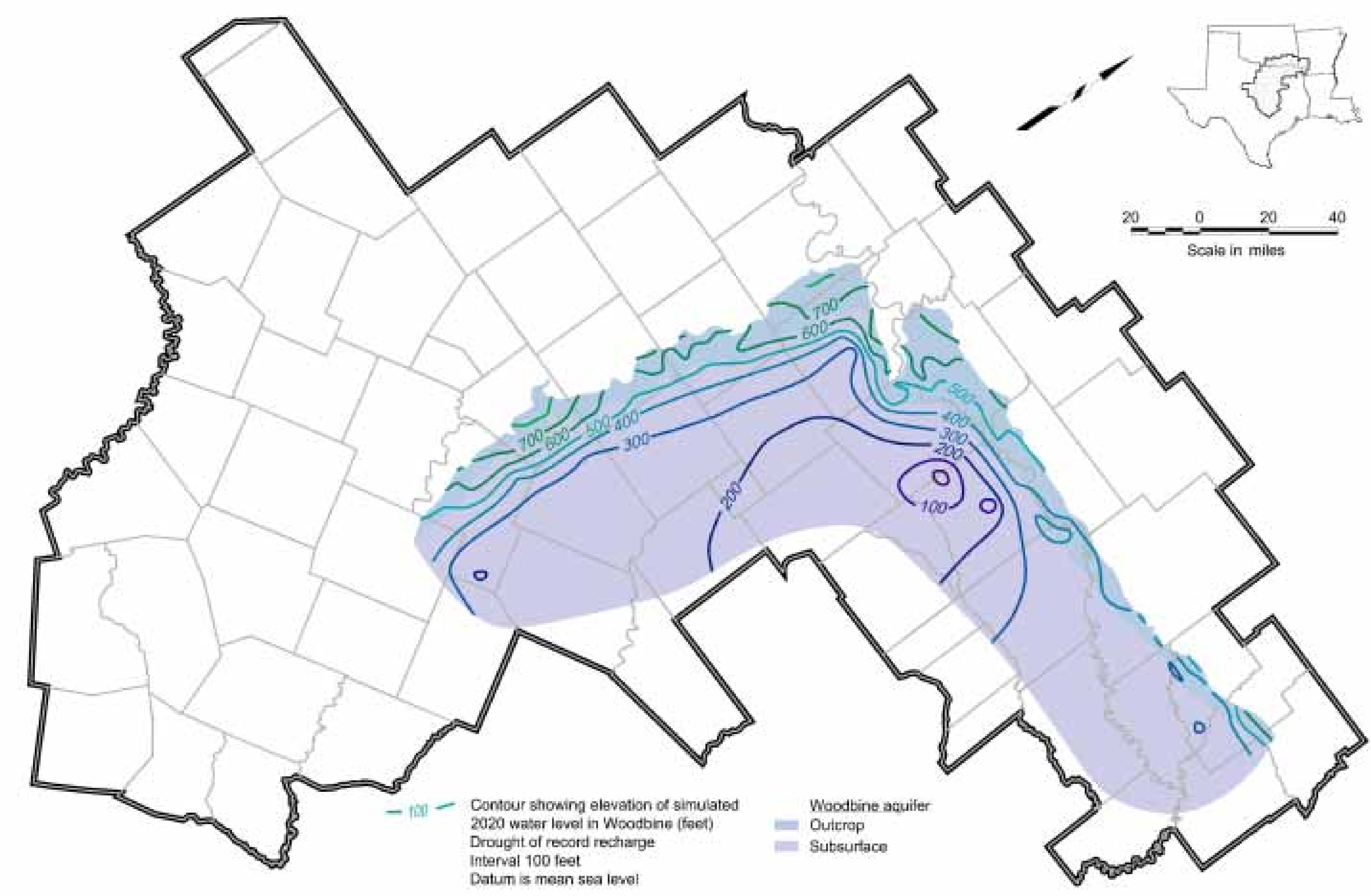



**Figure 10.8 Simulated 2020 Water Levels for Layer 1 (Woodbine) Assuming Drought of Record Recharge Distribution**

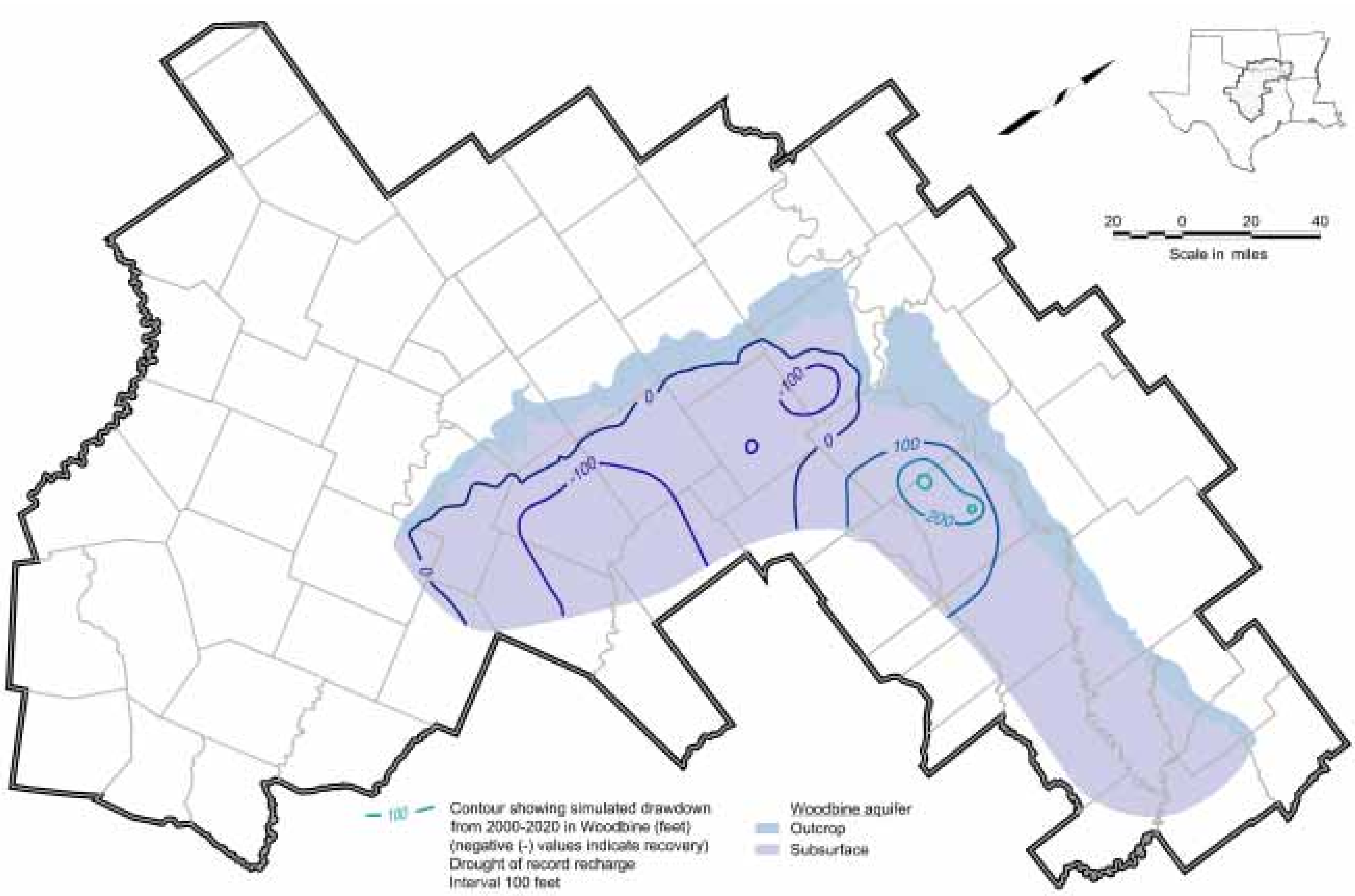



**Figure 10.9 Simulated Water Level Change From 2000 to 2020 for Layer 1 (Woodbine) Assuming Drought of Record Recharge Distribution**

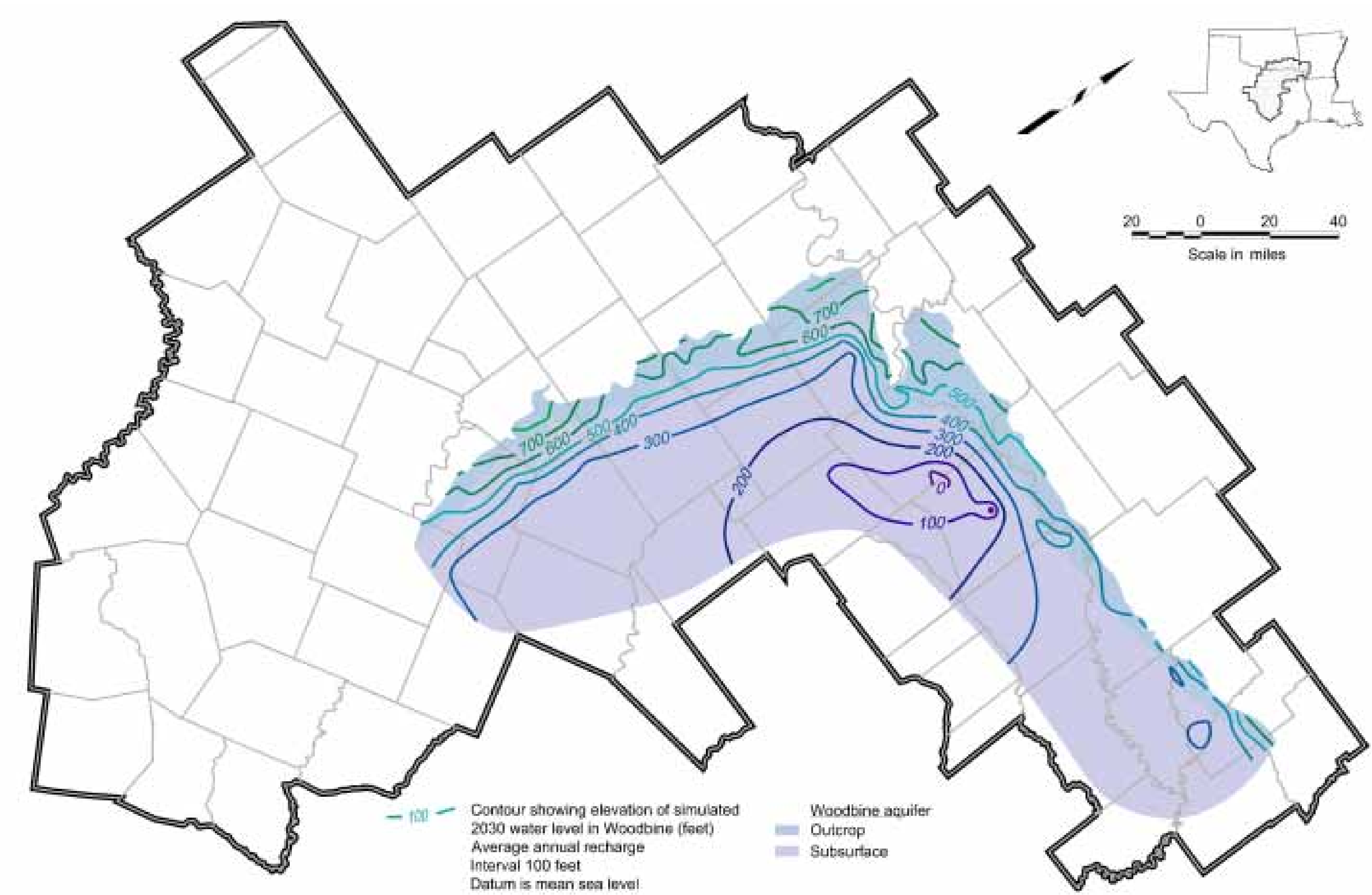



**Figure 10.10 Simulated 2030 Water Levels for Layer 1 (Woodbine) Assuming Average Annual Recharge**

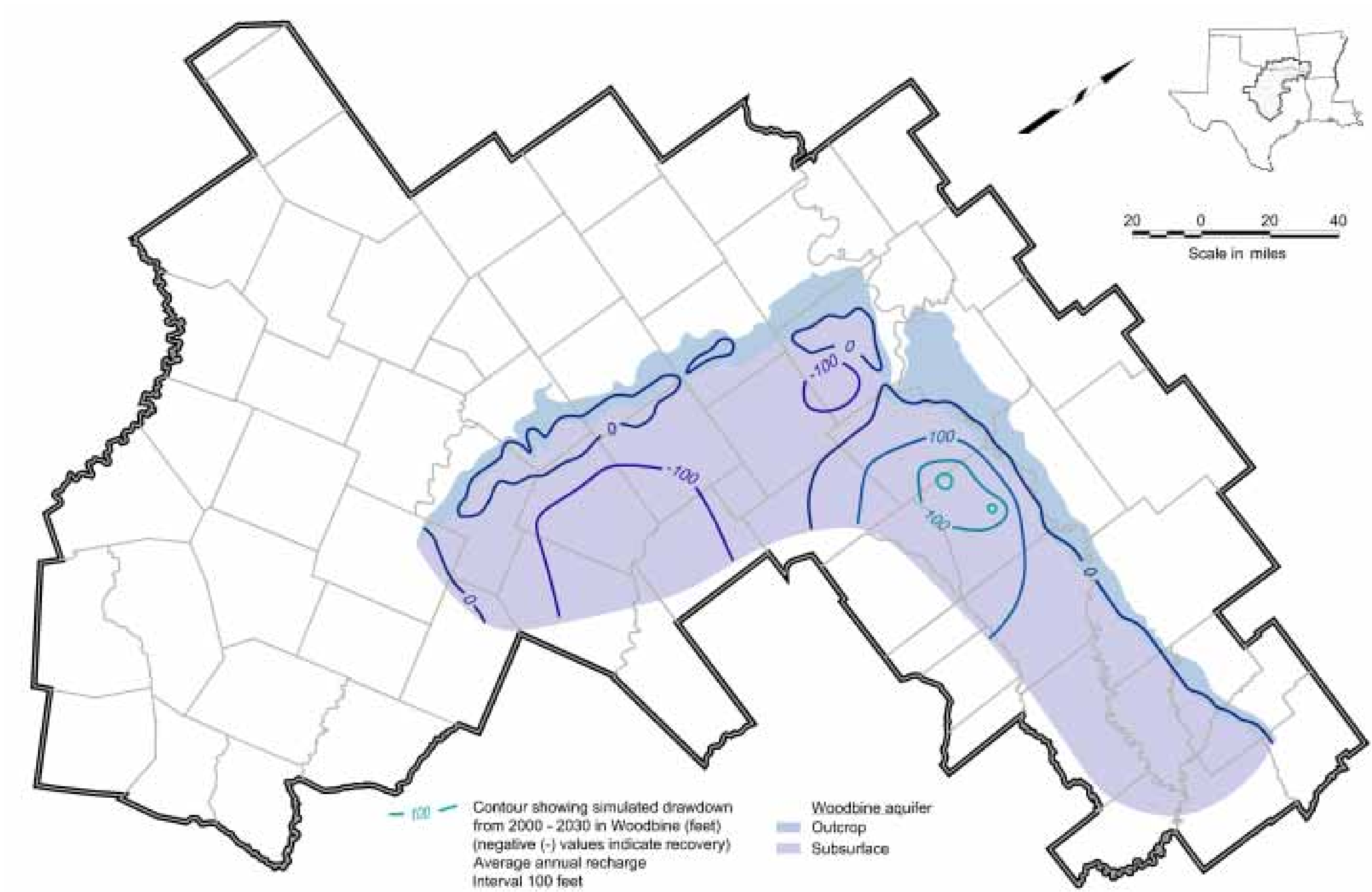



**Figure 10.11 Simulated Water Level Change From 2000 to 2030 for Layer 1 (Woodbine) Assuming Average Annual Recharge**

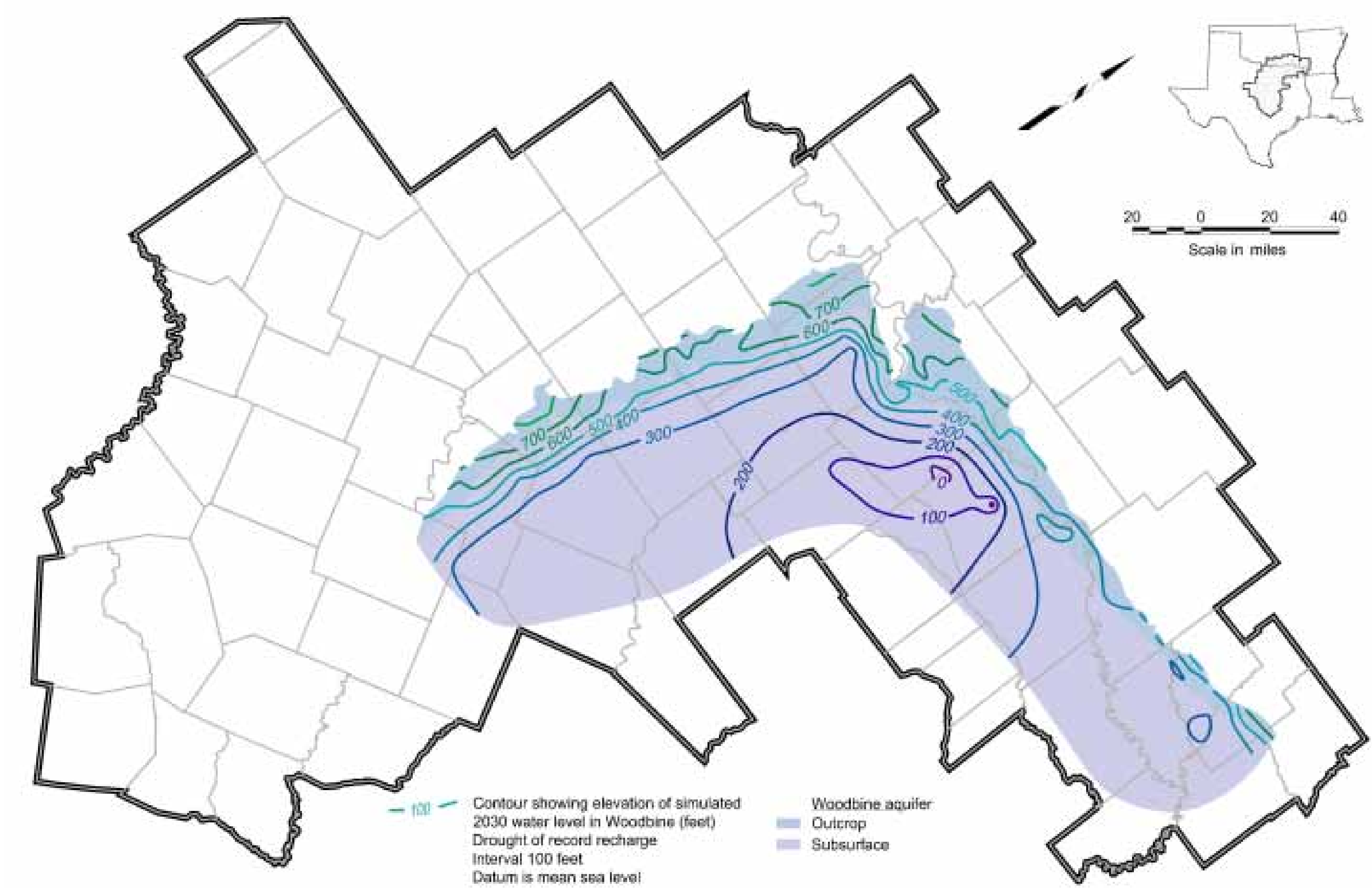



**Figure 10.12 Simulated 2030 Water Levels for Layer 1 (Woodbine) Assuming Drought of Record Recharge Distribution**

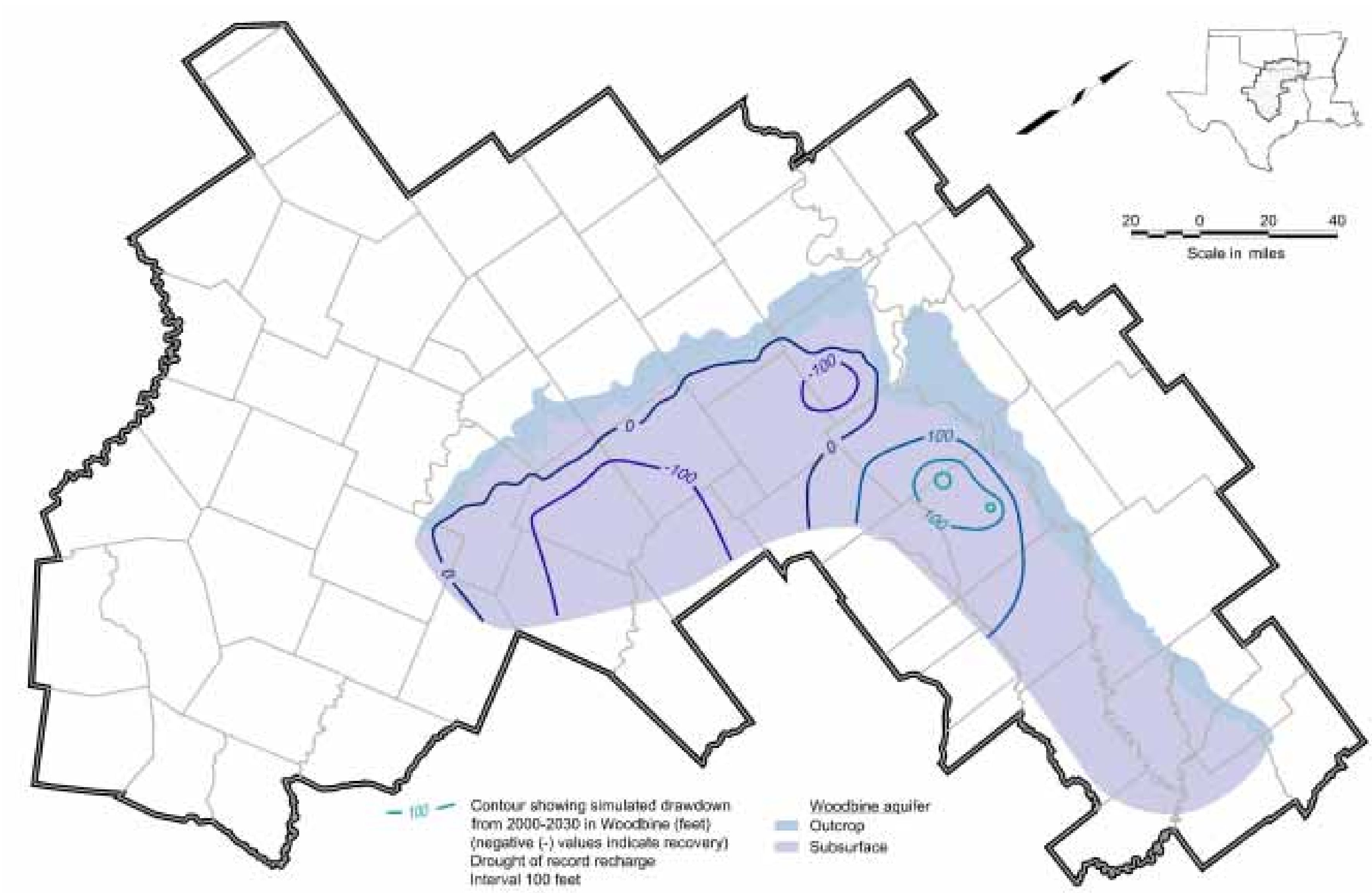



**Figure 10.13 Simulated Water Level Change From 2000 to 2030 for Layer 1 (Woodbine) Assuming Drought of Record Recharge Distribution**

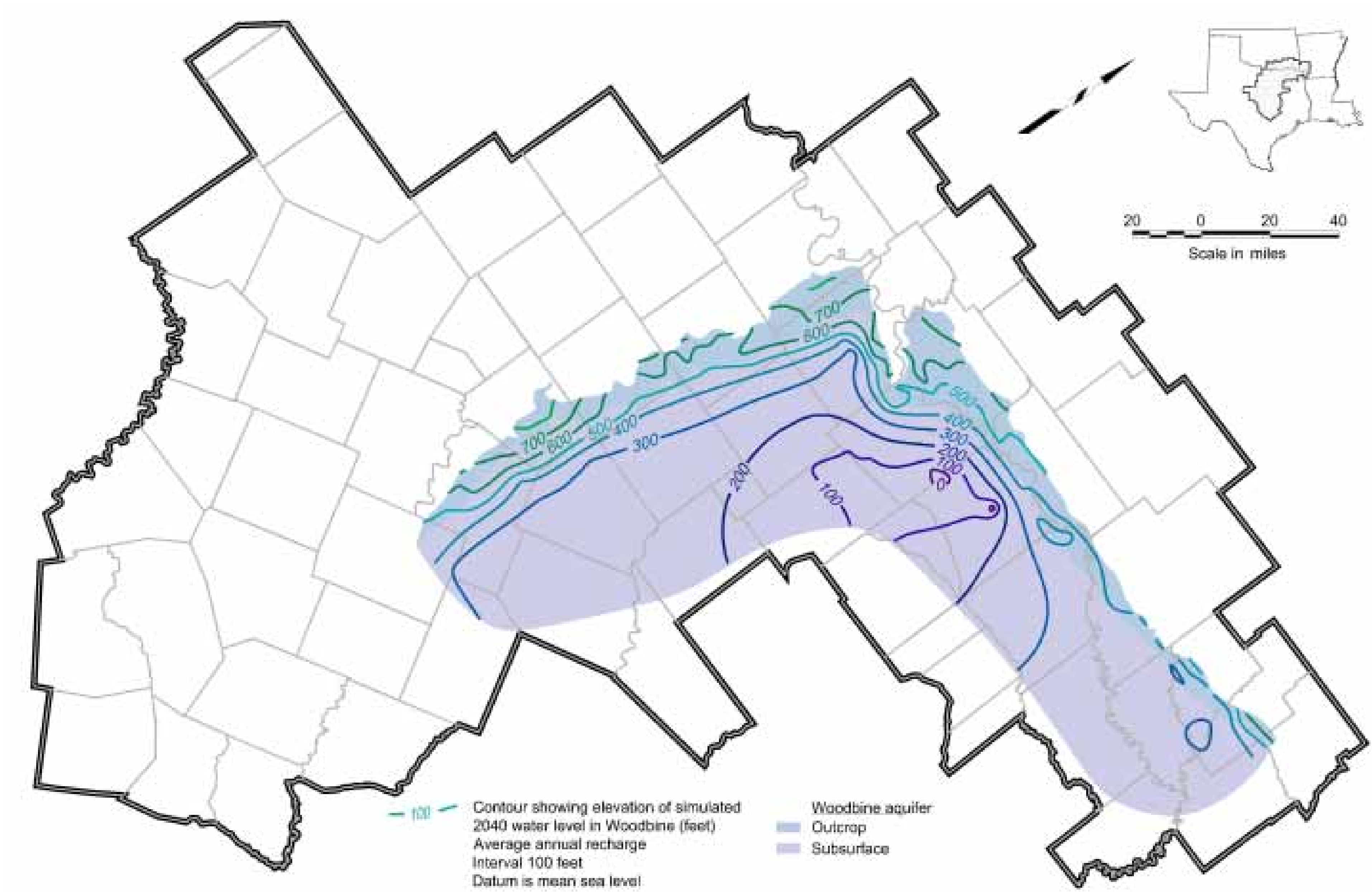



**Figure 10.14 Simulated 2040 Water Levels for Layer 1 (Woodbine) Assuming Average Annual Recharge**

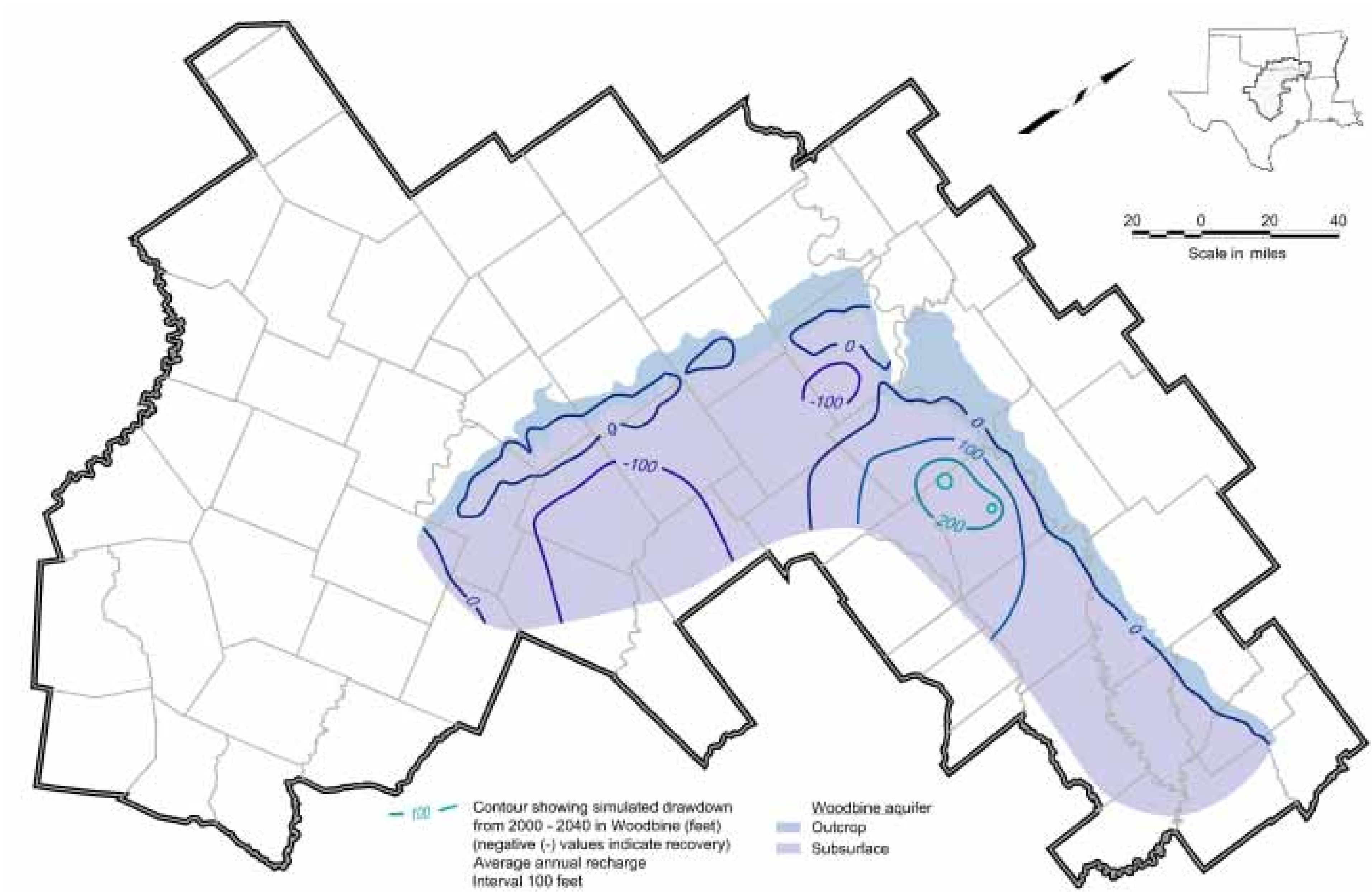



**Figure 10.15 Simulated Water Level Change From 2000 to 2040 for Layer 1 (Woodbine) Assuming Average Annual Recharge**

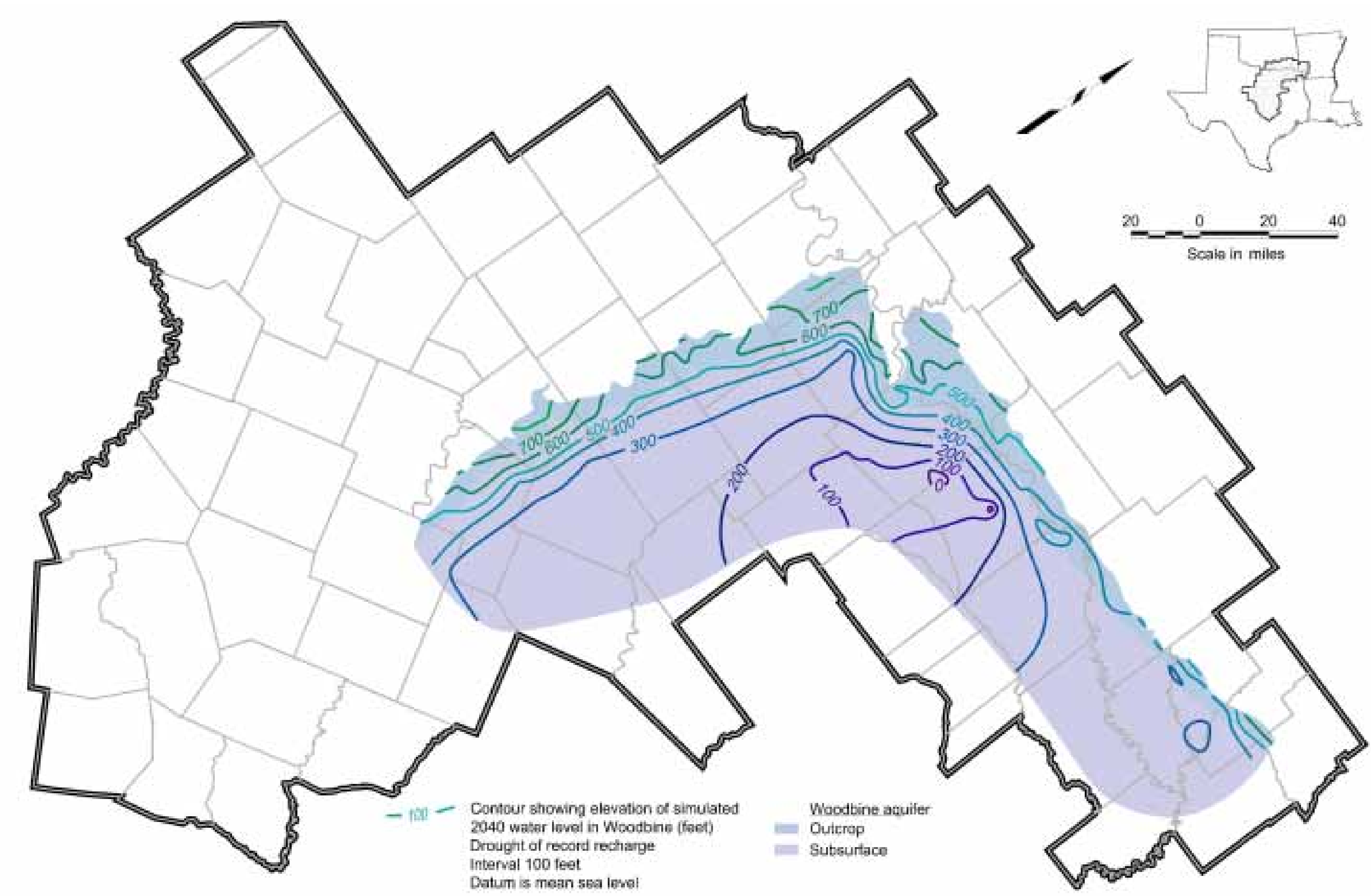



**Figure 10.16 Simulated 2040 Water Levels for Layer 1 (Woodbine) Assuming Drought of Record Recharge Distribution**

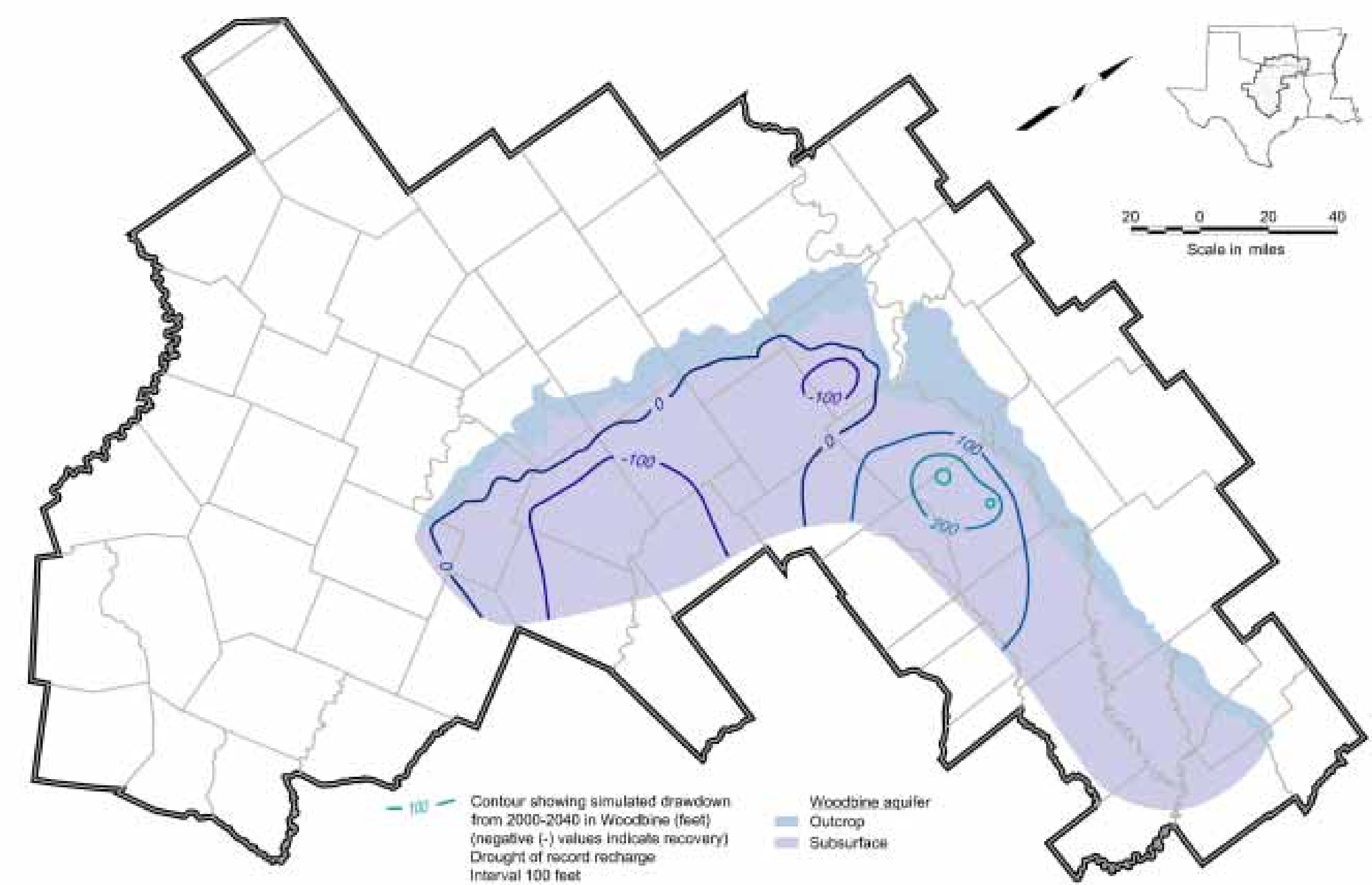



**Figure 10.17 Simulated Water Level Change From 2000 to 2040 for Layer 1 (Woodbine) Assuming Drought of Record Recharge Distribution**

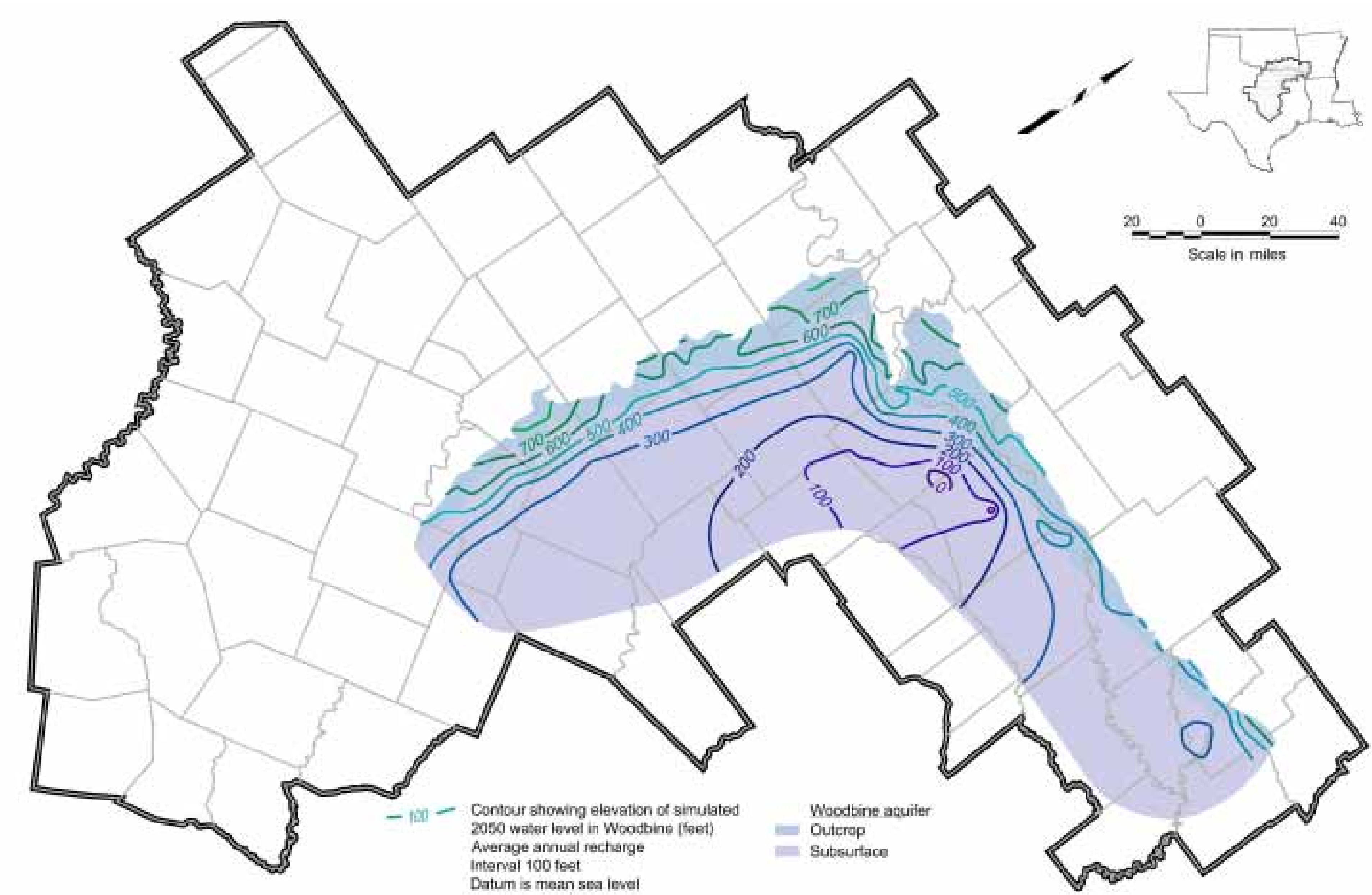



**Figure 10.18 Simulated 2050 Water Levels for Layer 1 (Woodbine) Assuming Average Annual Recharge**

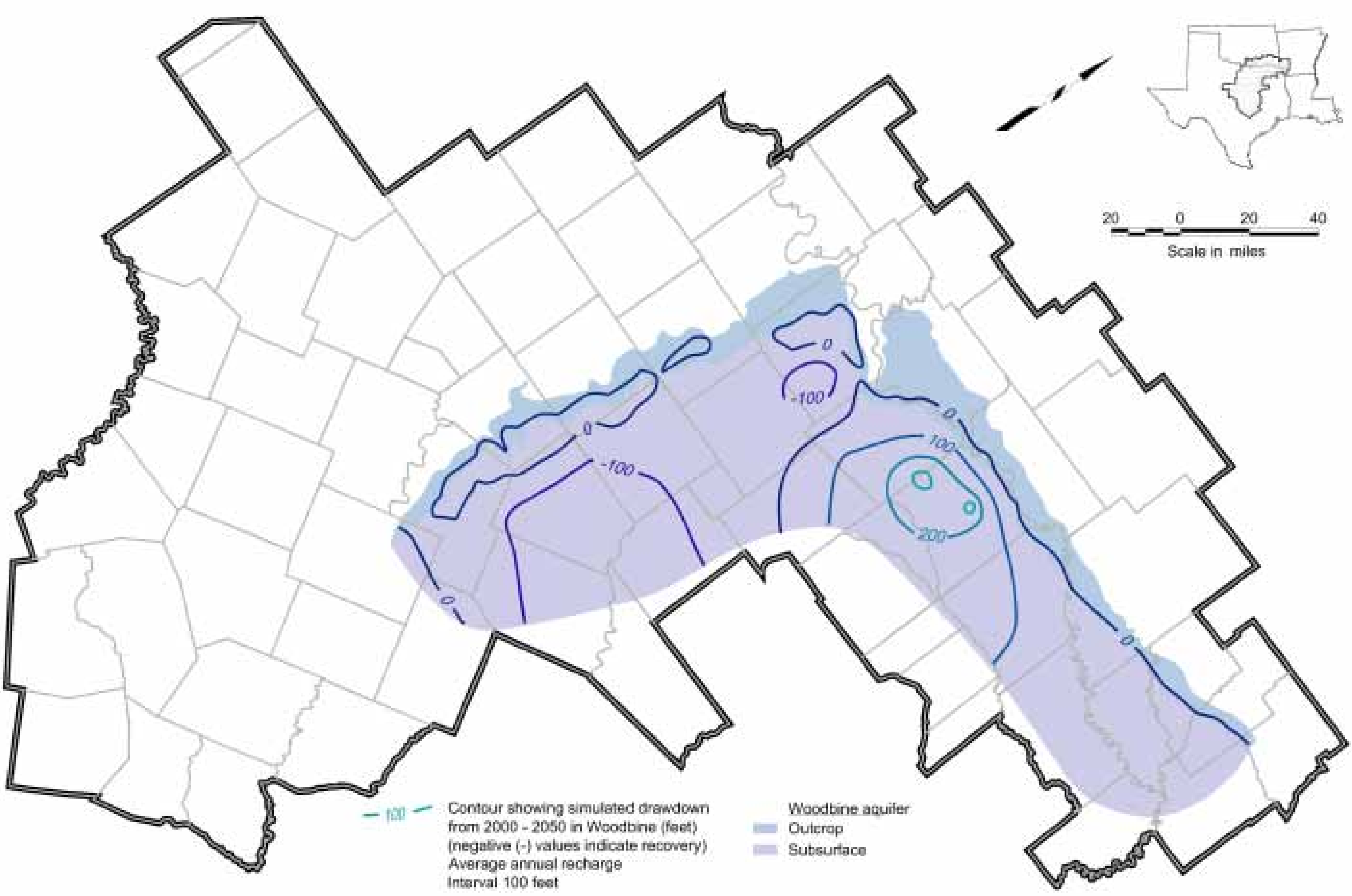



**Figure 10.19 Simulated Water Level Change From 2000 to 2050 for Layer 1 (Woodbine) Assuming Average Annual Recharge**

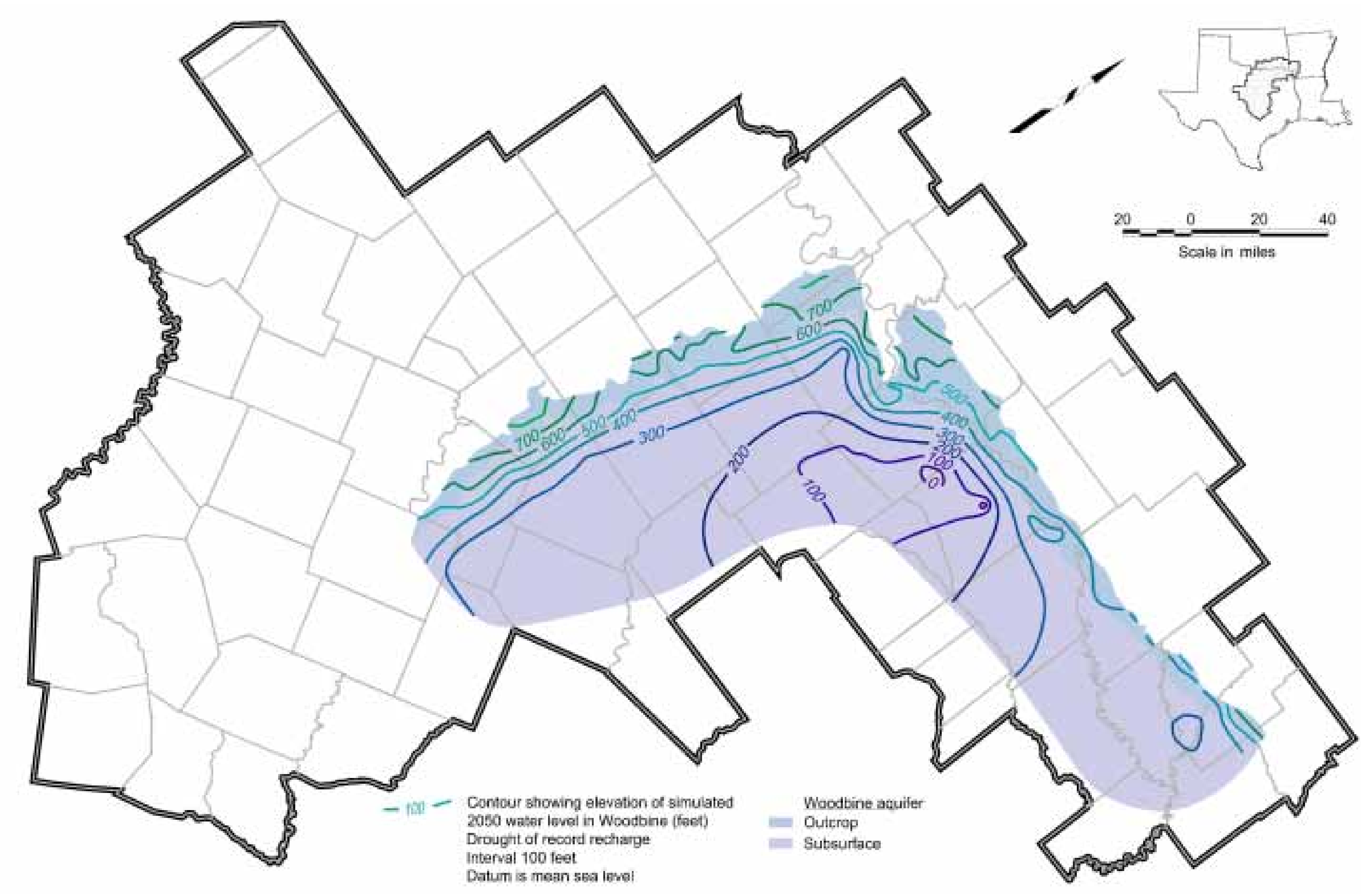



**Figure 10.20 Simulated 2050 Water Levels for Layer 1 (Woodbine) Assuming Drought of Record Recharge Distribution**

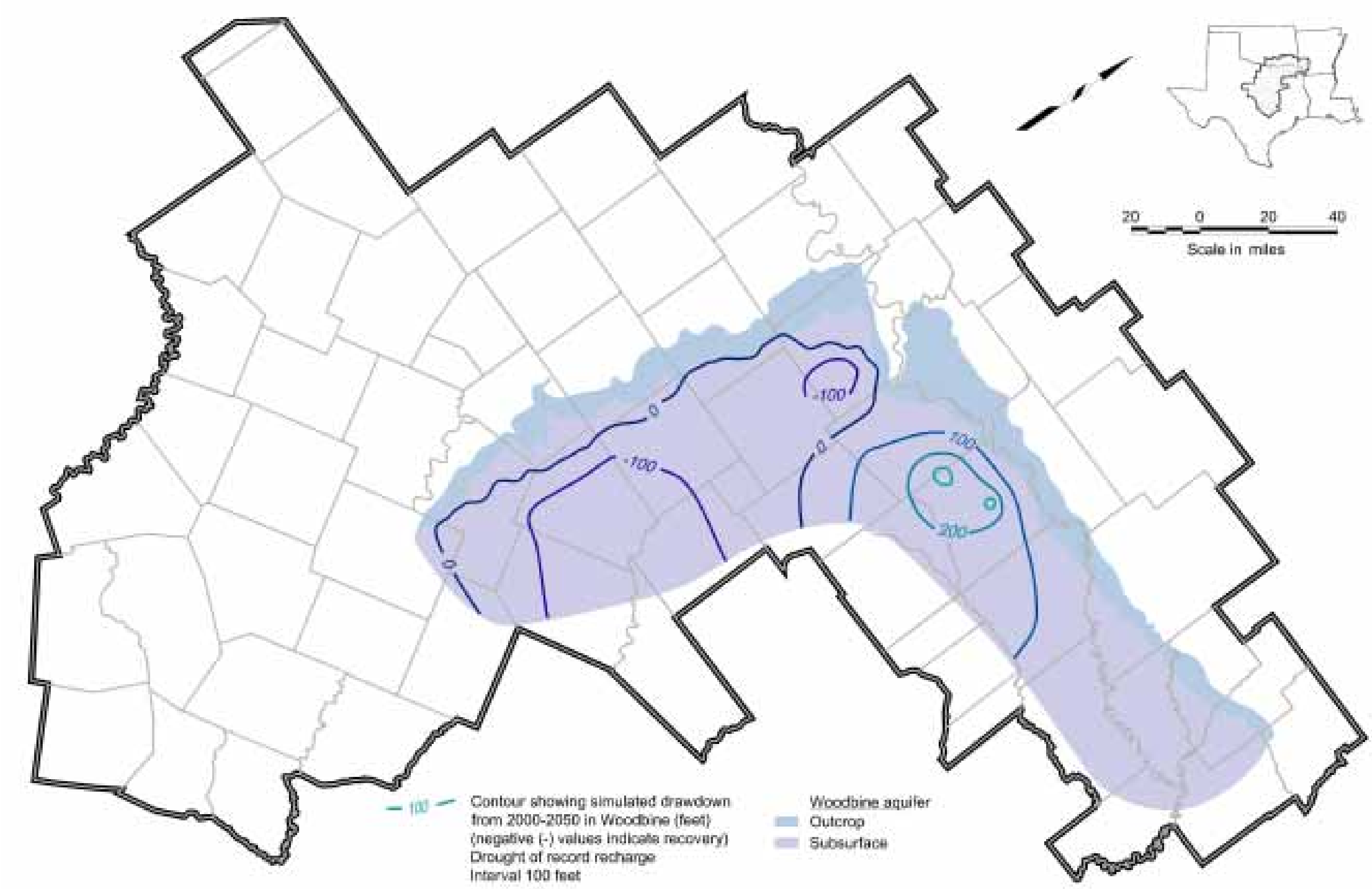



**Figure 10.21 Simulated Water Level Change From 2000 to 2050 for Layer 1 (Woodbine) Assuming Drought of Record Recharge Distribution**

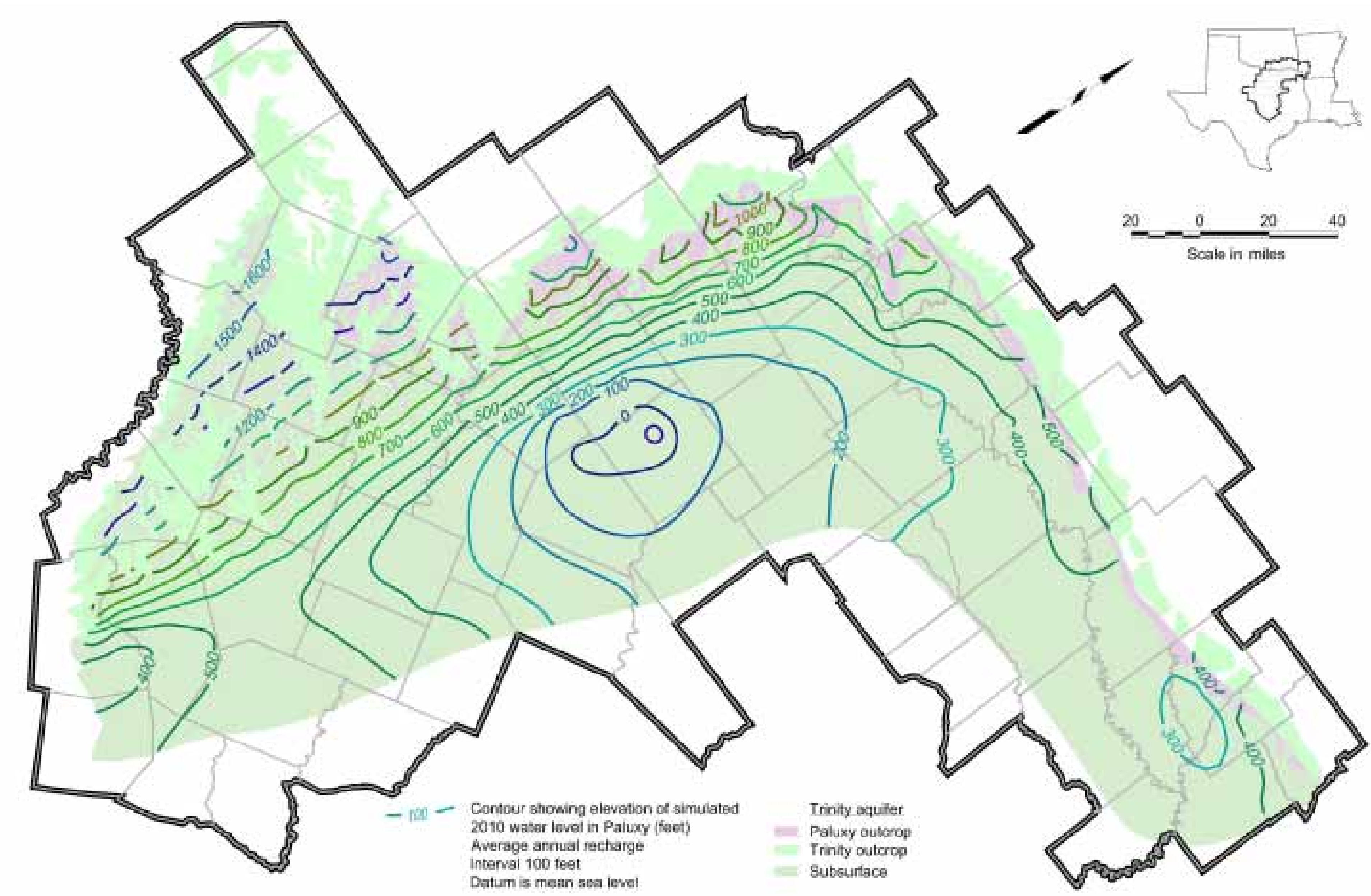



**Figure 10.22 Simulated 2010 Water Levels for Layer 3 (Paluxy) Assuming Average Annual Recharge**

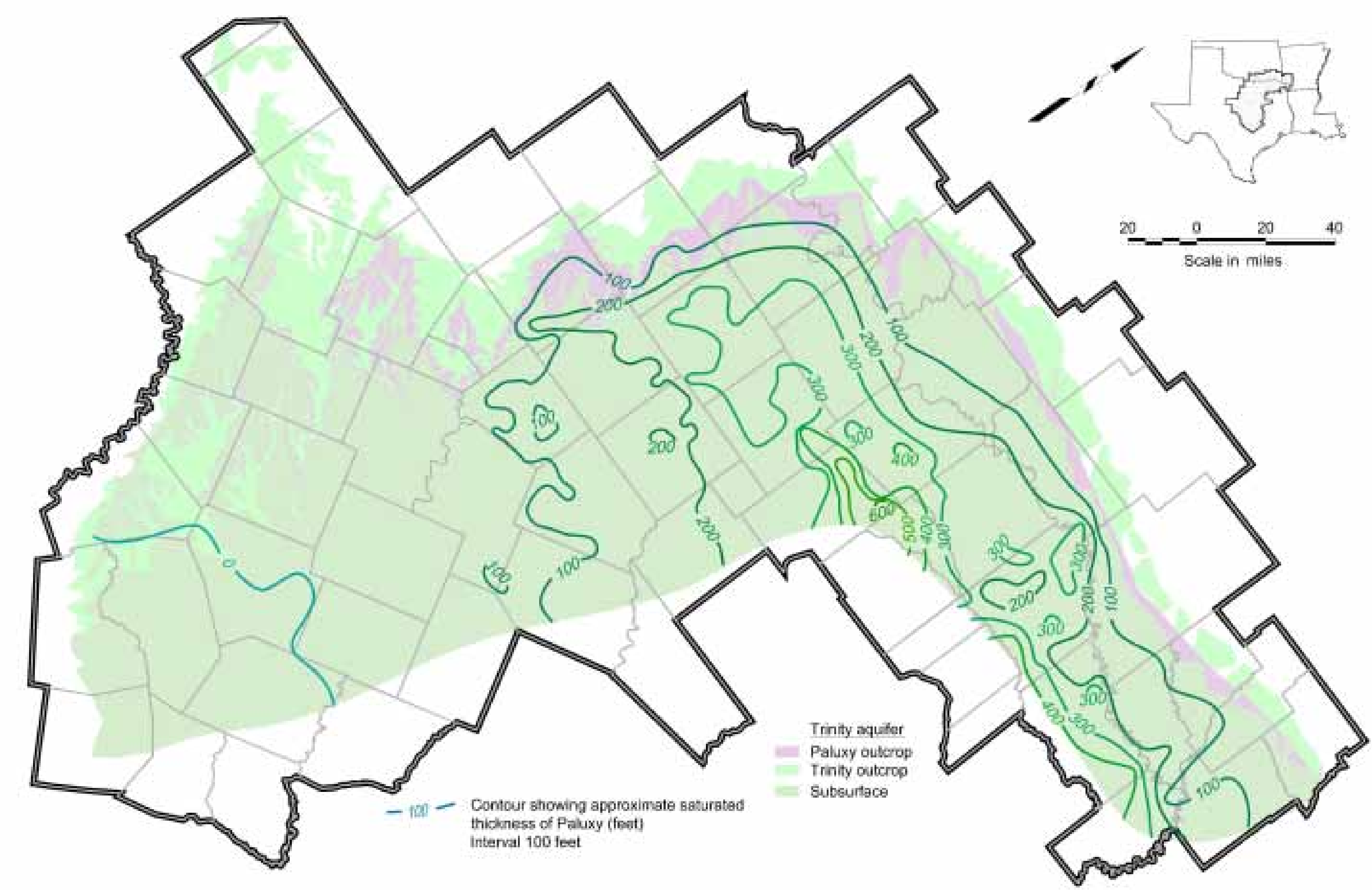



**Figure 10.23 Simulated 2010 Saturated Thickness for Layer 3 (Paluxy) Assuming Average Annual Recharge**

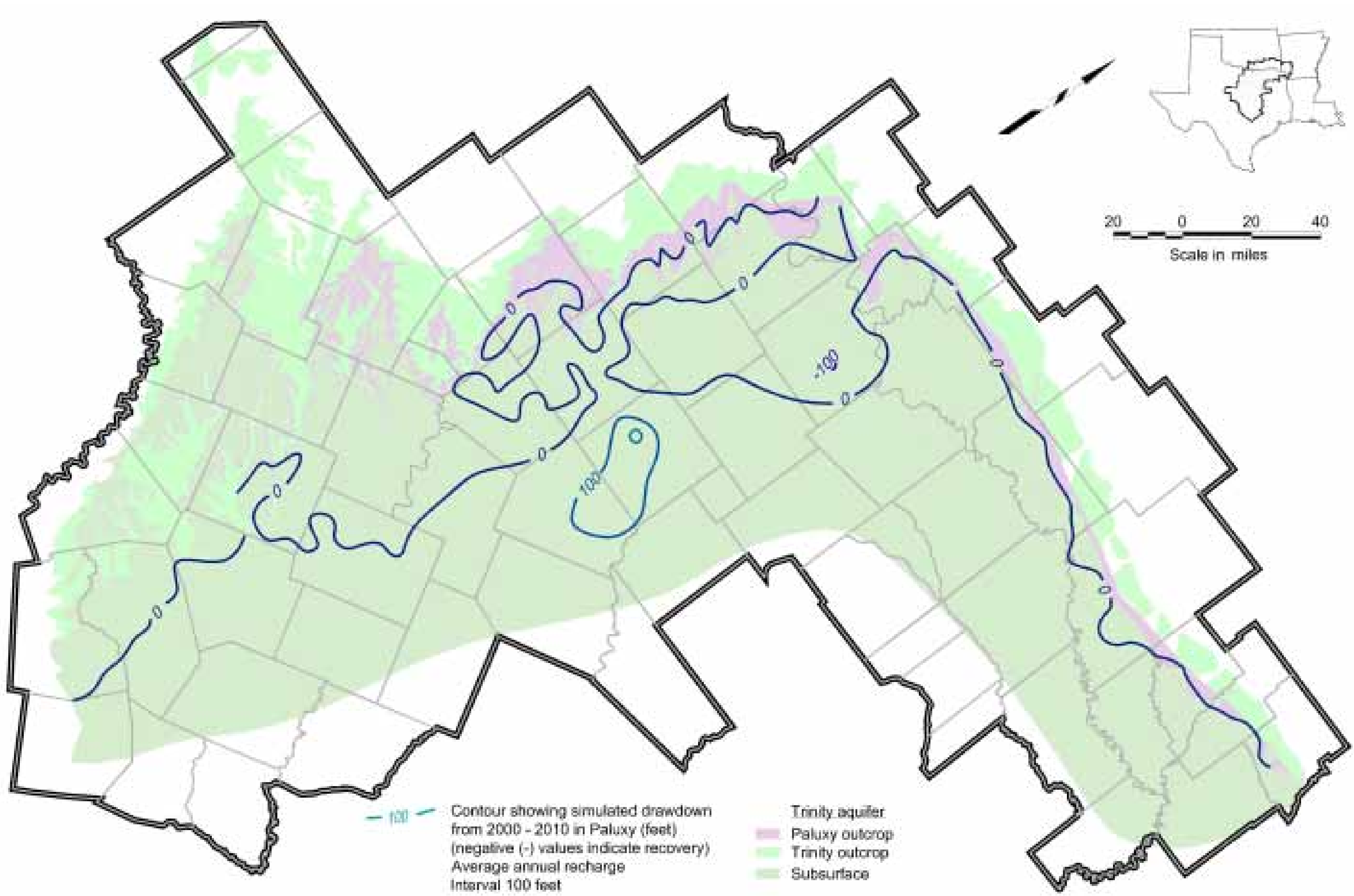



**Figure 10.24 Simulated Water Level Change From 2000 to 2010 for Layer 3 (Paluxy) Assuming Average Annual Recharge**

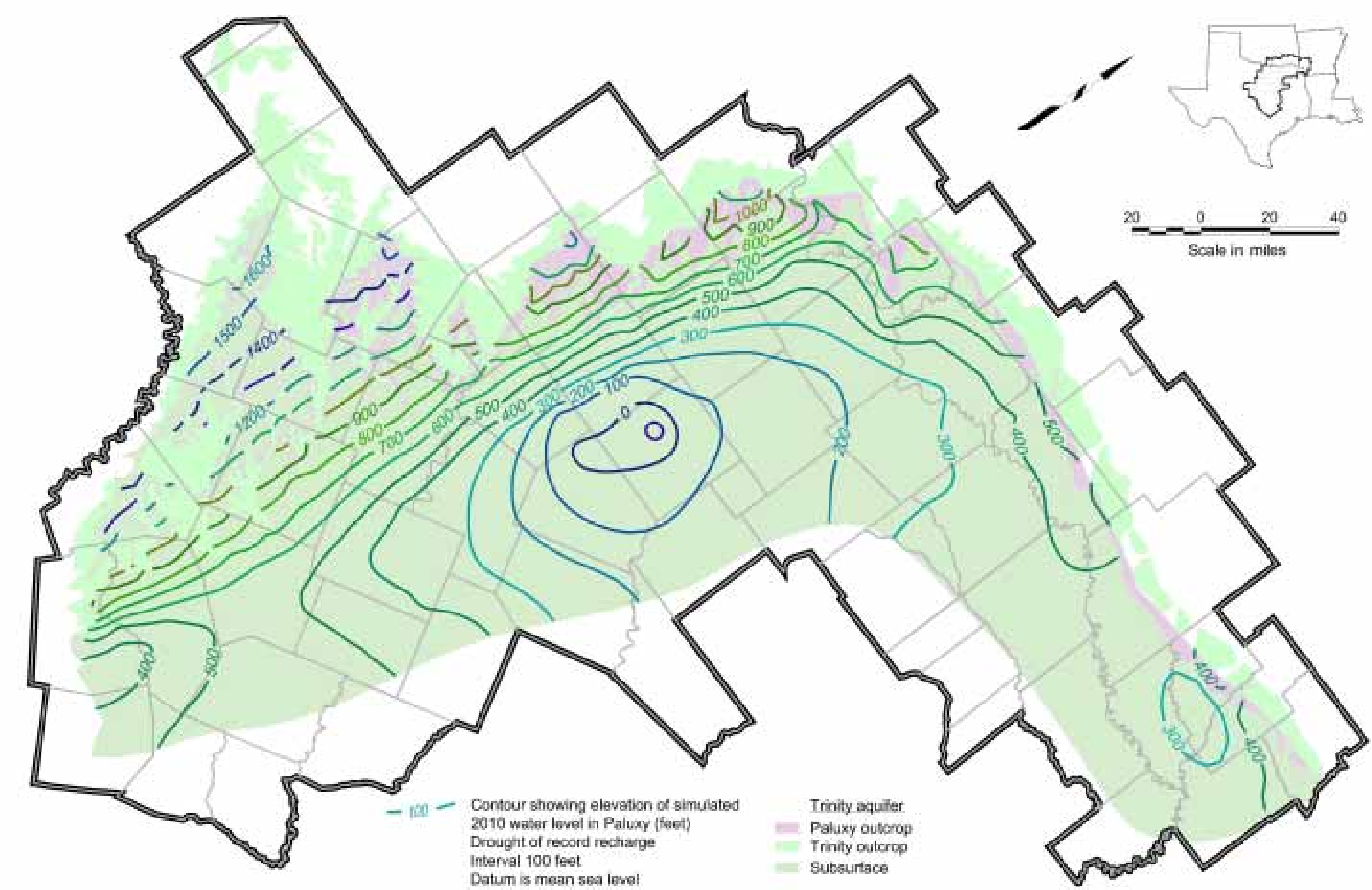



**Figure 10.25 Simulated 2010 Water Levels for Layer 3 (Paluxy) Assuming Drought of Record Recharge Distribution**

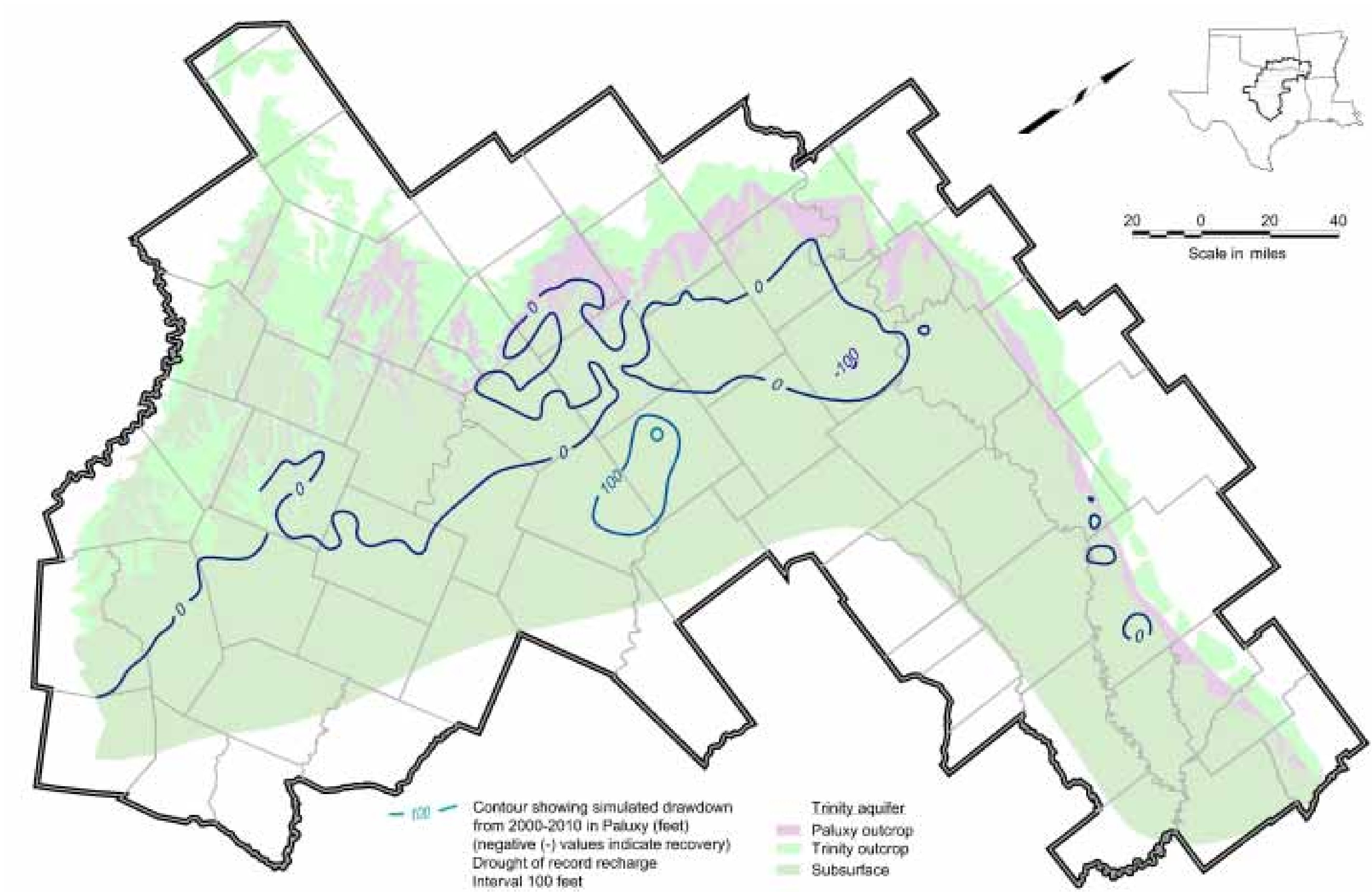



**Figure 10.26 Simulated Water Level Change From 2000 to 2010 for Layer 3 (Paluxy) Assuming Drought of Record Recharge Distribution**

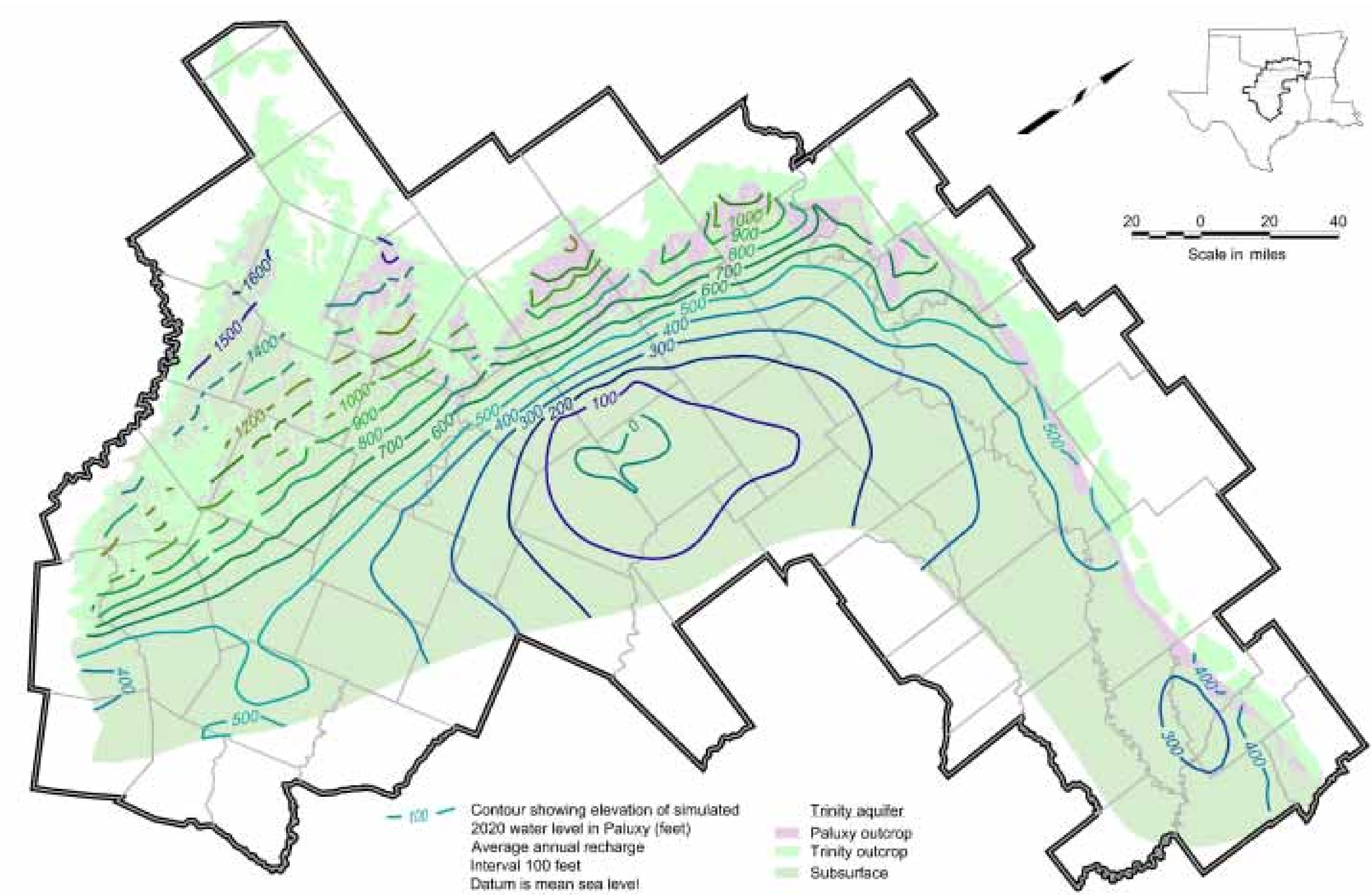



**Figure 10.27 Simulated 2020 Water Levels for Layer 3 (Paluxy) Assuming Average Annual Recharge**

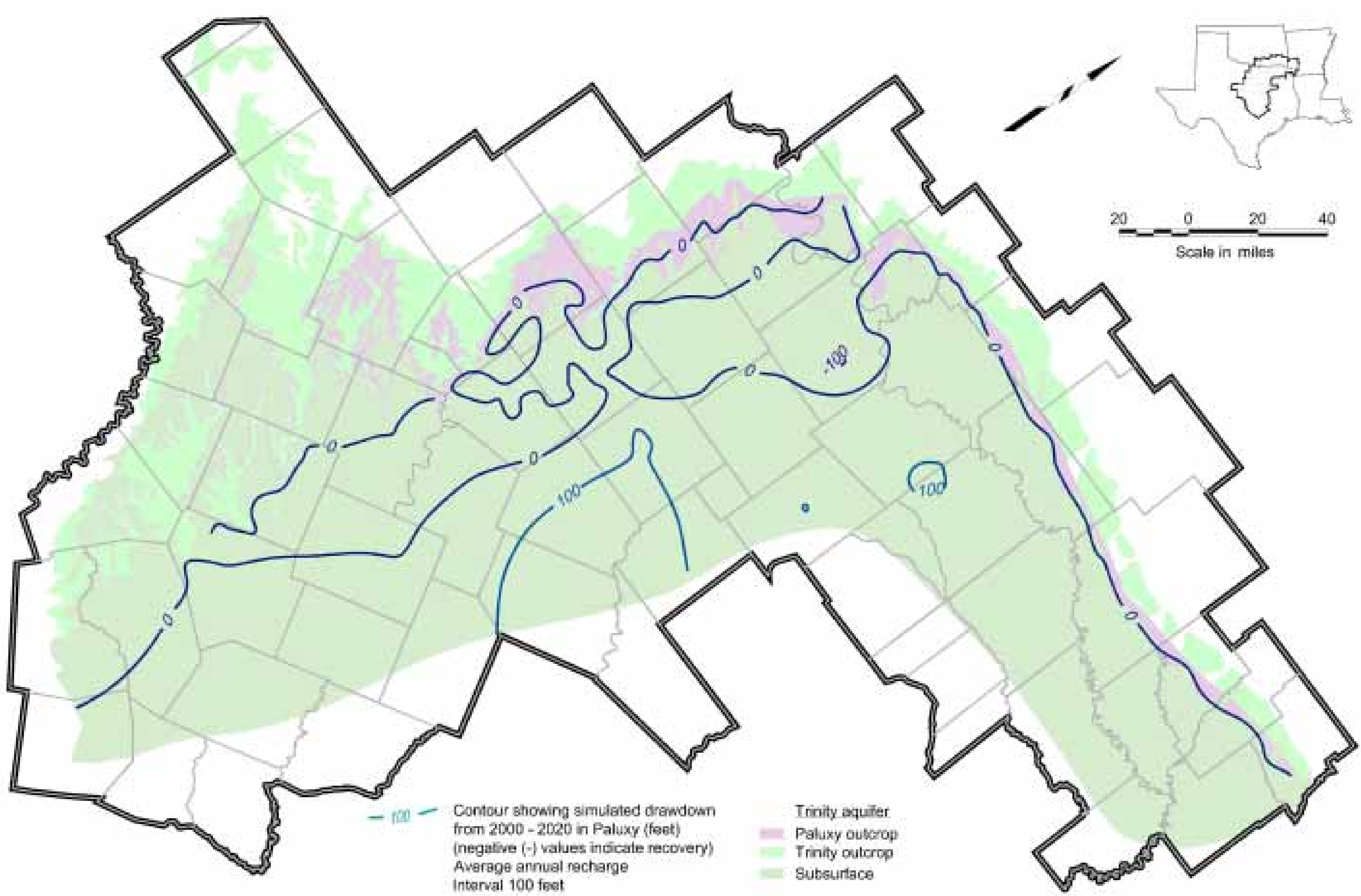



**Figure 10.28 Simulated Water Level Change From 2000 to 2020 for Layer 3 (Paluxy) Assuming Average Annual Recharge**

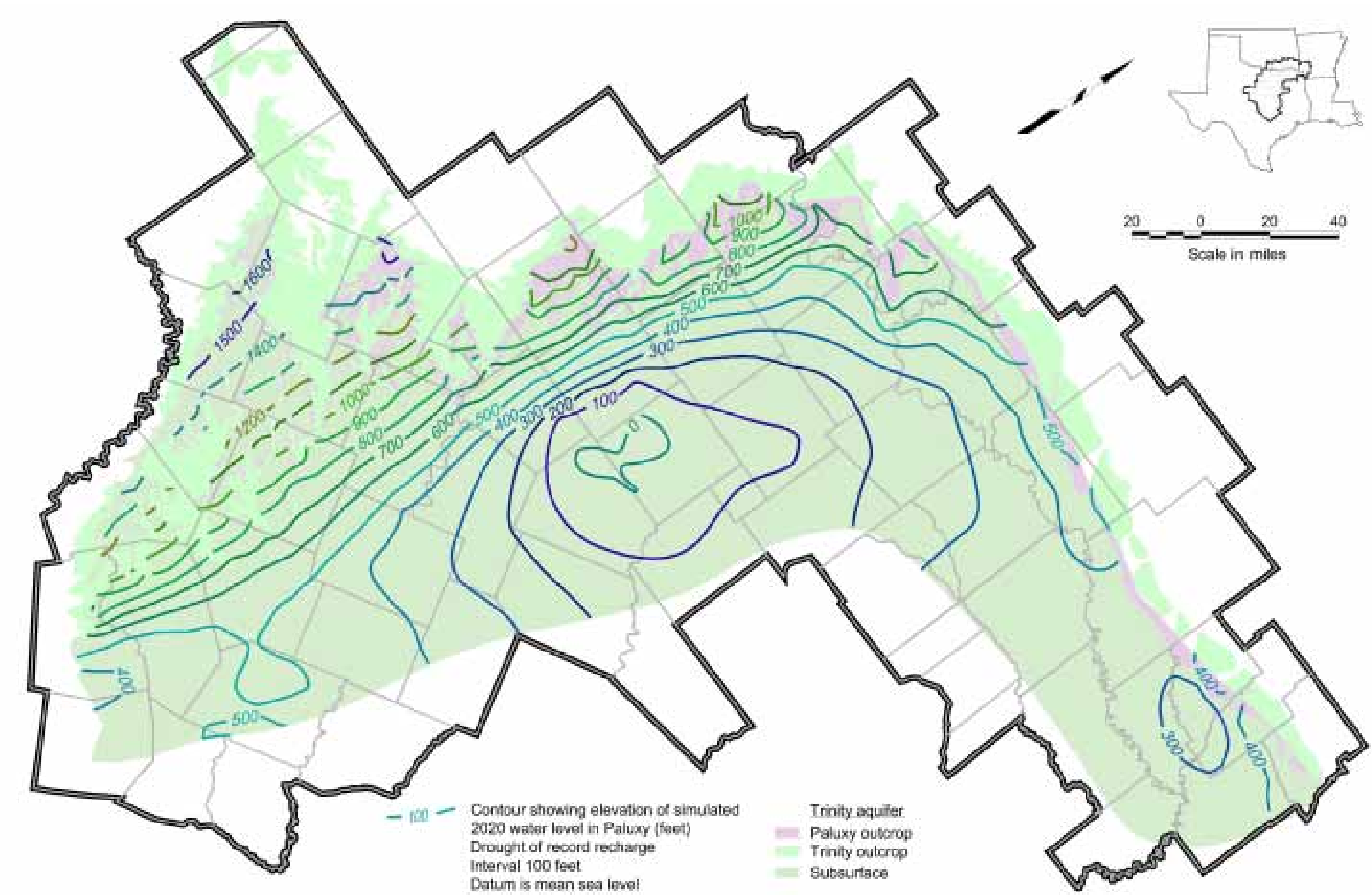



**Figure 10.29 Simulated 2020 Water Levels for Layer 3 (Paluxy) Assuming Drought of Record Recharge Distribution**

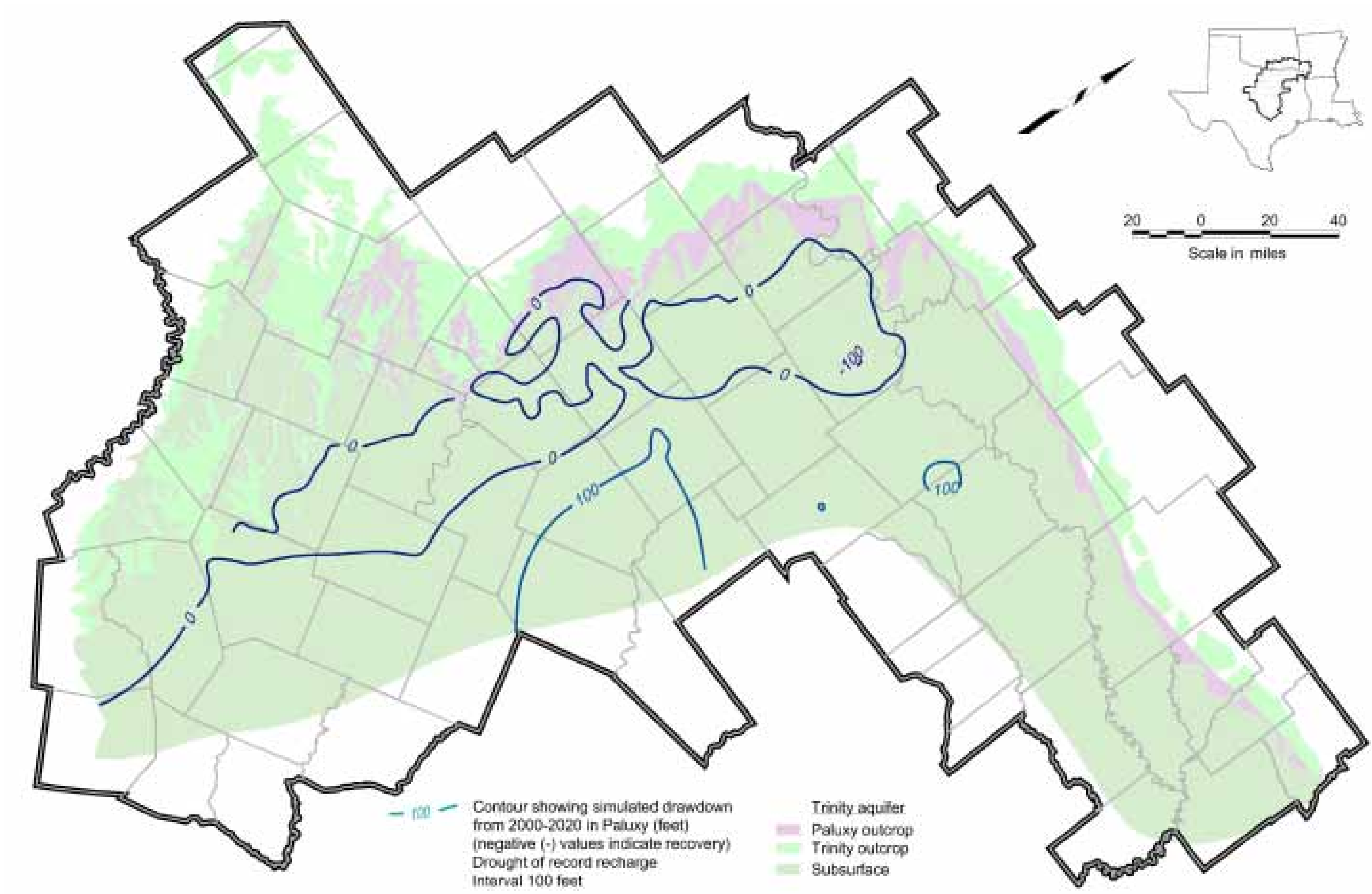



**Figure 10.30 Simulated Water Level Change From 2000 to 2020 for Layer 3 (Paluxy) Assuming Drought of Record Recharge Distribution**

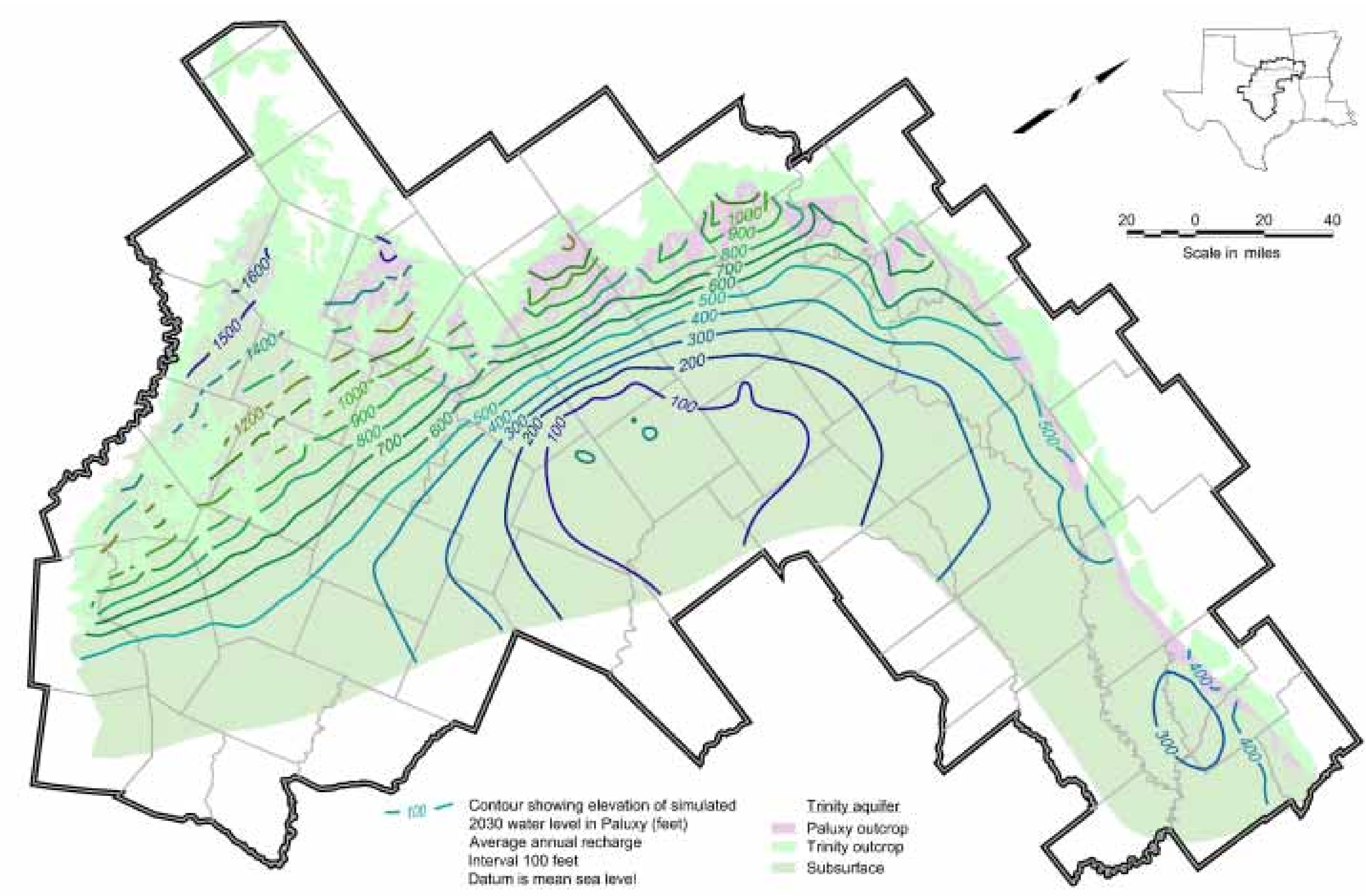



**Figure 10.31 Simulated 2030 Water Levels for Layer 3 (Paluxy) Assuming Average Annual Recharge**

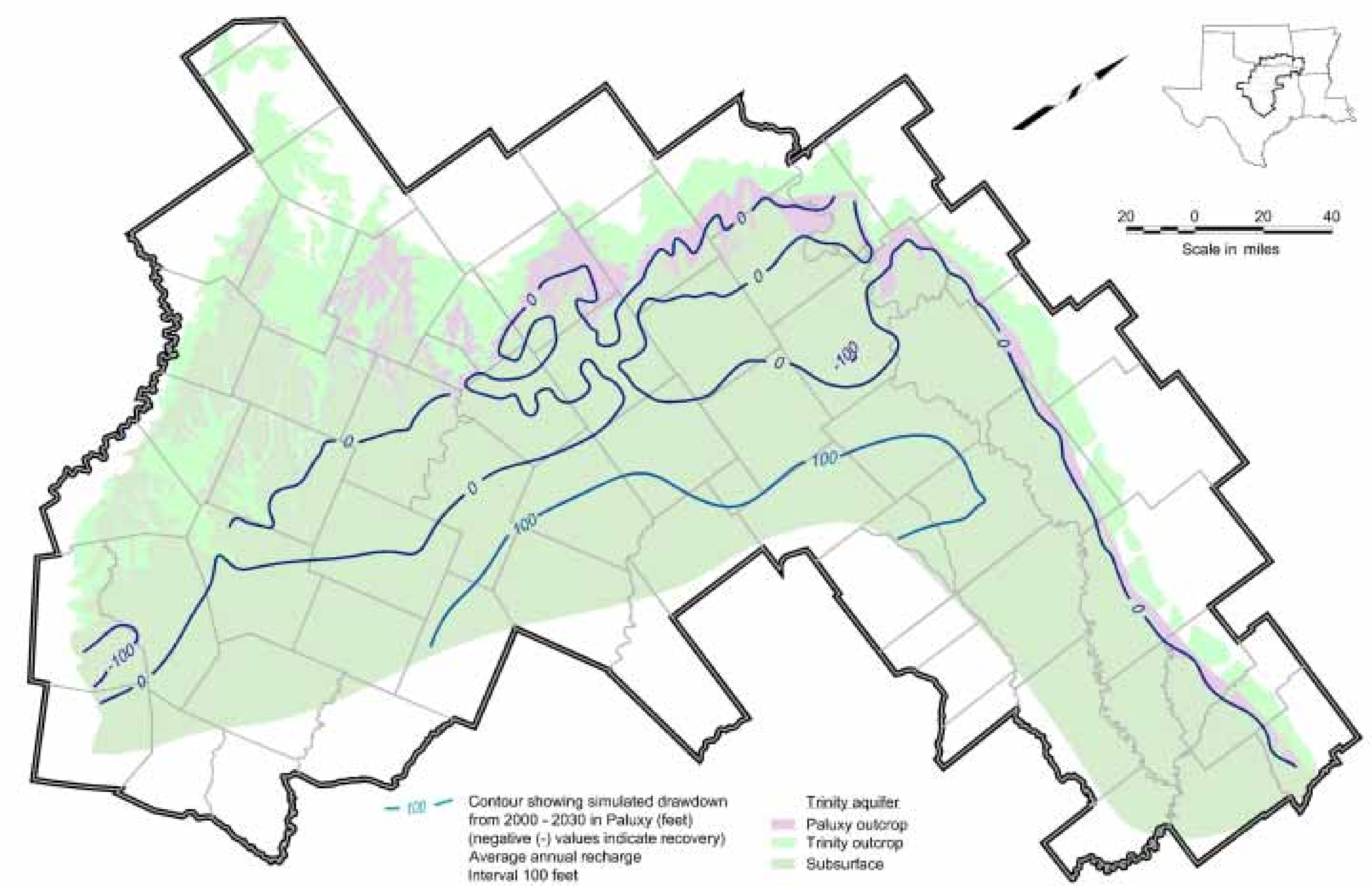



**Figure 10.32 Simulated Water Level Change From 2000 to 2030 for Layer 3 (Paluxy) Assuming Average Annual Recharge**

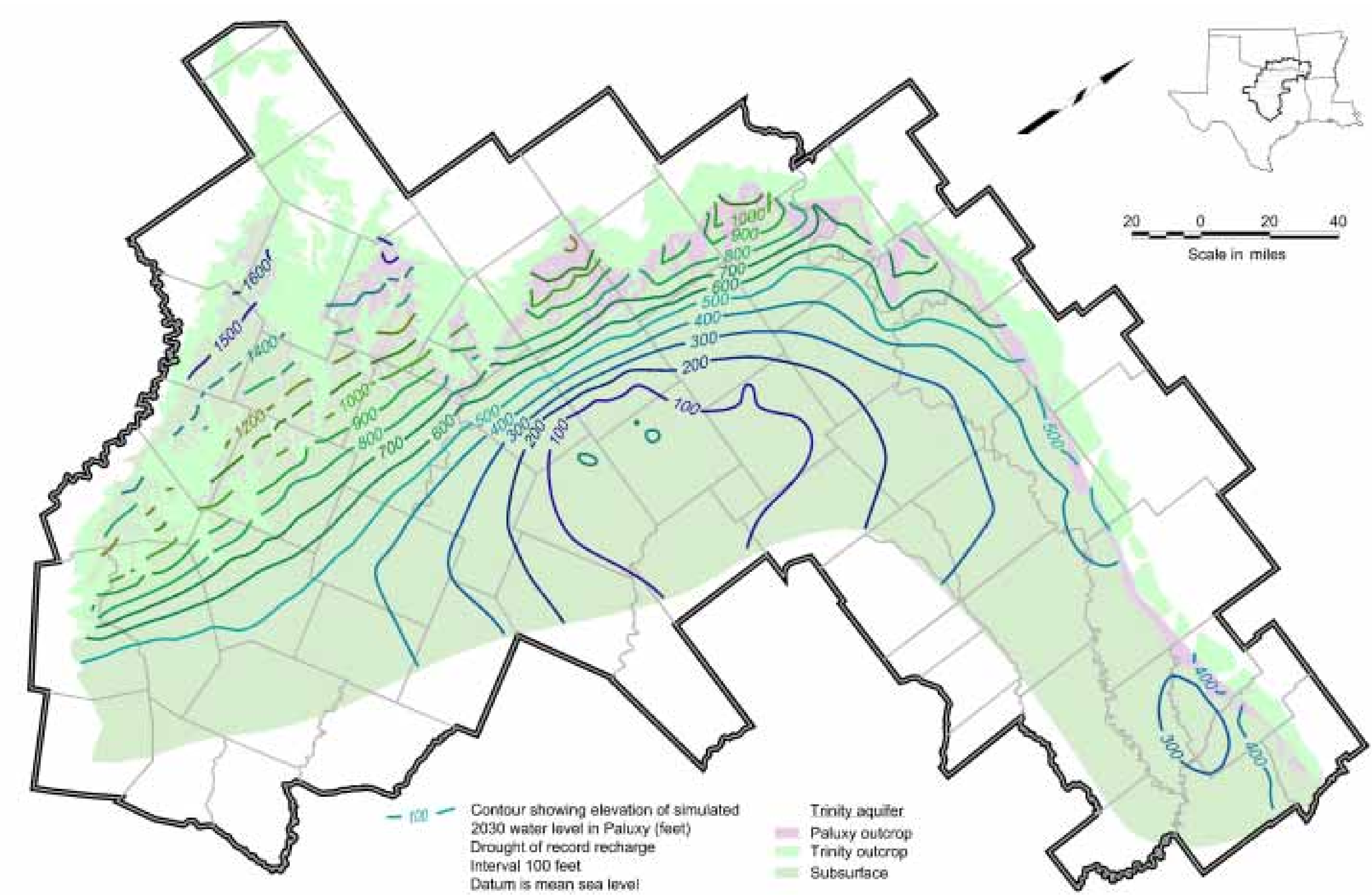



**Figure 10.33 Simulated 2030 Water Levels for Layer 3 (Paluxy) Assuming Drought of Record Recharge Distribution**

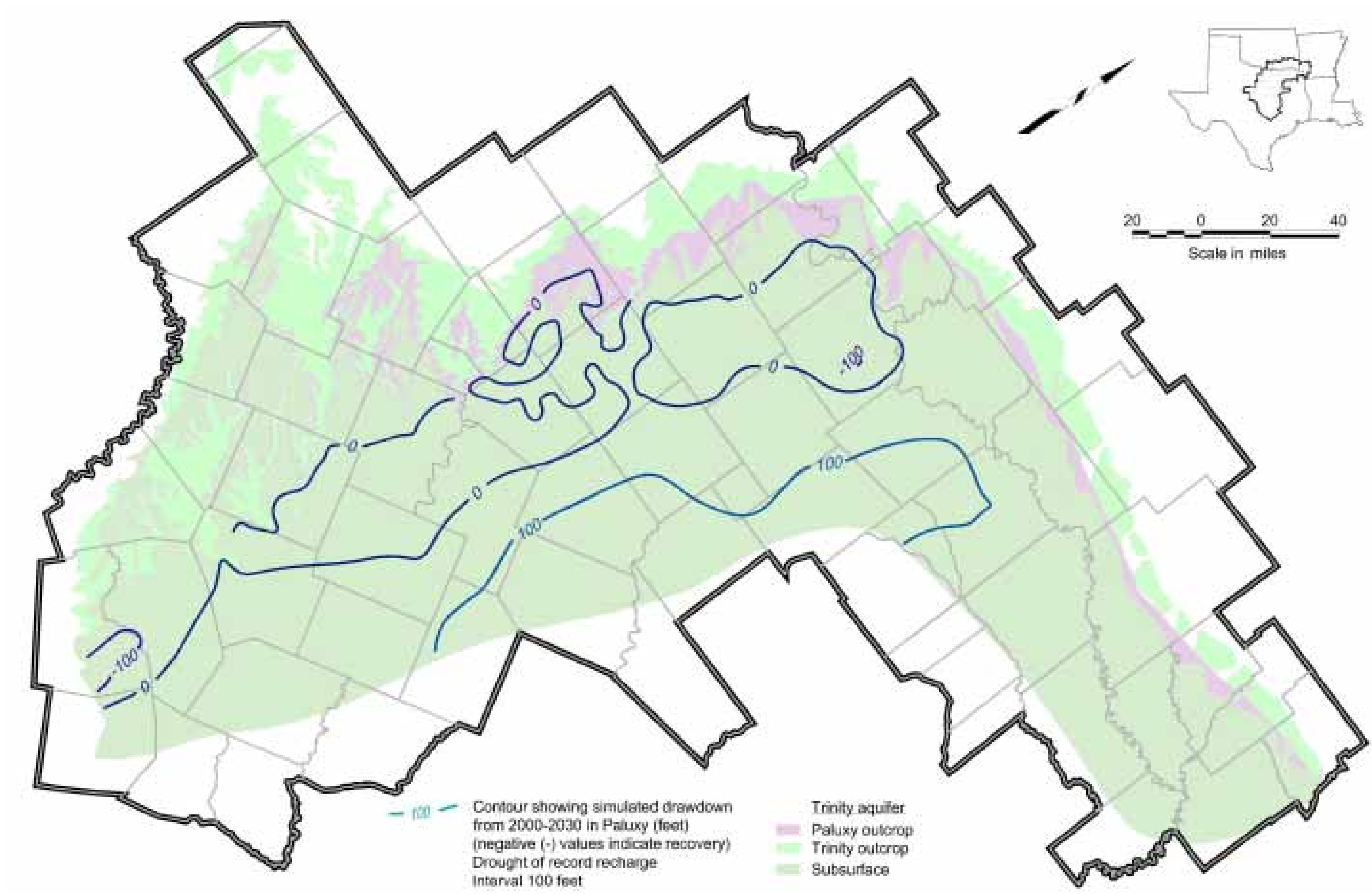



**Figure 10.34 Simulated Water Level Change From 2000 to 2030 for Layer 3 (Paluxy) Assuming Drought of Record Recharge Distribution**

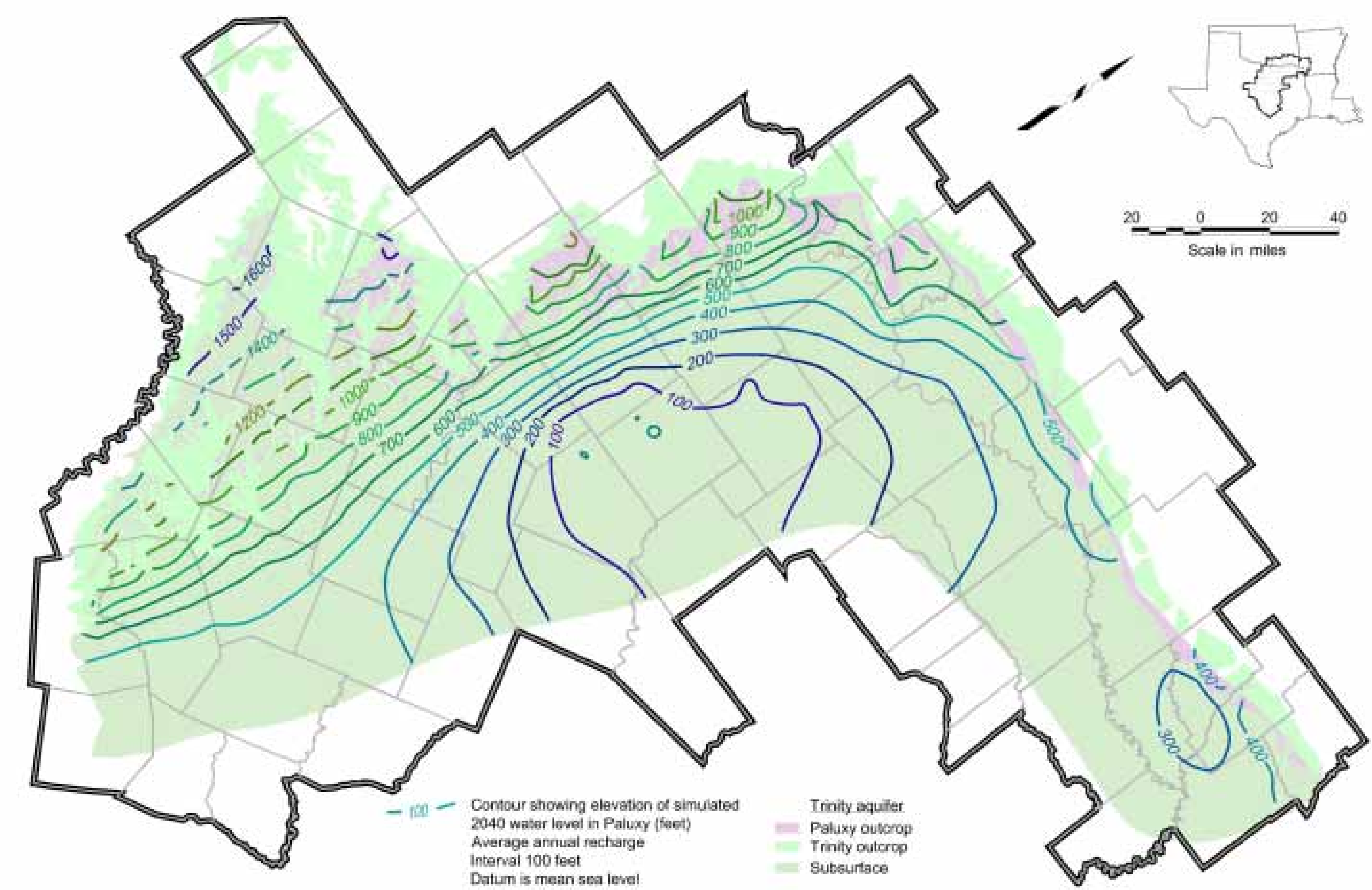



**Figure 10.35 Simulated 2040 Water Levels for Layer 3 (Paluxy) Assuming Average Annual Recharge**

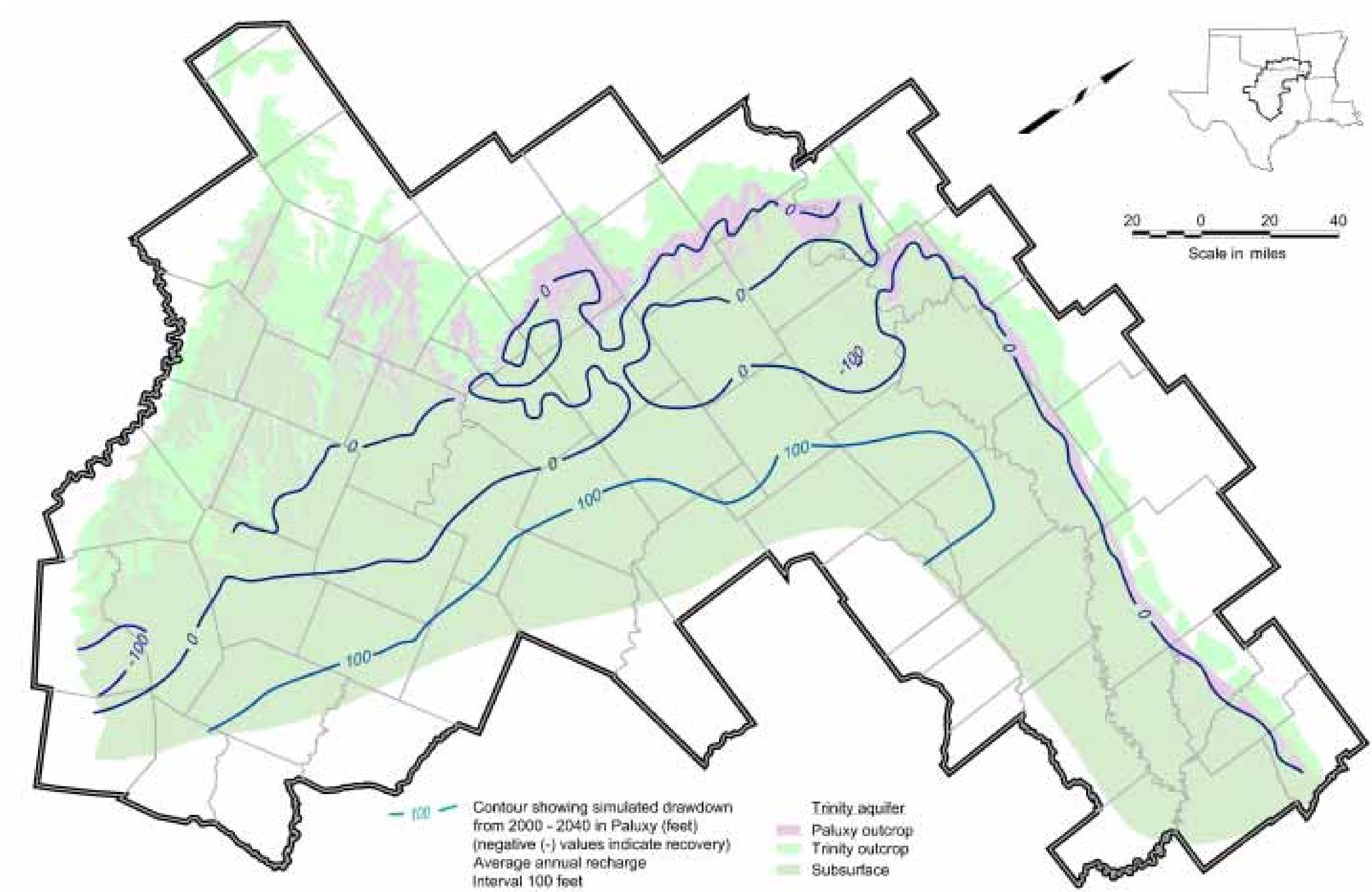



**Figure 10.36 Simulated Water Level Change From 2000 to 2040 for Layer 3 (Paluxy) Assuming Average Annual Recharge**

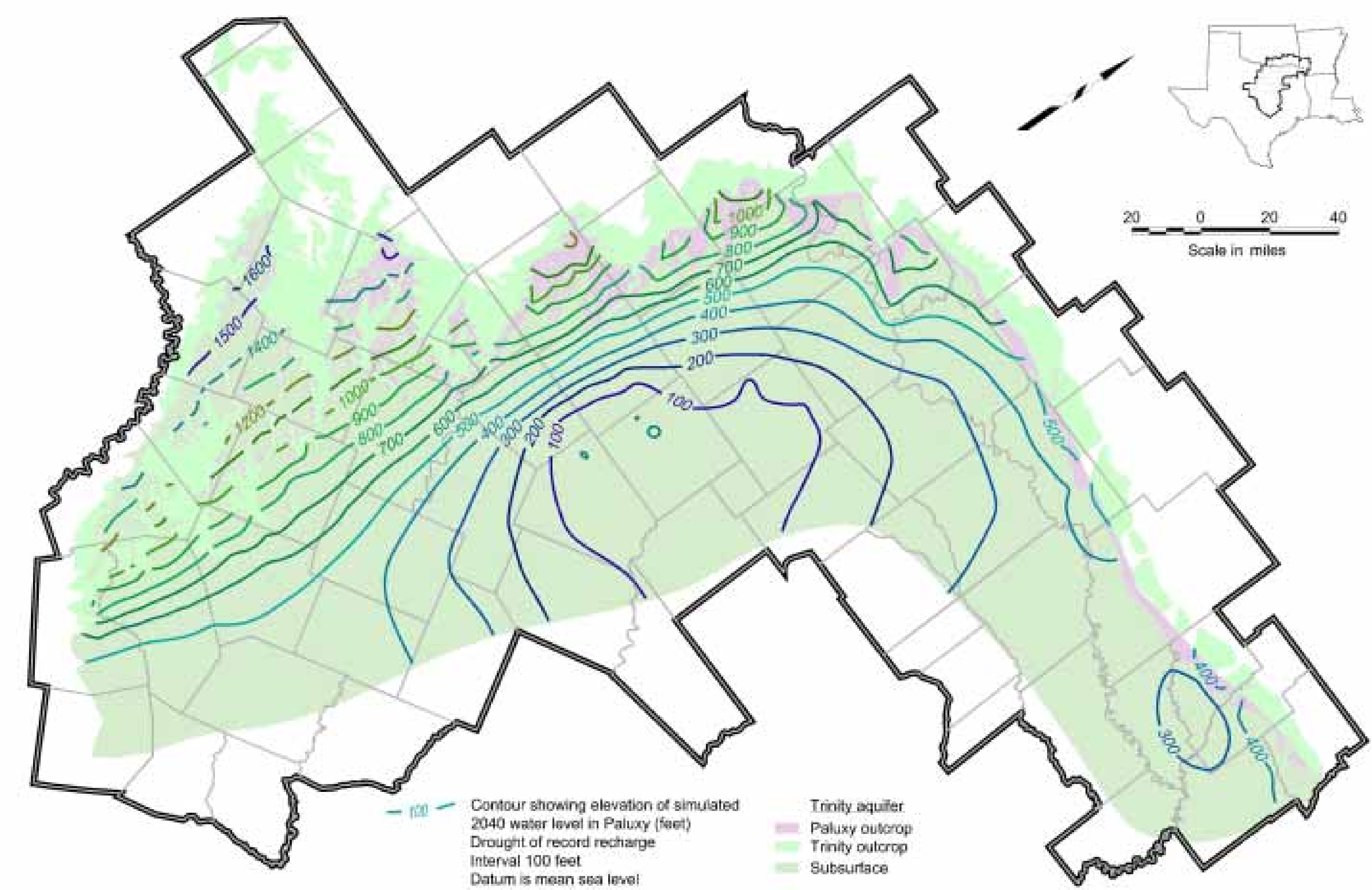



**Figure 10.37 Simulated 2040 Water Levels for Layer 3 (Paluxy) Assuming Drought of Record Recharge Distribution**

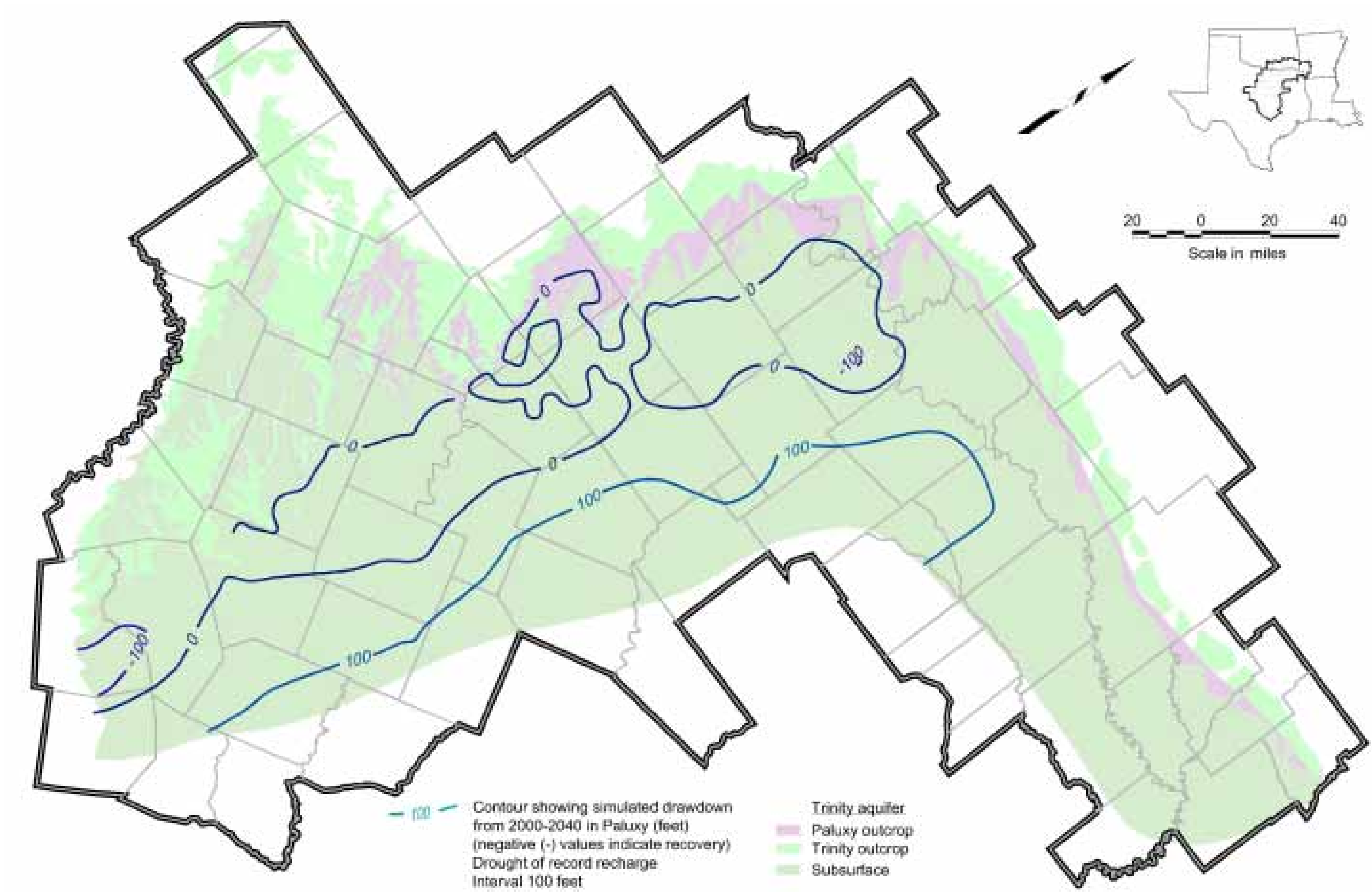



**Figure 10.38 Simulated Water Level Change From 2000 to 2040 for Layer 3 (Paluxy) Assuming Drought of Record Recharge Distribution**

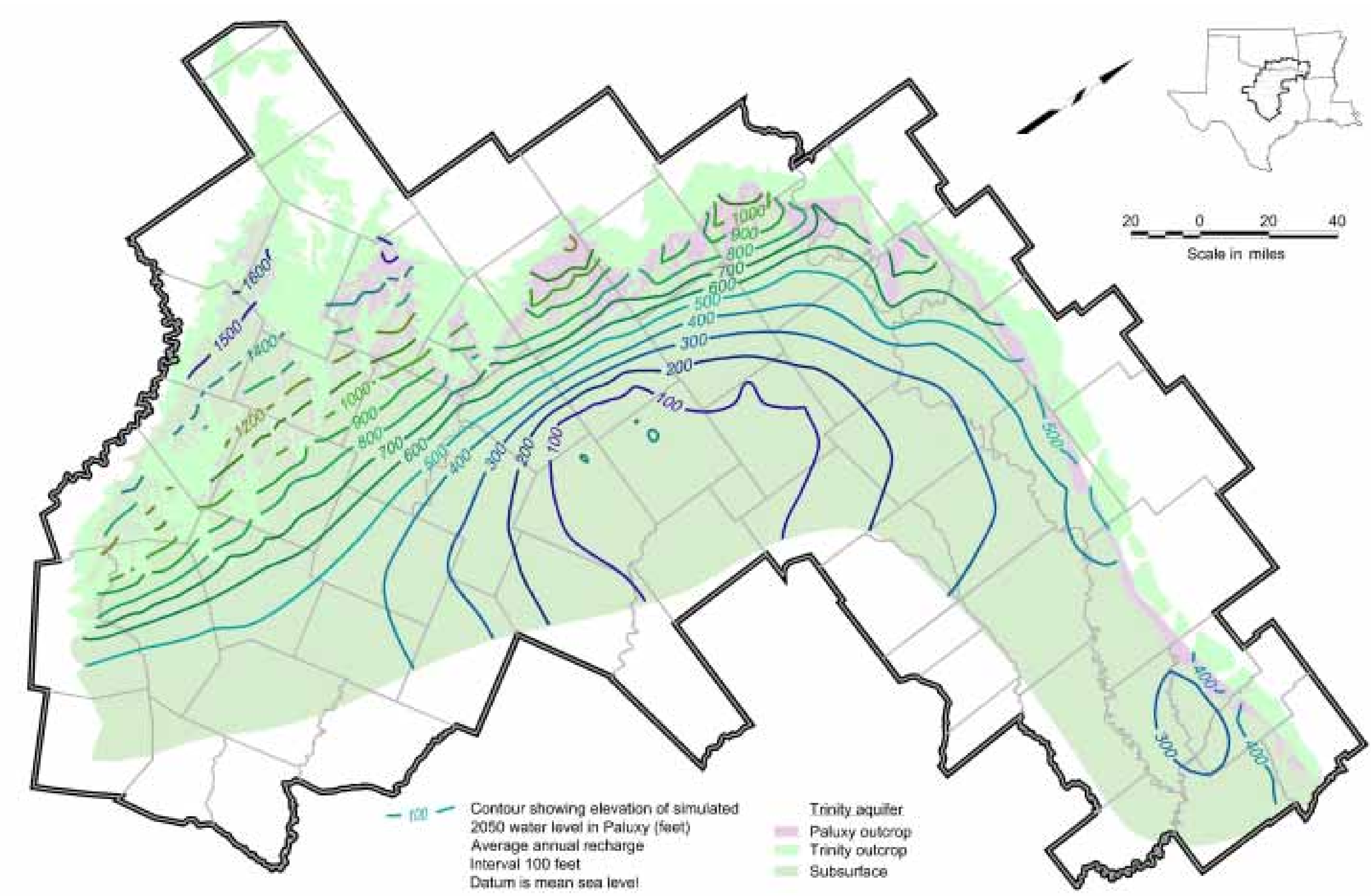



**Figure 10.39 Simulated 2050 Water Levels for Layer 3 (Paluxy) Assuming Average Annual Recharge**

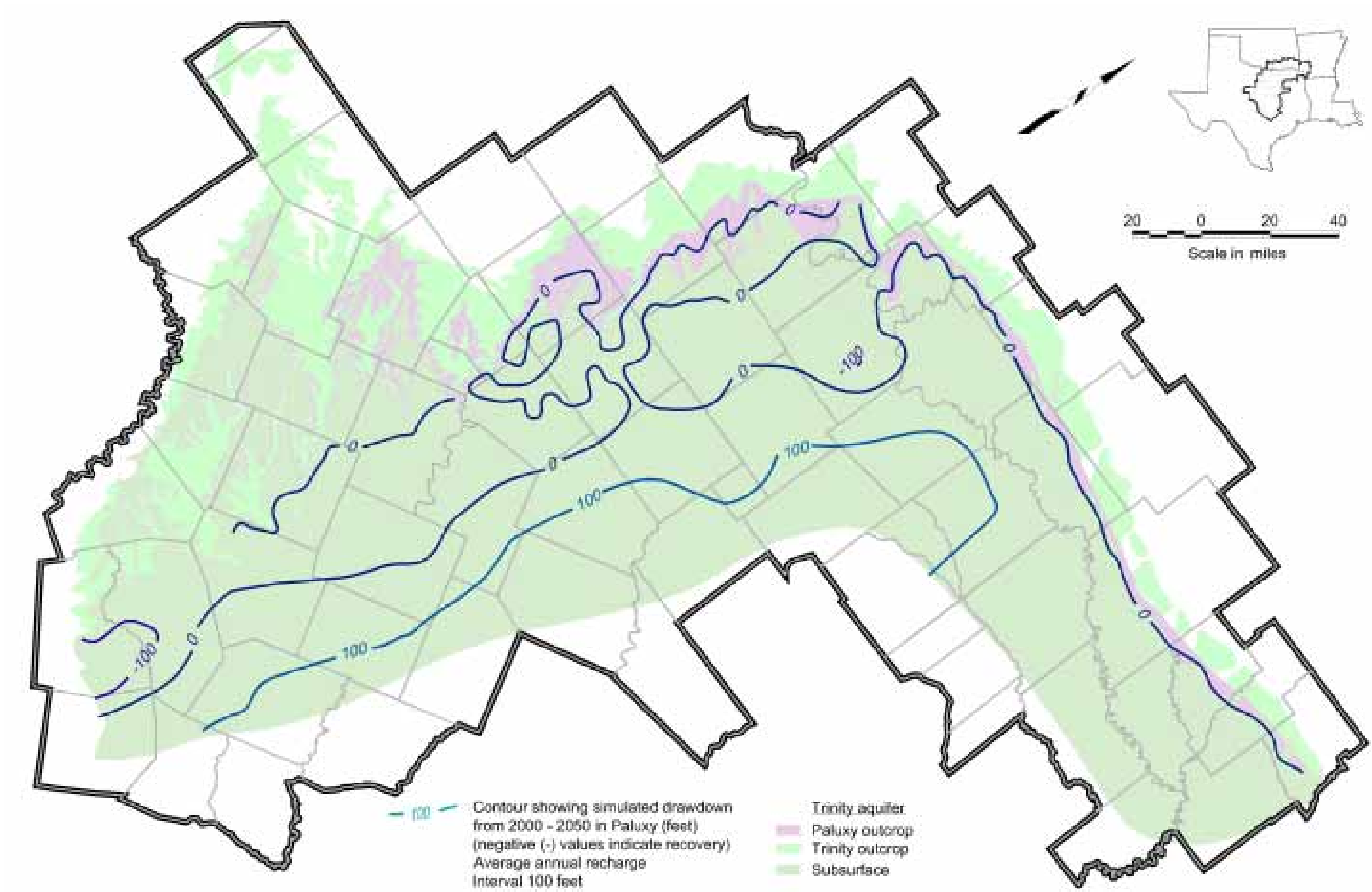



**Figure 10.40 Simulated Water Level Change From 2000 to 2050 for Layer 3 (Paluxy) Assuming Average Annual Recharge**

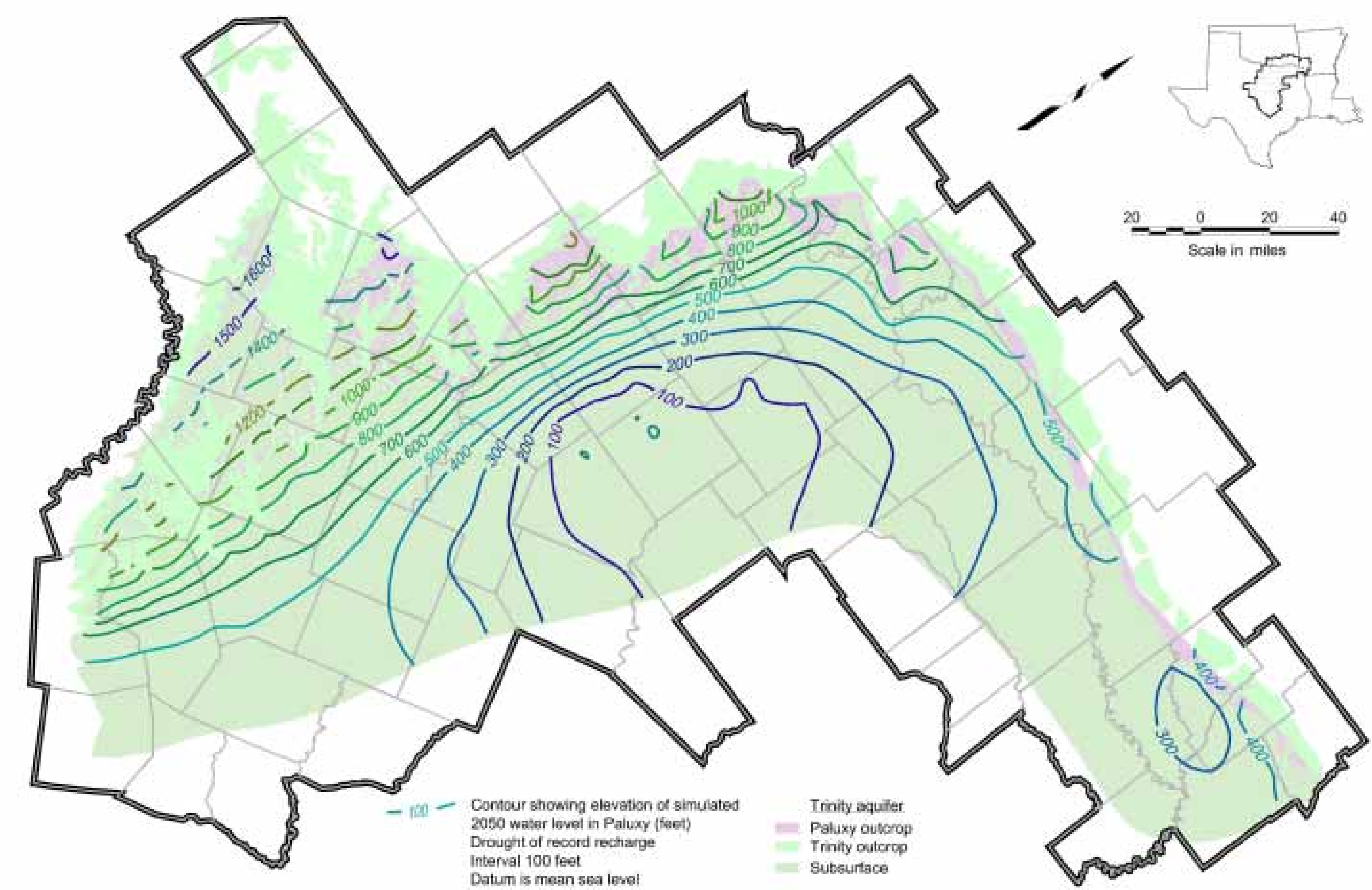



**Figure 10.41 Simulated 2050 Water Levels for Layer 3 (Paluxy) Assuming Drought of Record Recharge Distribution**

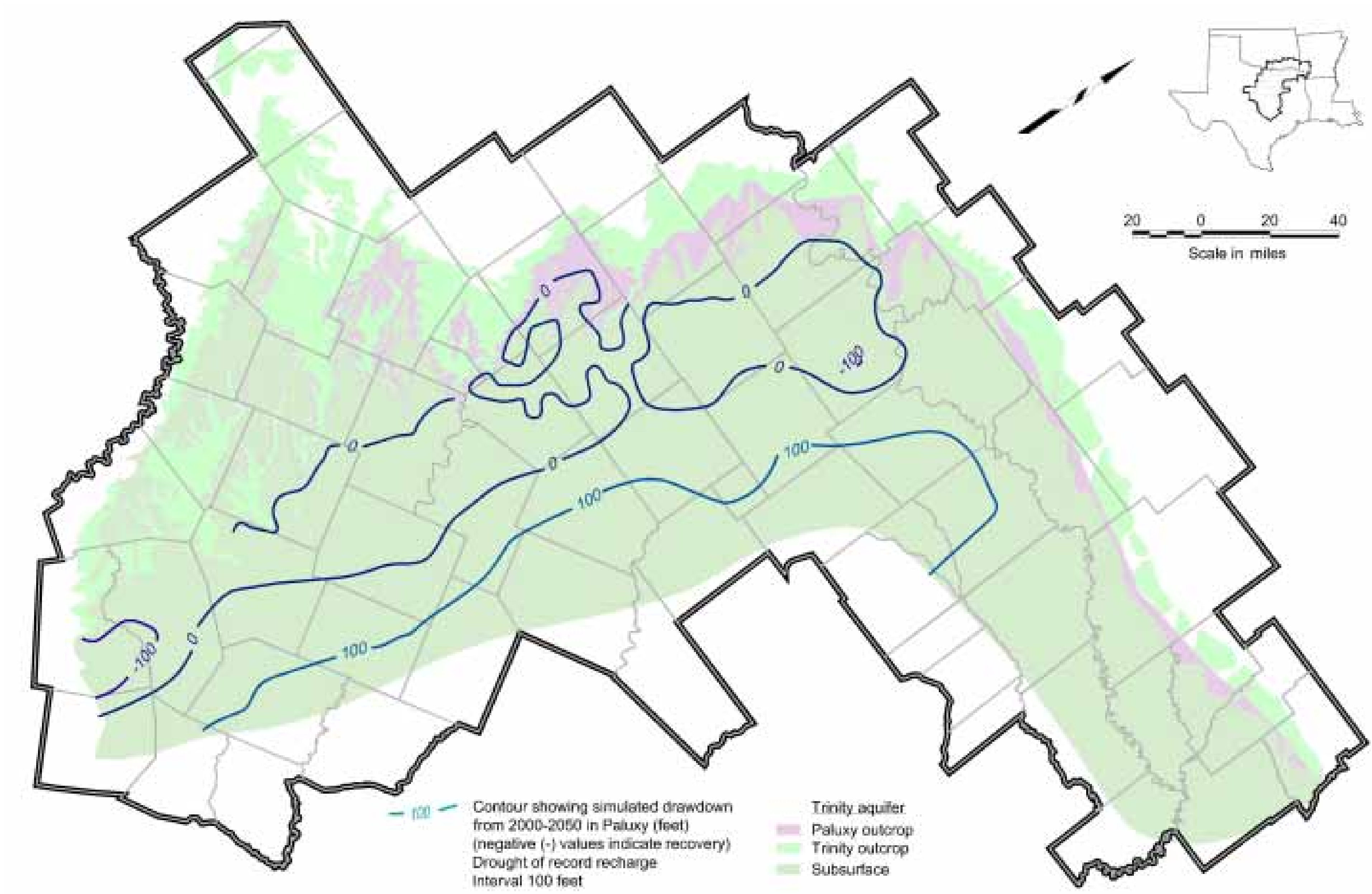



**Figure 10.42 Simulated Water Level Change From 2000 to 2050 for Layer 3 (Paluxy) Assuming Drought of Record Recharge Distribution**

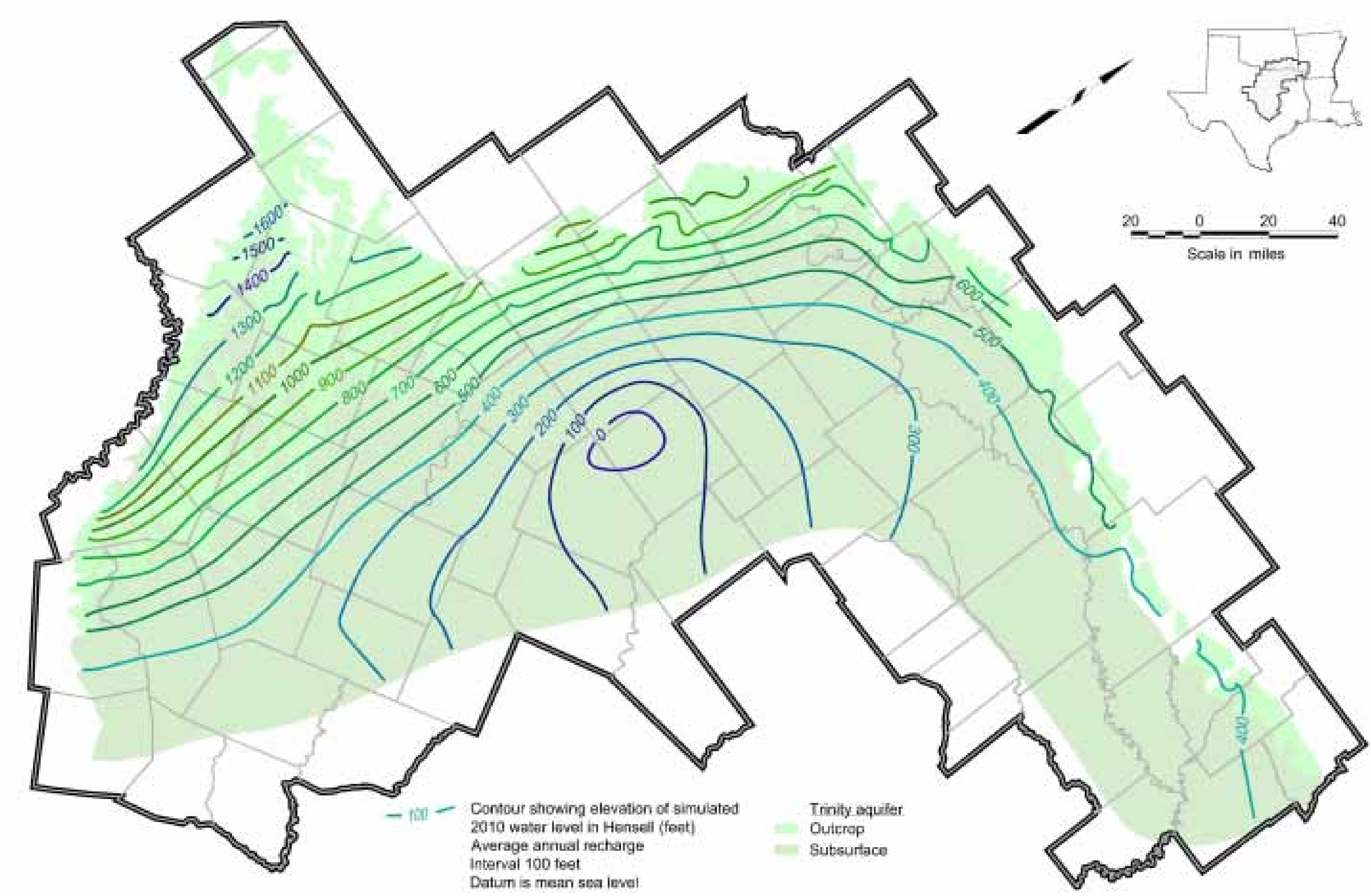



**Figure 10.43 Simulated 2010 Water Levels for Layer 5 (Hensell) Assuming Average Annual Recharge**

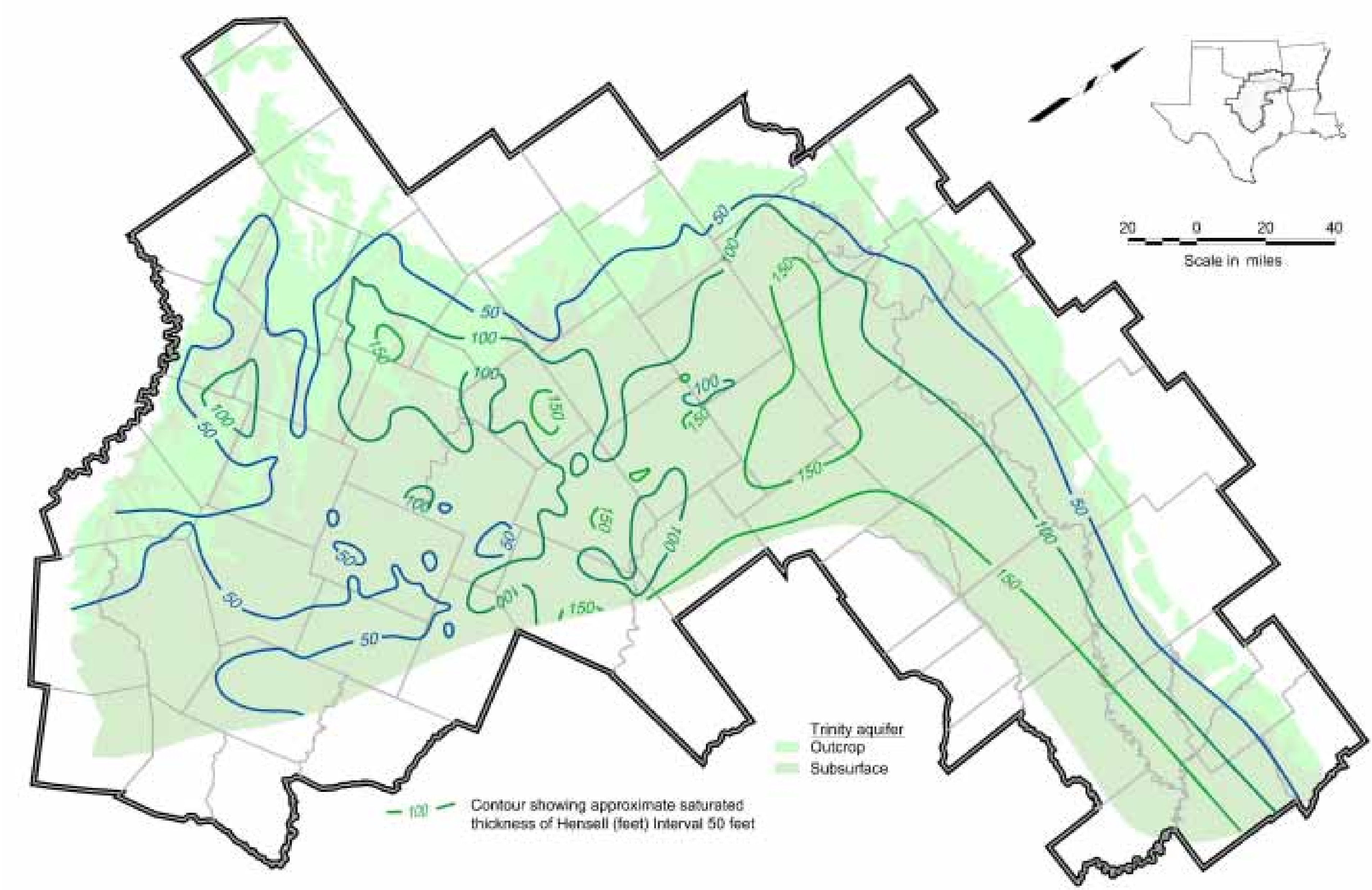



**Figure 10.44 Simulated 2010 Saturated Thickness for Layer 5 (Hensell) Assuming Average Annual Recharge**

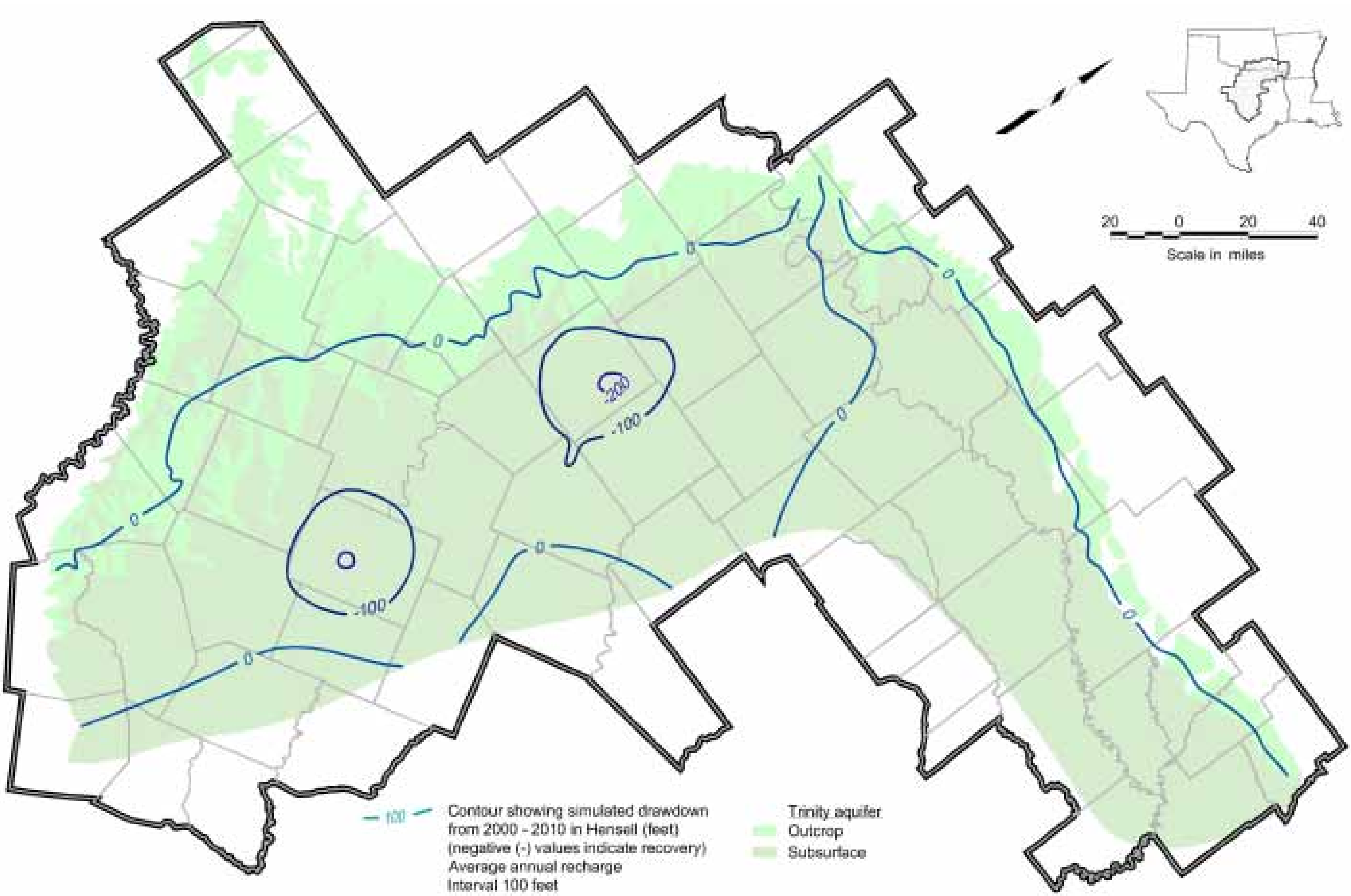



**Figure 10.45 Simulated Water Level Change From 2000 to 2010 for Layer 5 (Hensell) Assuming Average Annual Recharge**

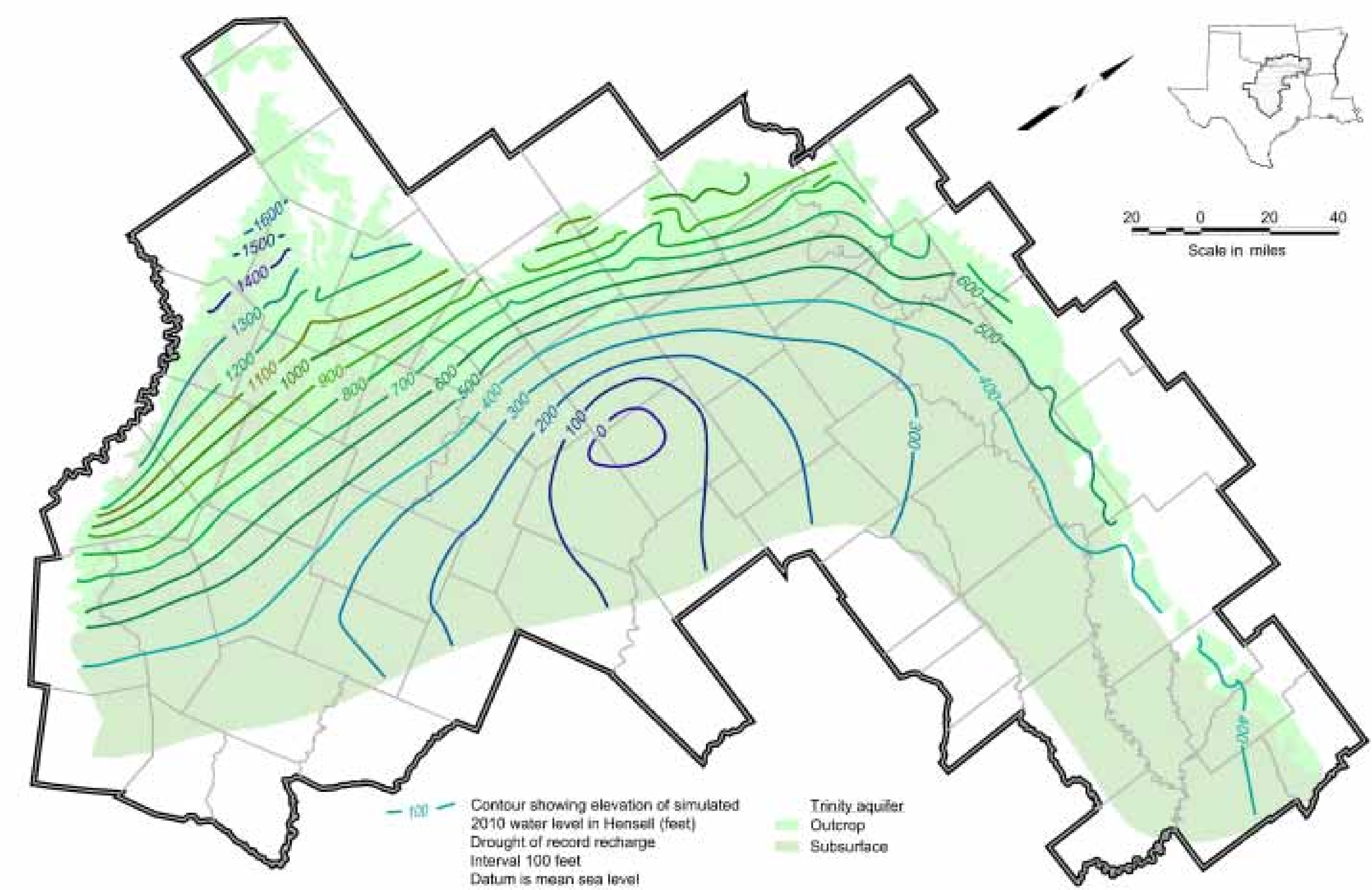



**Figure 10.46 Simulated 2010 Water Levels for Layer 5 (Hensell) Assuming Drought of Record Recharge Distribution**

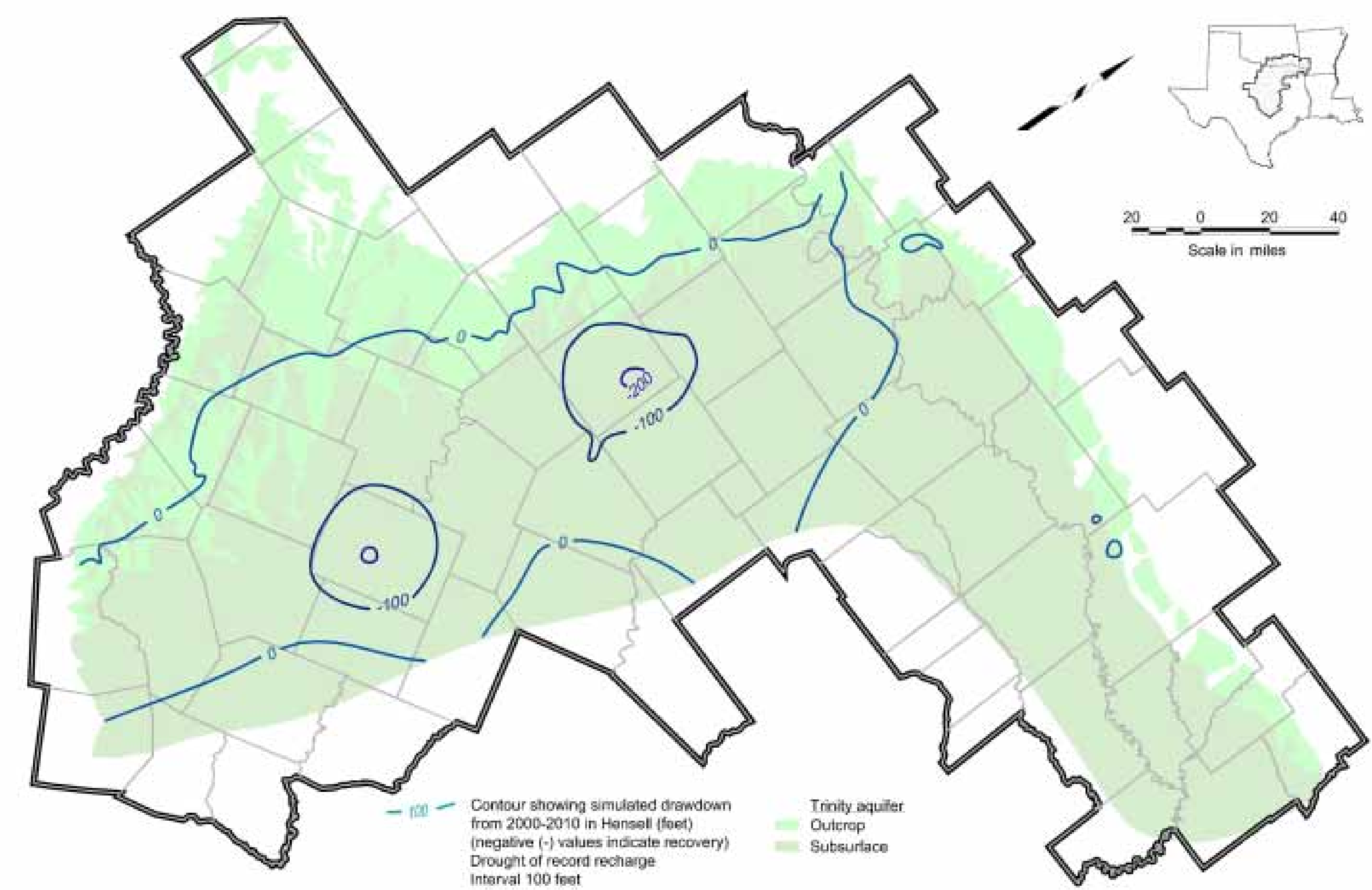



**Figure 10.47 Simulated Water Level Change From 2000 to 2010 for Layer 5 (Hensell) Assuming Drought of Record Recharge Distribution**

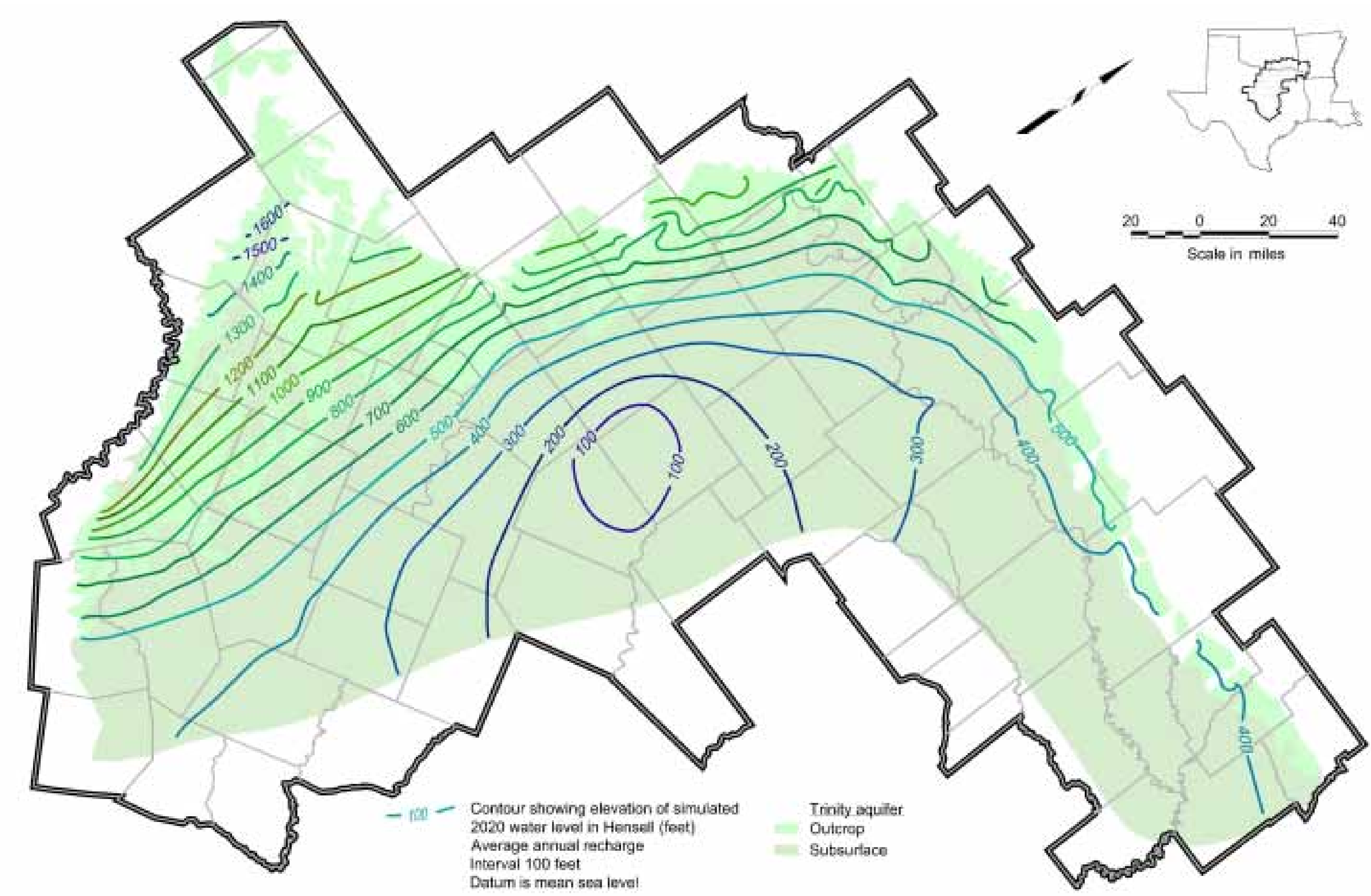



**Figure 10.48 Simulated 2020 Water Levels for Layer 5 (Hensell) Assuming Average Annual Recharge**

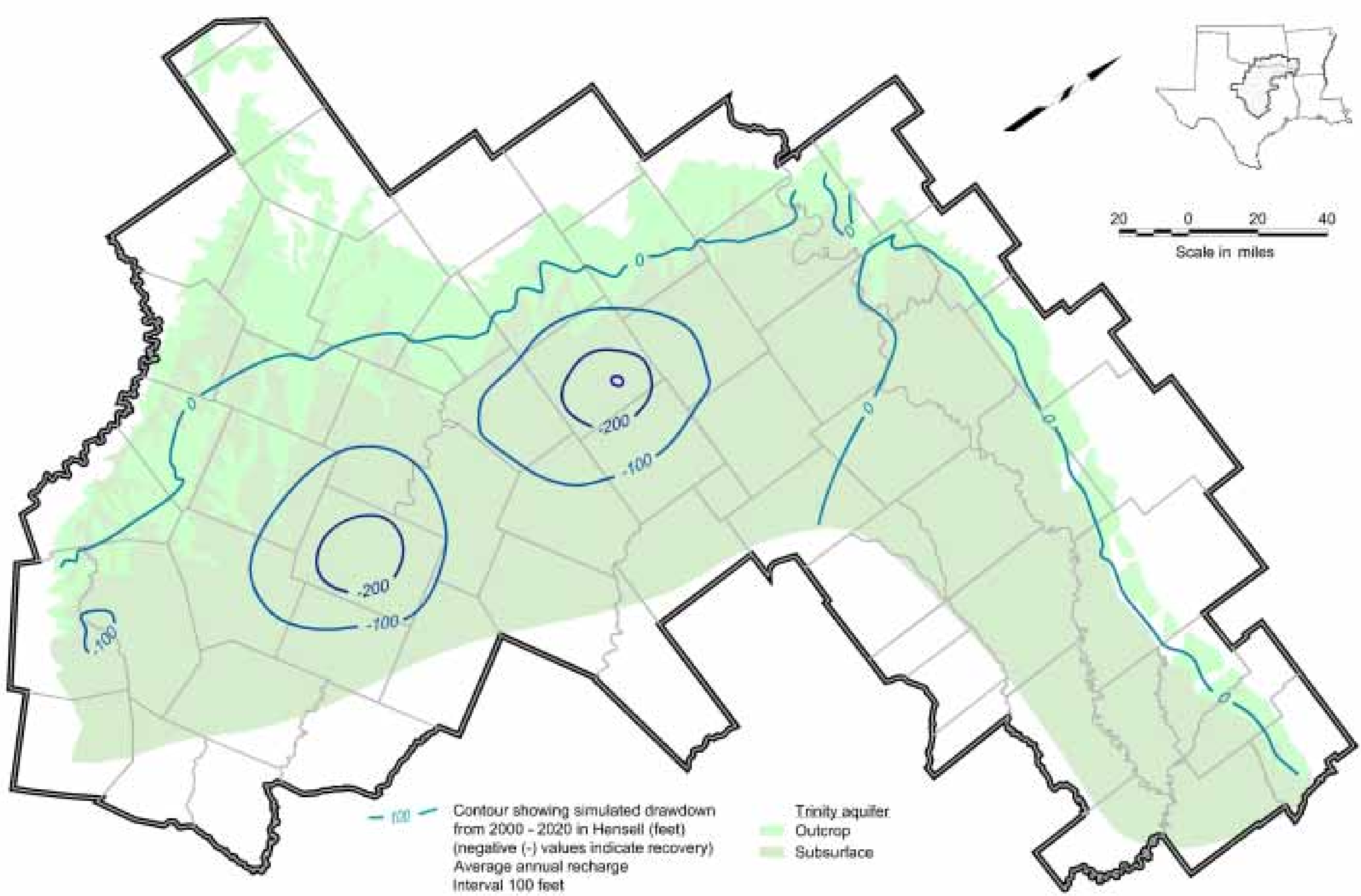



**Figure 10.49 Simulated Water Level Change From 2000 to 2020 for Layer 5 (Hensell) Assuming Average Annual Recharge**

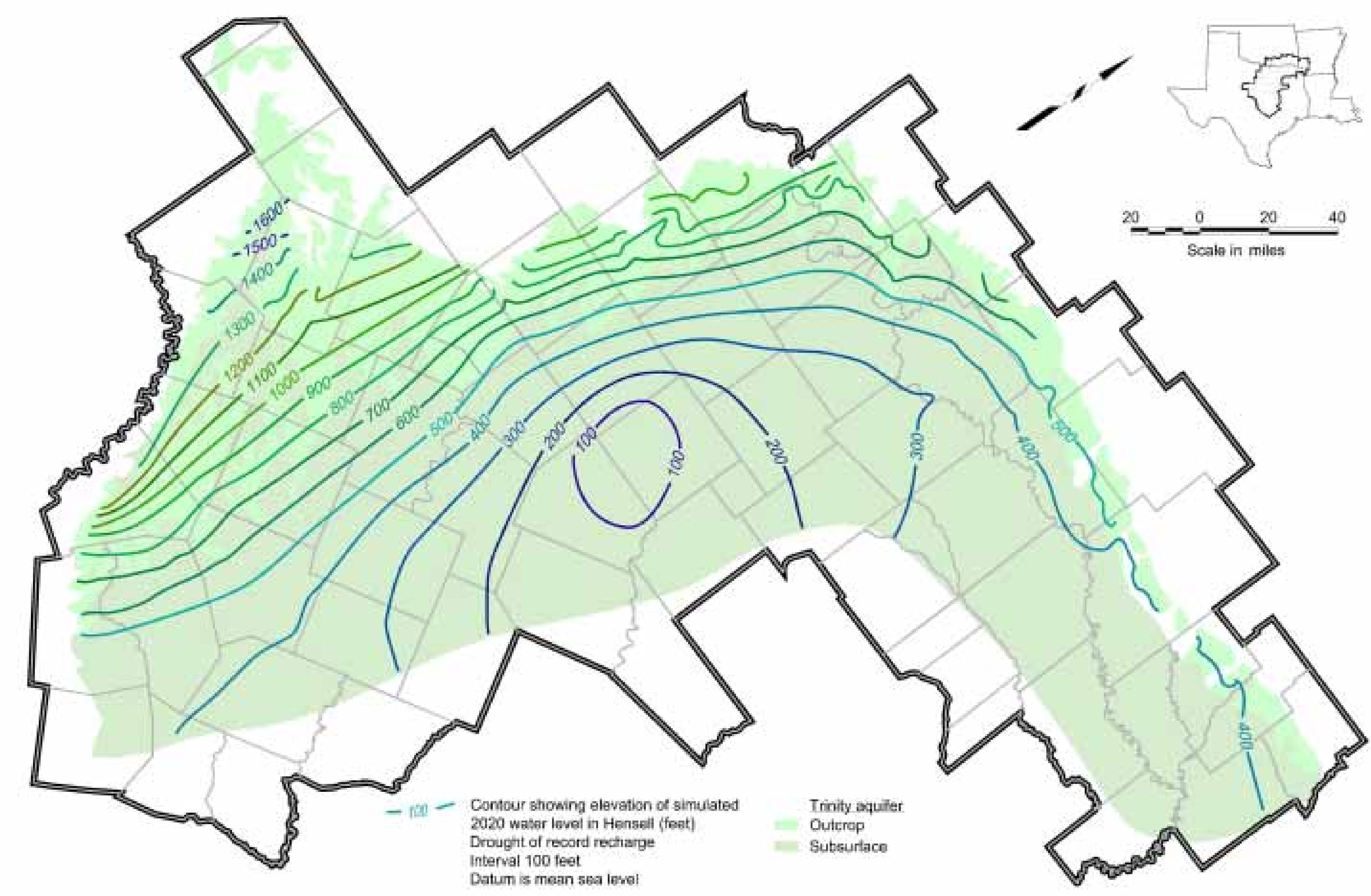



**Figure 10.50 Simulated 2020 Water Levels for Layer 5 (Hensell) Assuming Drought of Record Recharge Distribution**

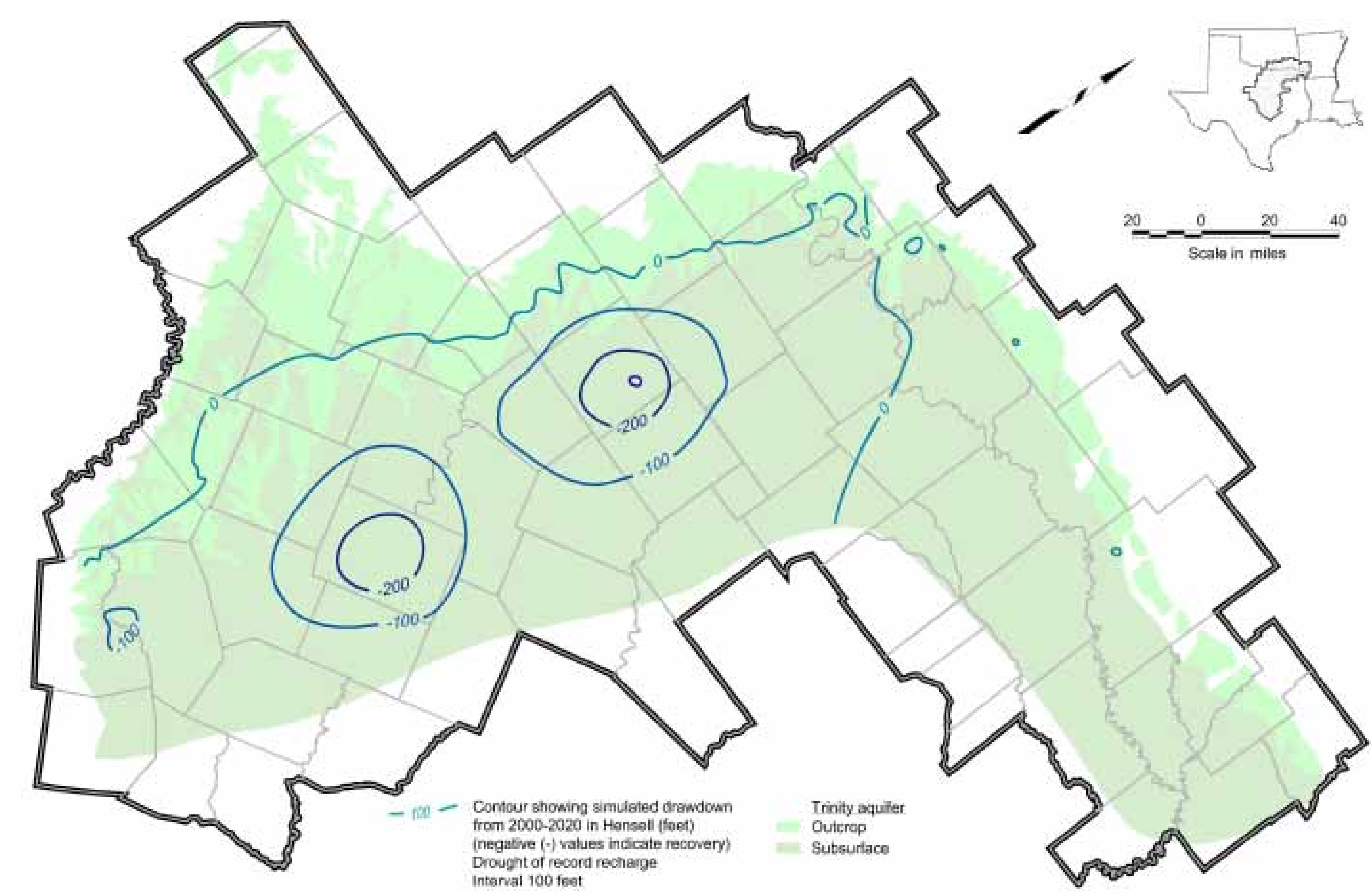



**Figure 10.51 Simulated Water Level Change From 2000 to 2020 for Layer 5 (Hensell) Assuming Drought of Record Recharge Distribution**

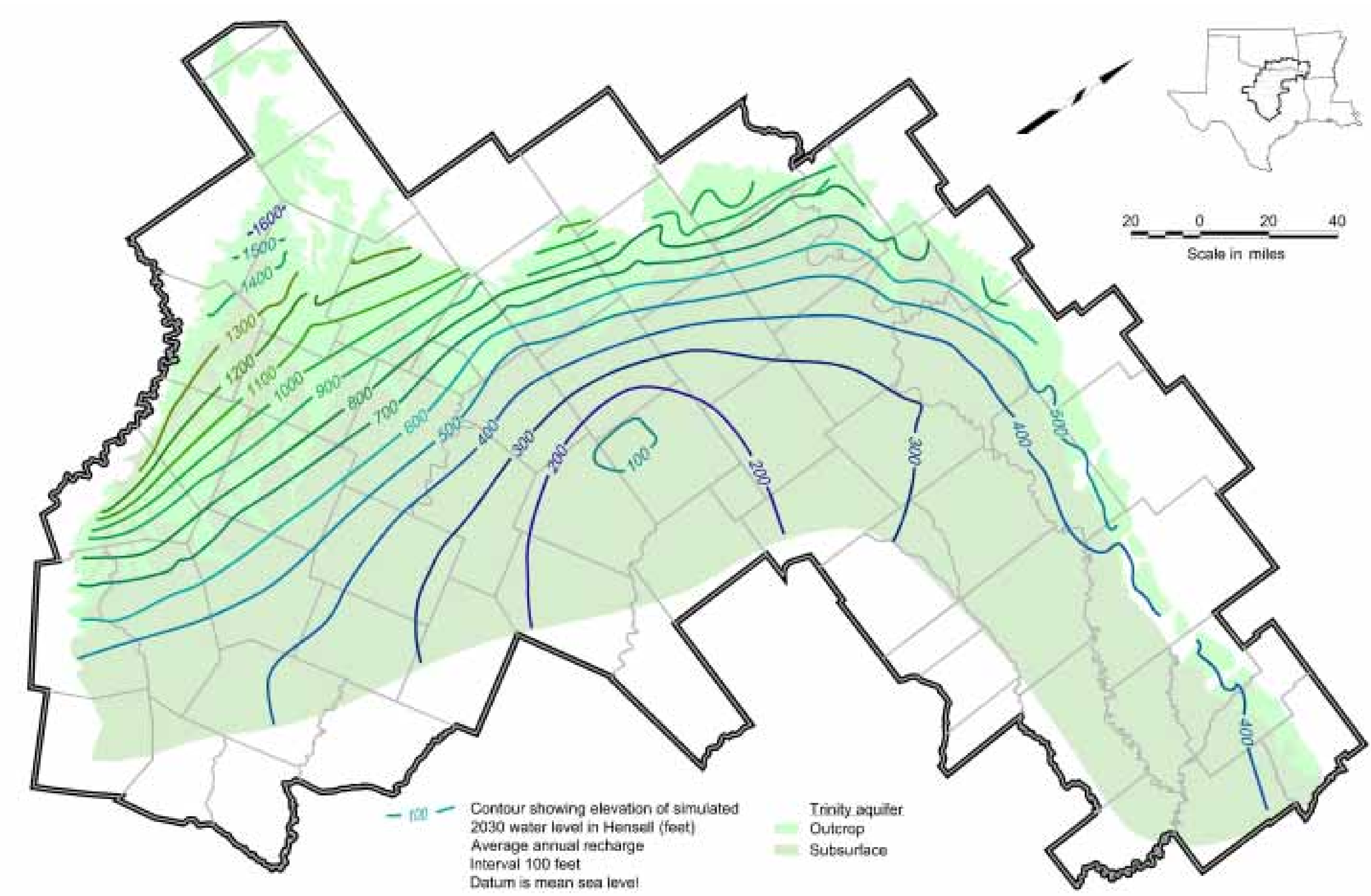



**Figure 10.52 Simulated 2030 Water Levels for Layer 5 (Hensell) Assuming Average Annual Recharge**

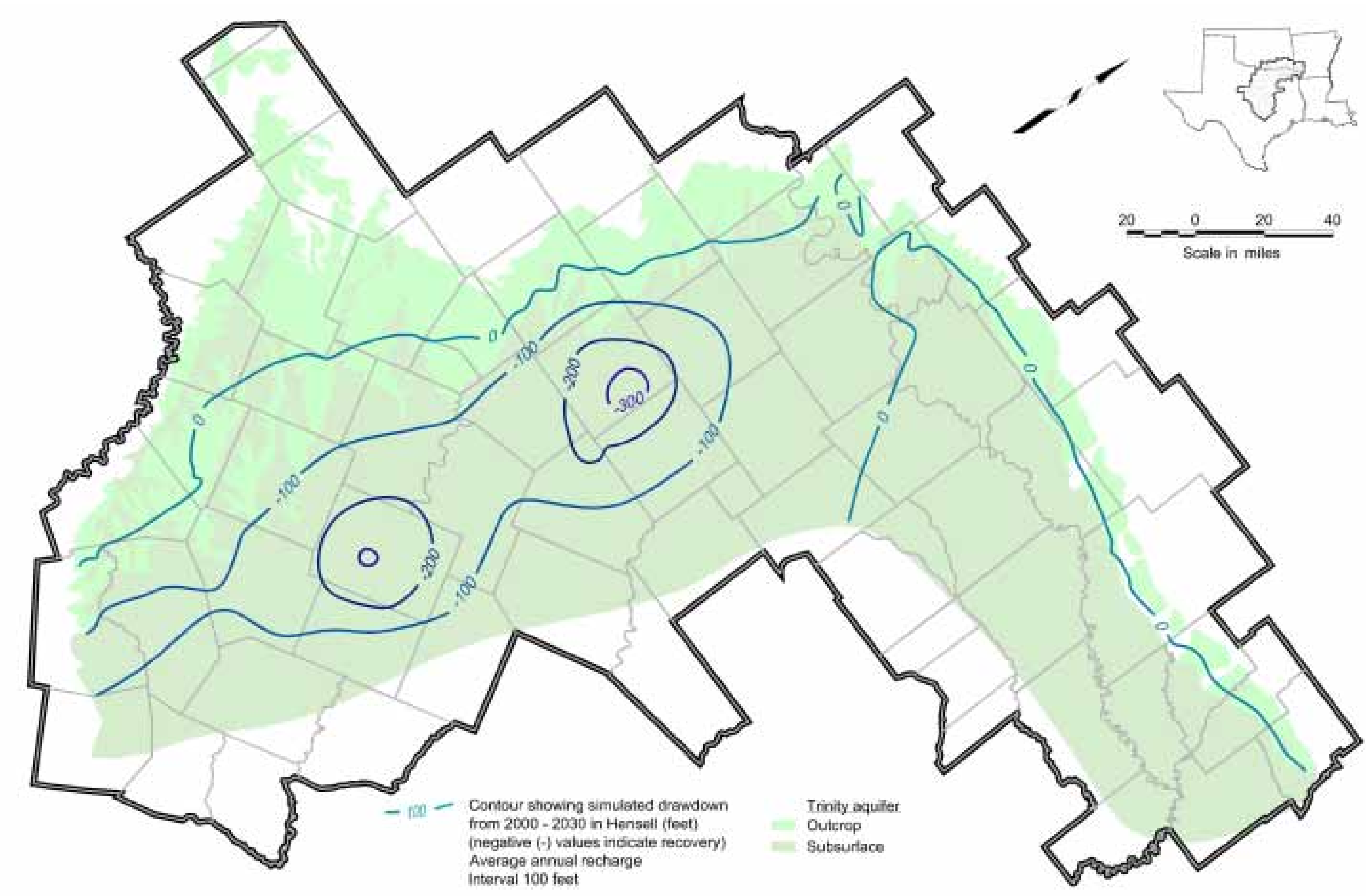



**Figure 10.53 Simulated Water Level Change From 2000 to 2030 for Layer 5 (Hensell) Assuming Average Annual Recharge**

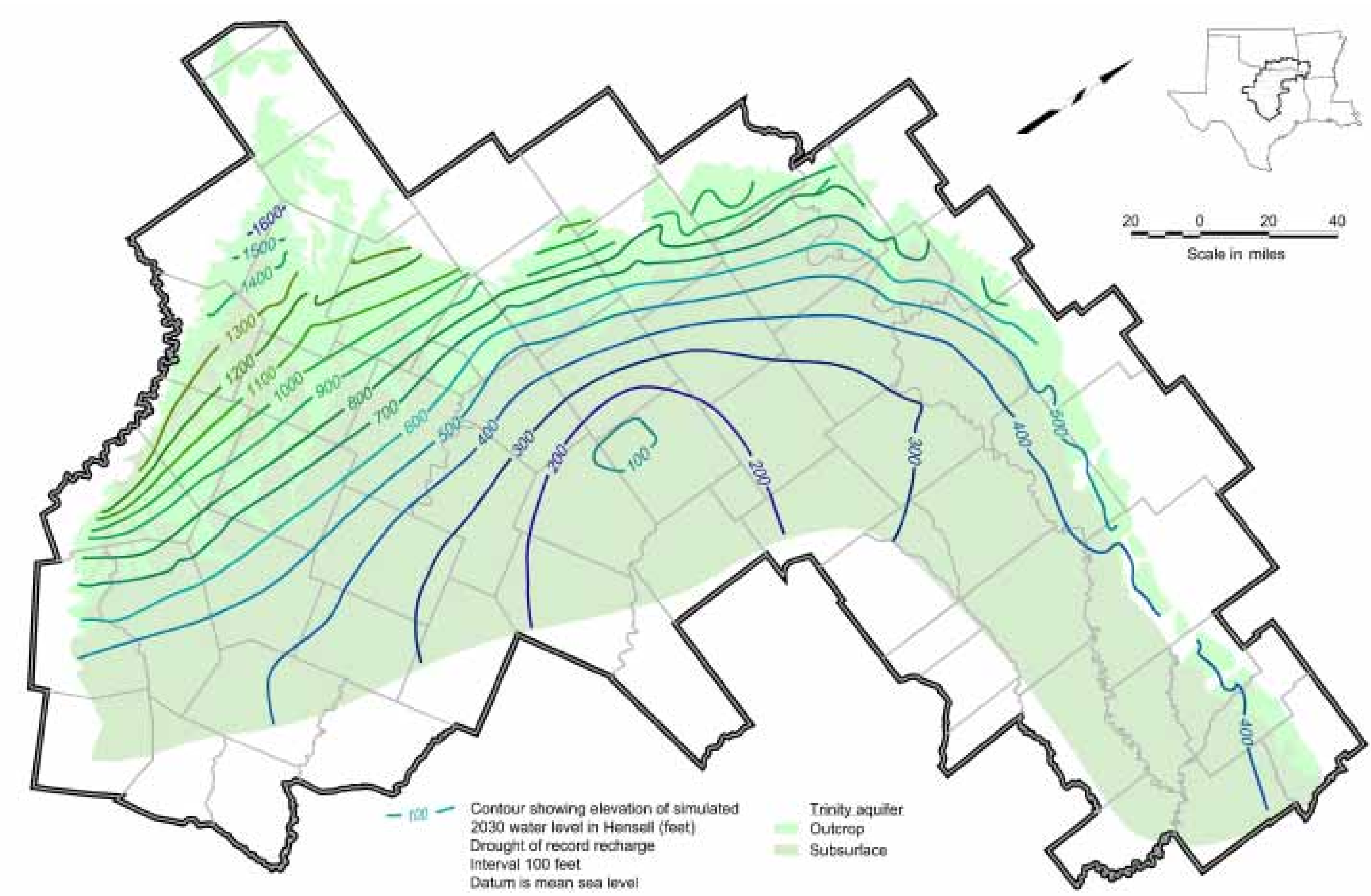



**Figure 10.54 Simulated 2030 Water Levels for Layer 5 (Hensell) Assuming Drought of Record Recharge Distribution**

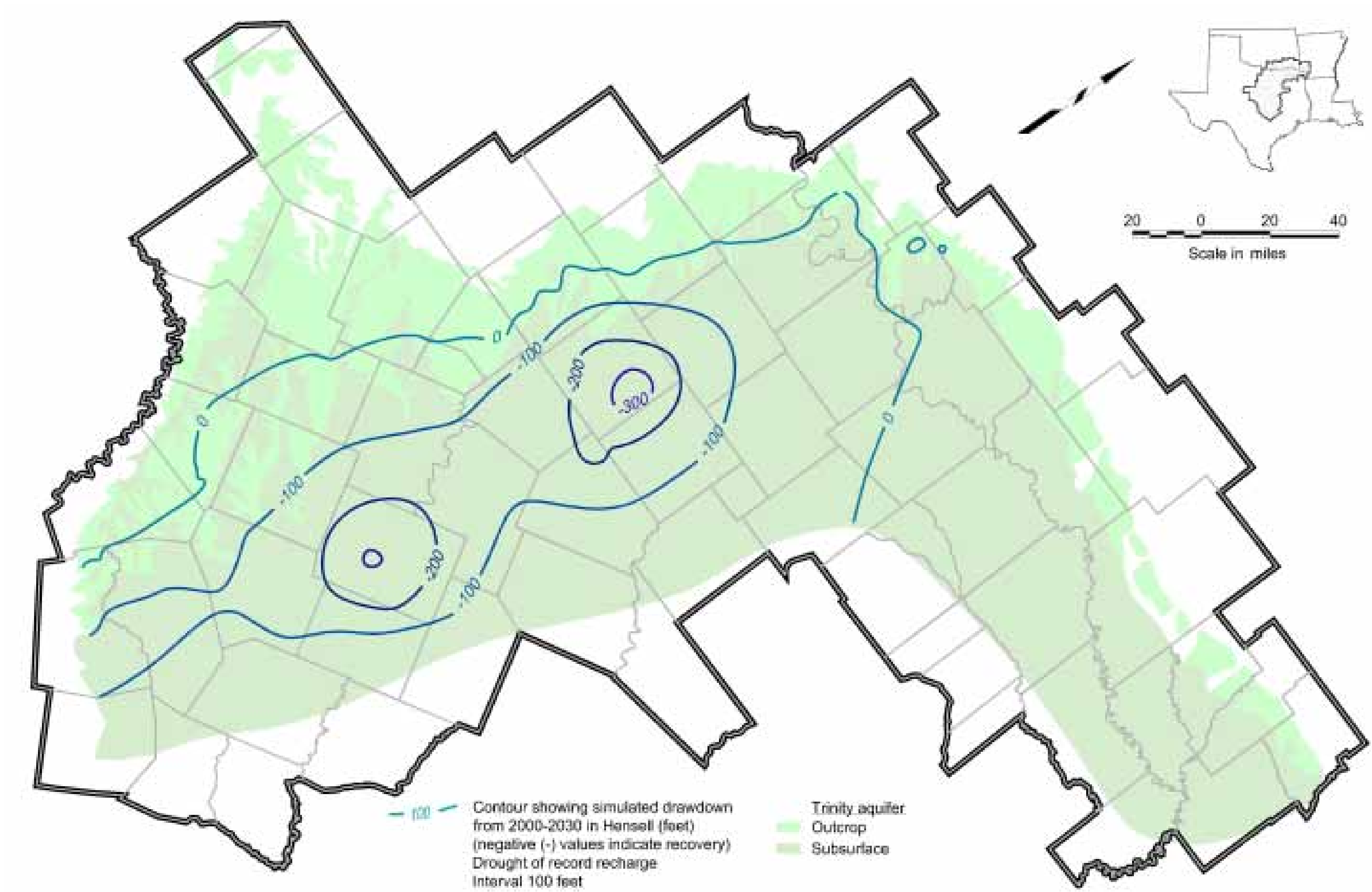



**Figure 10.55 Simulated Water Level Change From 2000 to 2030 for Layer 5 (Hensell) Assuming Drought of Record Recharge Distribution**

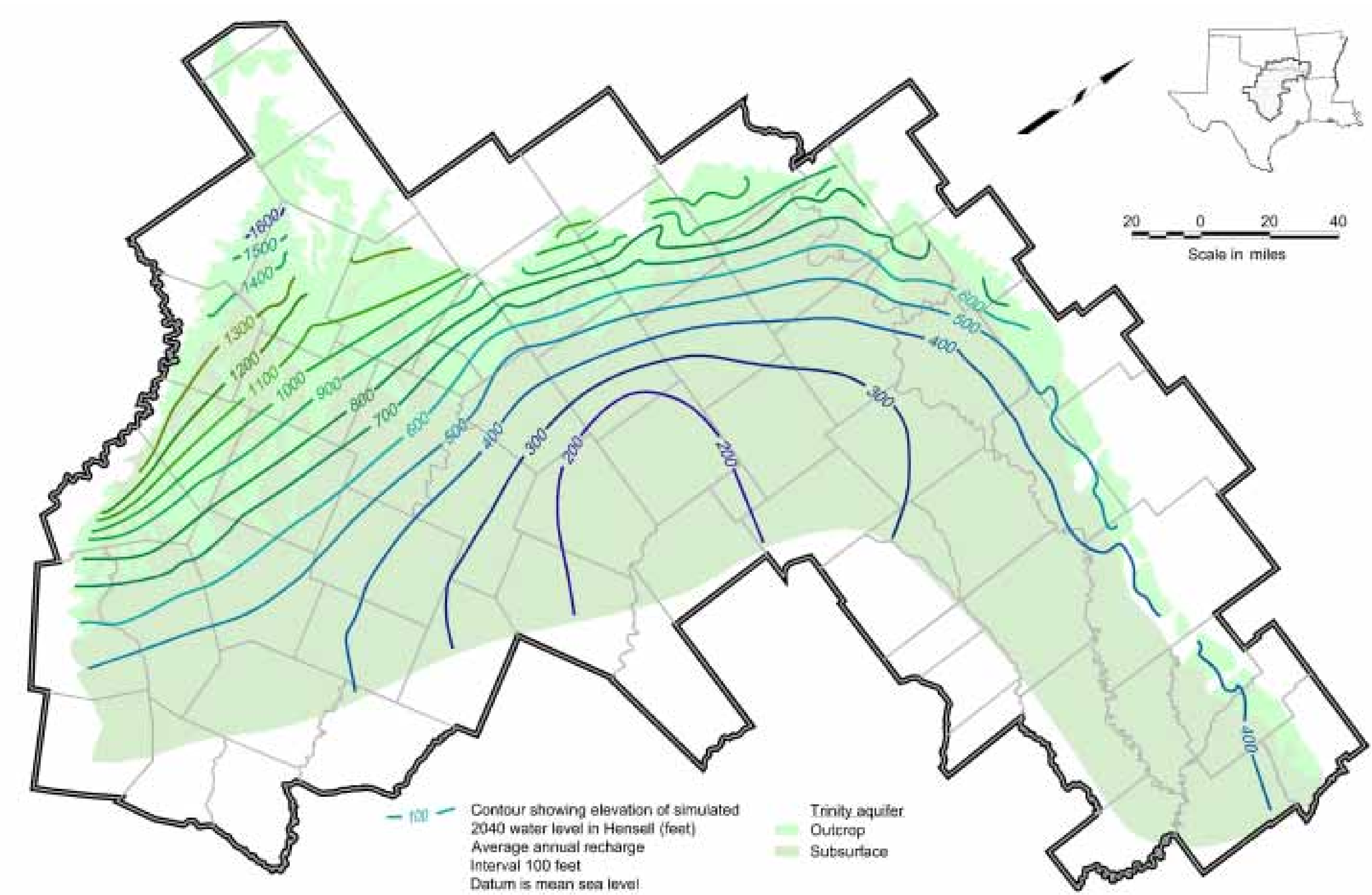



**Figure 10.56 Simulated 2040 Water Levels for Layer 5 (Hensell) Assuming Average Annual Recharge**

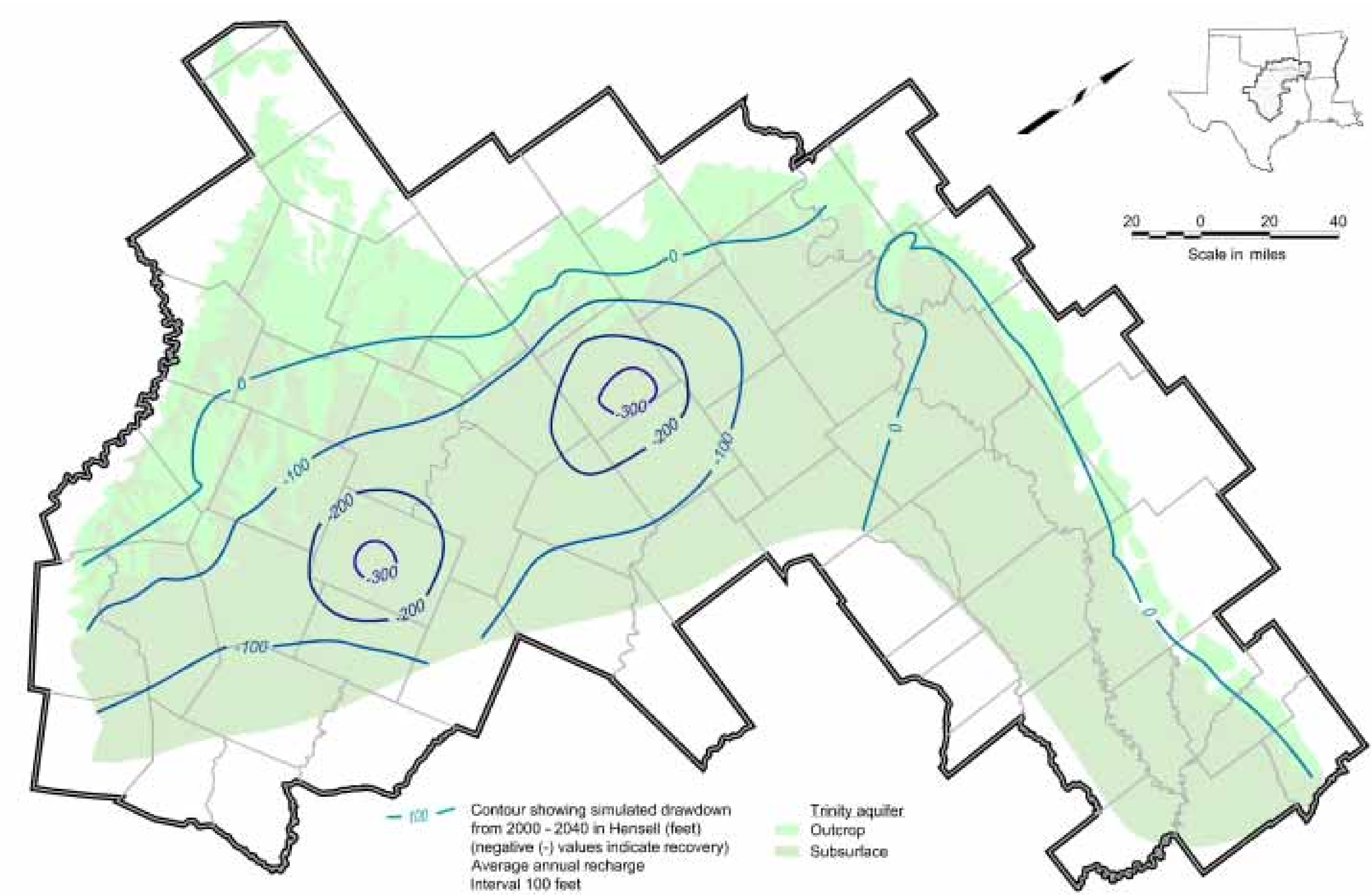



**Figure 10.57 Simulated Water Level Change From 2000 to 2040 for Layer 5 (Hensell) Assuming Average Annual Recharge**

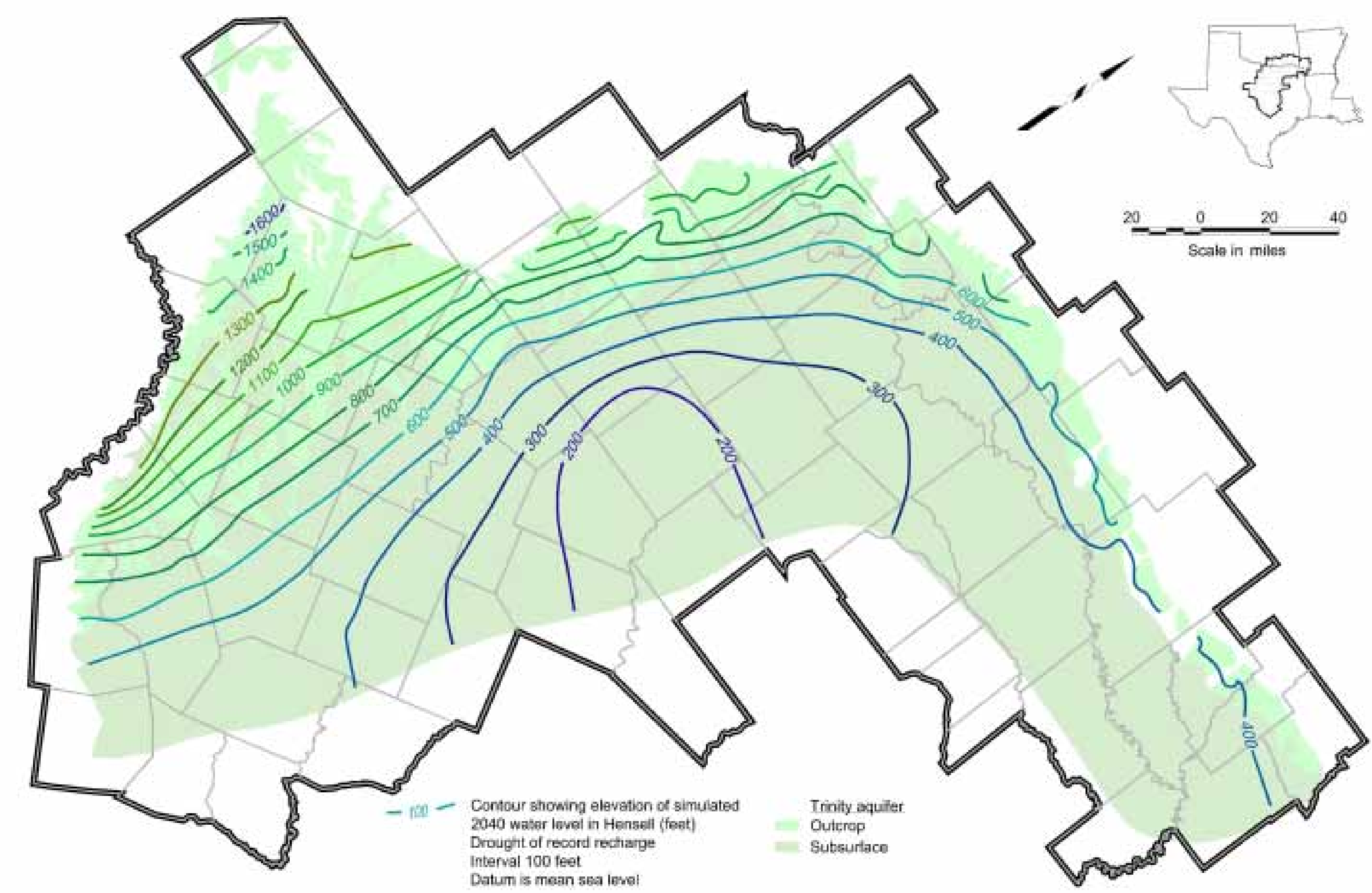



**Figure 10.58 Simulated 2040 Water Levels for Layer 5 (Hensell) Assuming Drought of Record Recharge Distribution**

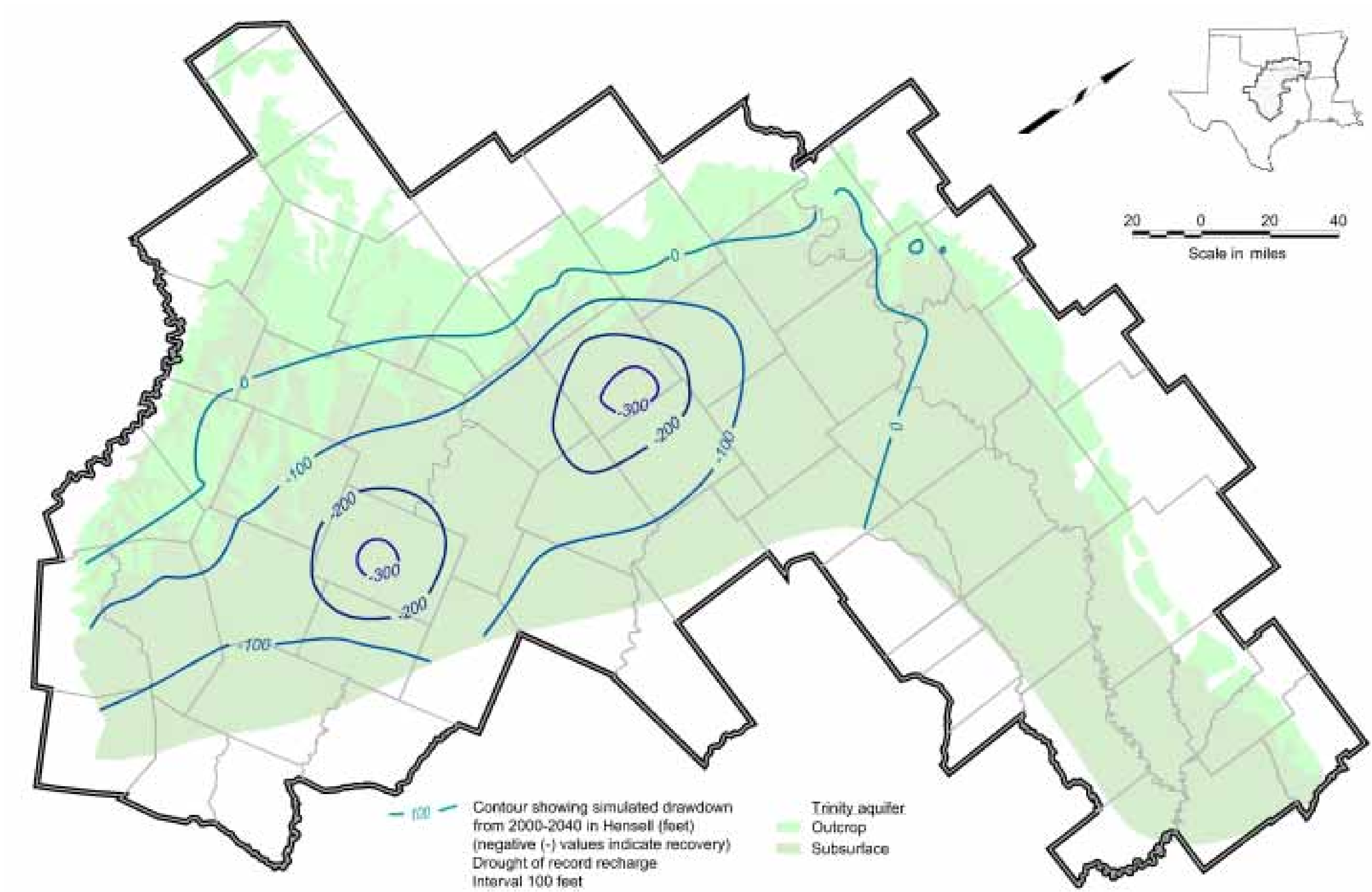



**Figure 10.59 Simulated Water Level Change From 2000 to 2040 for Layer 5 (Hensell) Assuming Drought of Record Recharge Distribution**

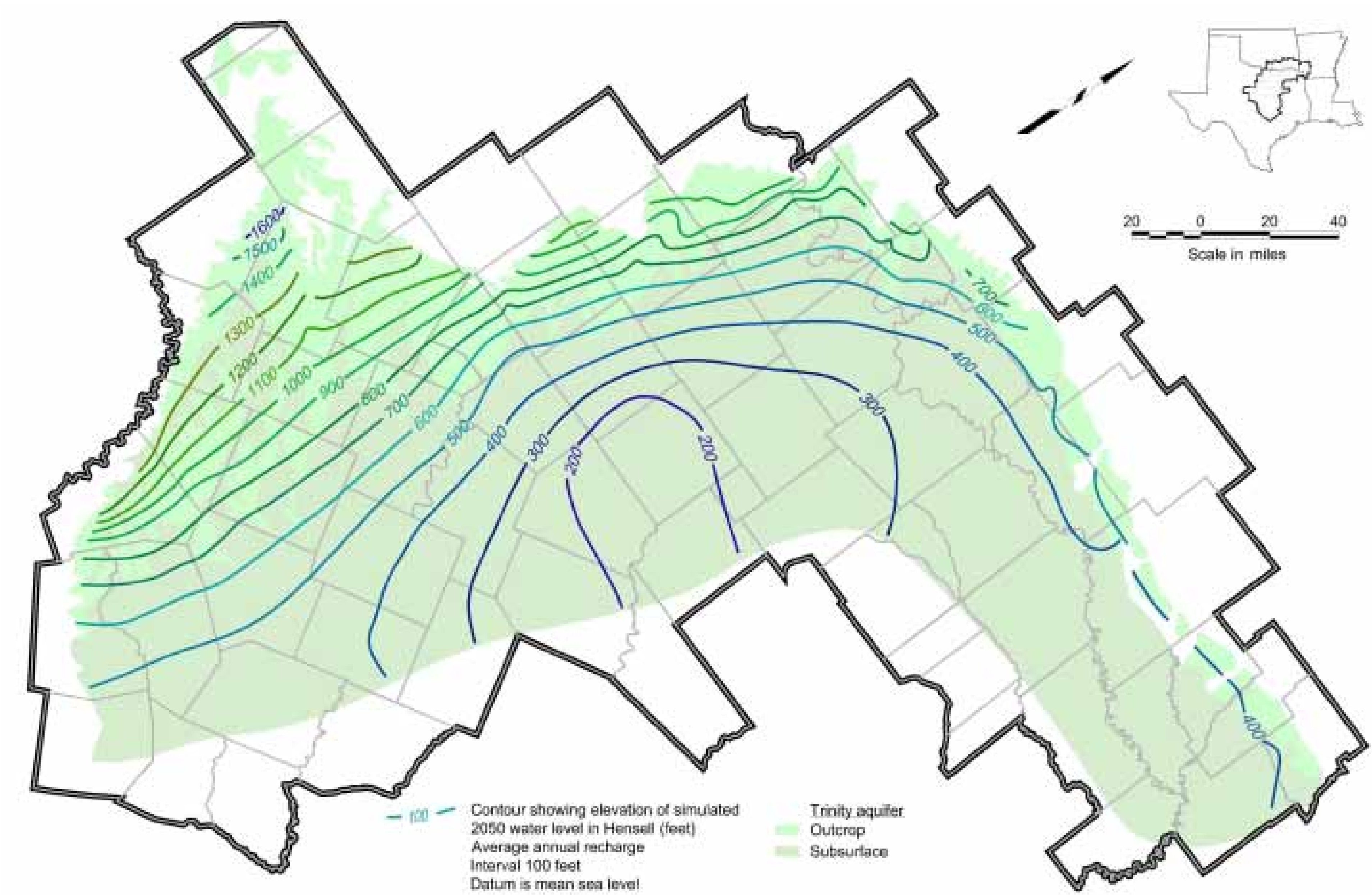



**Figure 10.60 Simulated 2050 Water Levels for Layer 5 (Hensell) Assuming Average Annual Recharge**

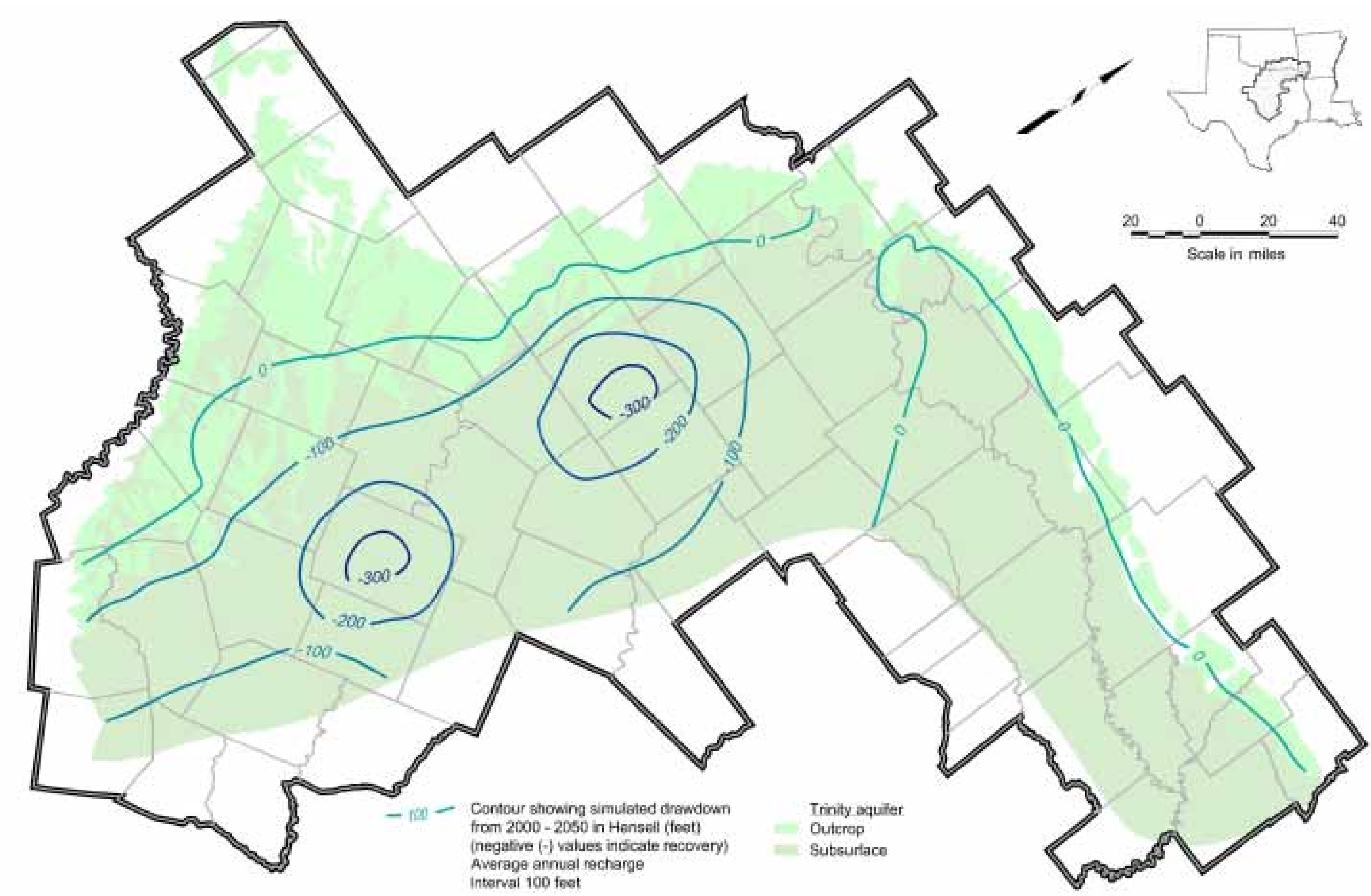



**Figure 10.61 Simulated Water Level Change From 2000 to 2050 for Layer 5 (Hensell) Assuming Average Annual Recharge**

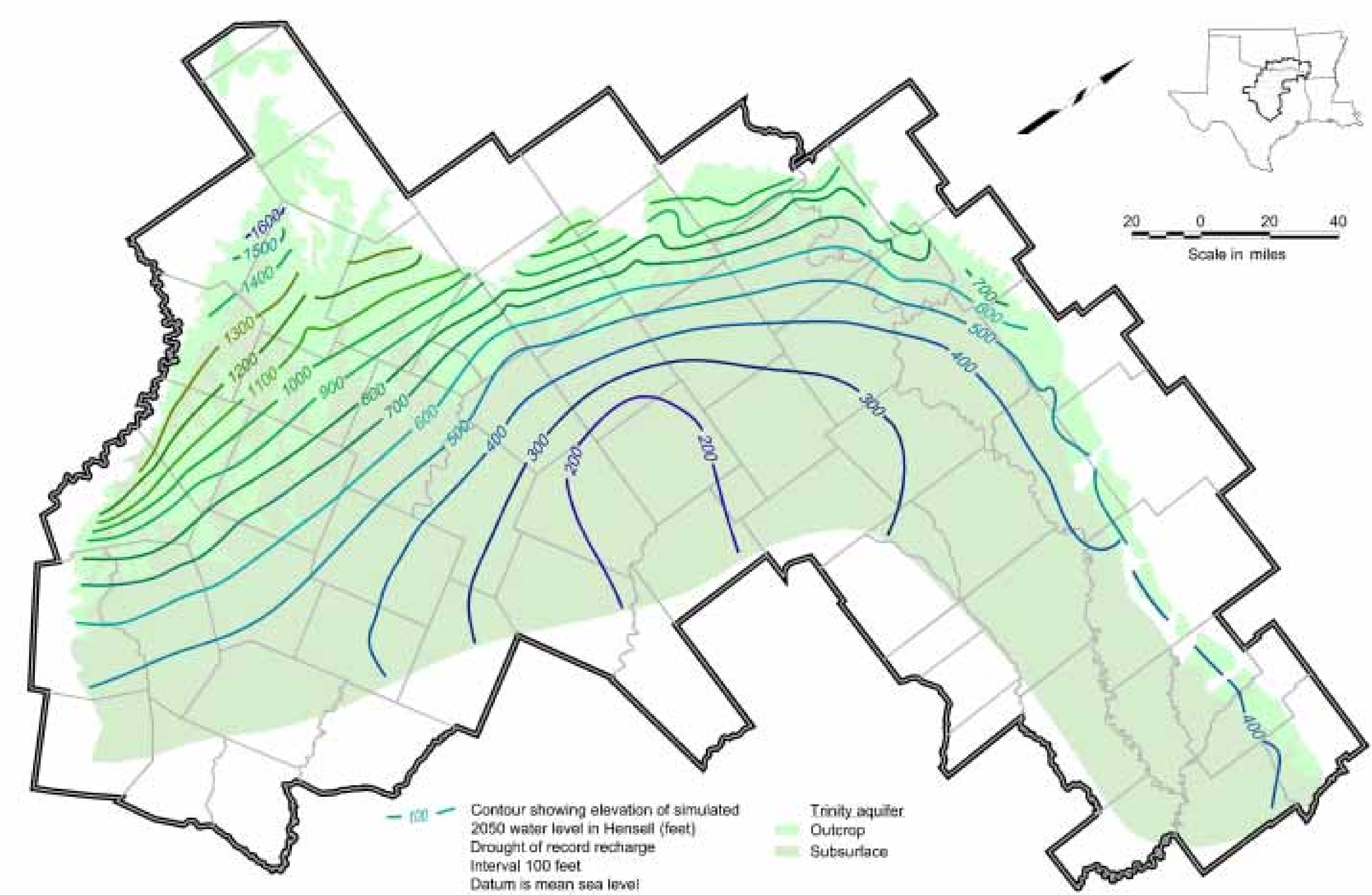



**Figure 10.62 Simulated 2050 Water Levels for Layer 5 (Hensell) Assuming Drought of Record Recharge Distribution**

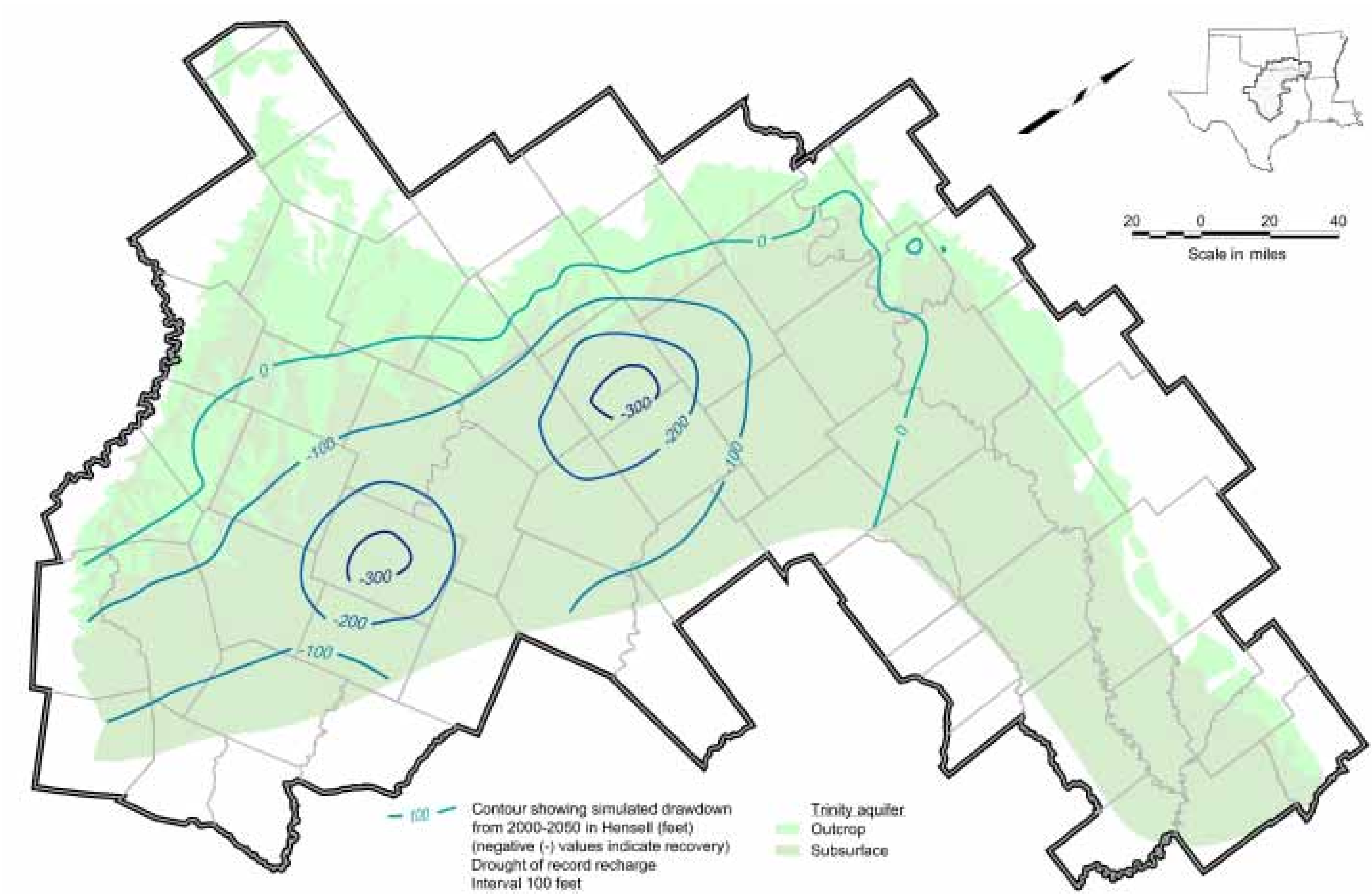



**Figure 10.63 Simulated Water Level Change From 2000 to 2050 for Layer 5 (Hensell) Assuming Drought of Record Recharge Distribution**

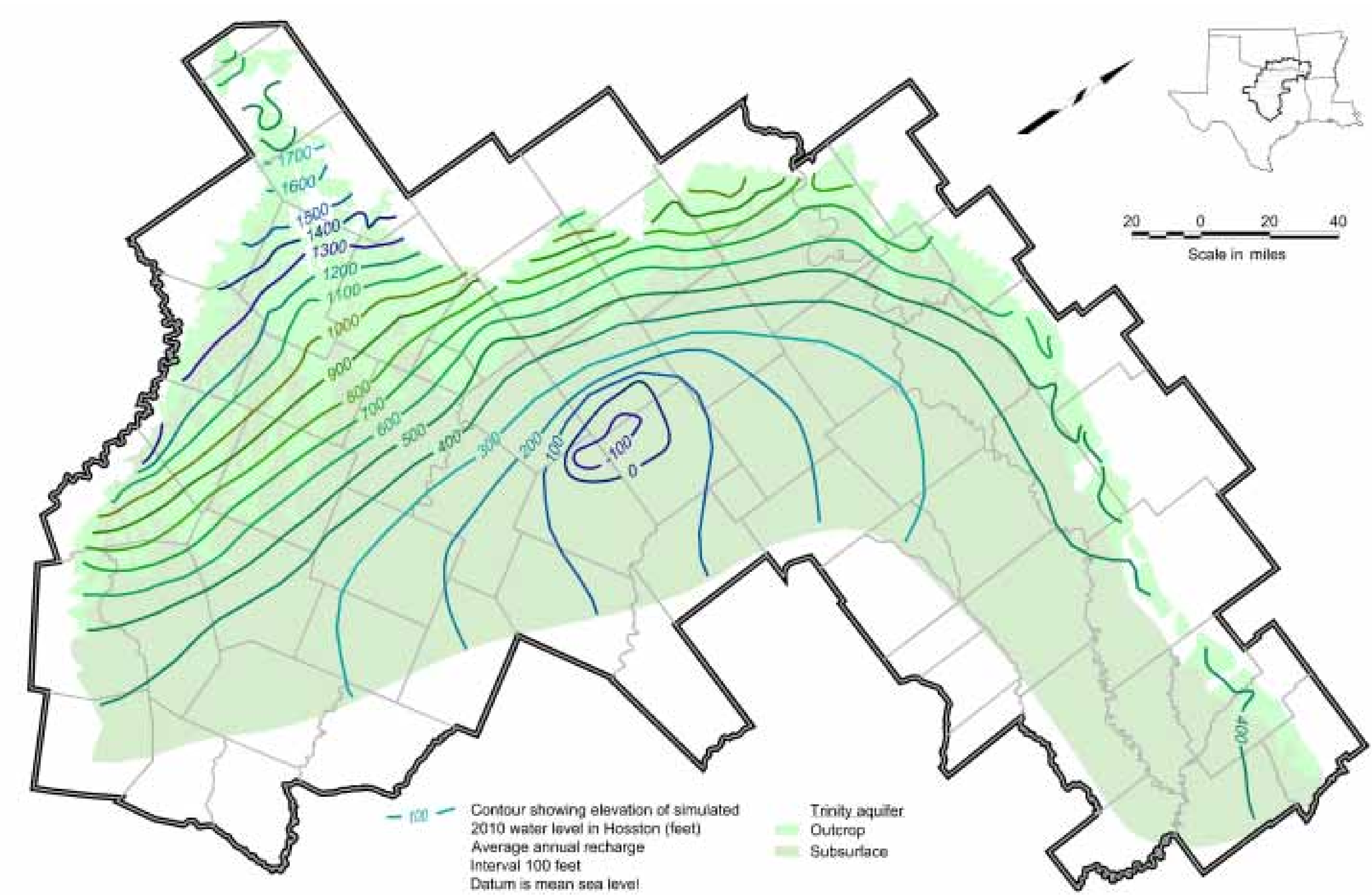



**Figure 10.64 Simulated 2010 Water Levels for Layer 7 (Hosston) Assuming Average Annual Recharge**

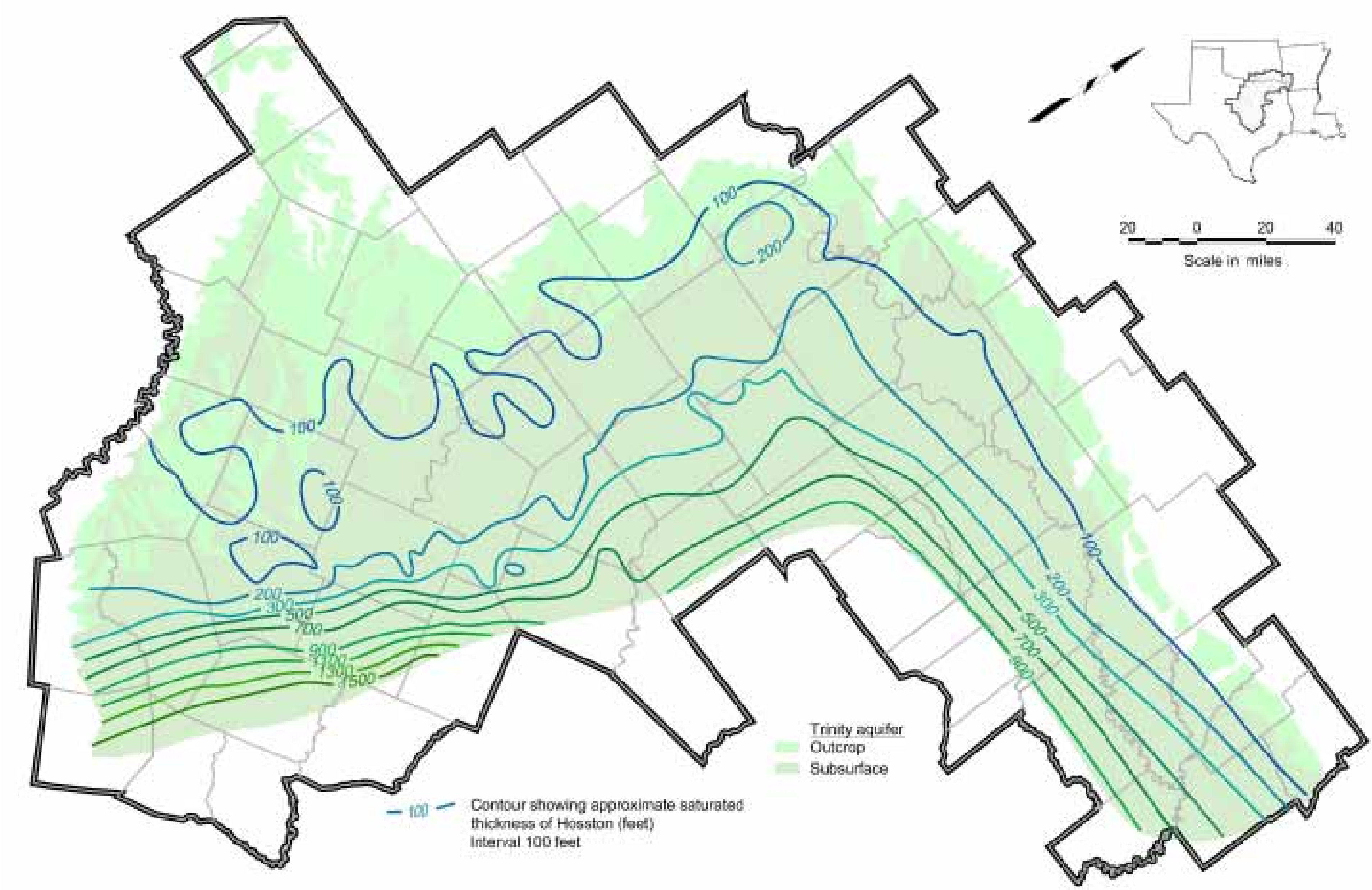



**Figure 10.65 Simulated 2010 Saturated Thickness for Layer 7 (Hosston) Assuming Average Annual Recharge**

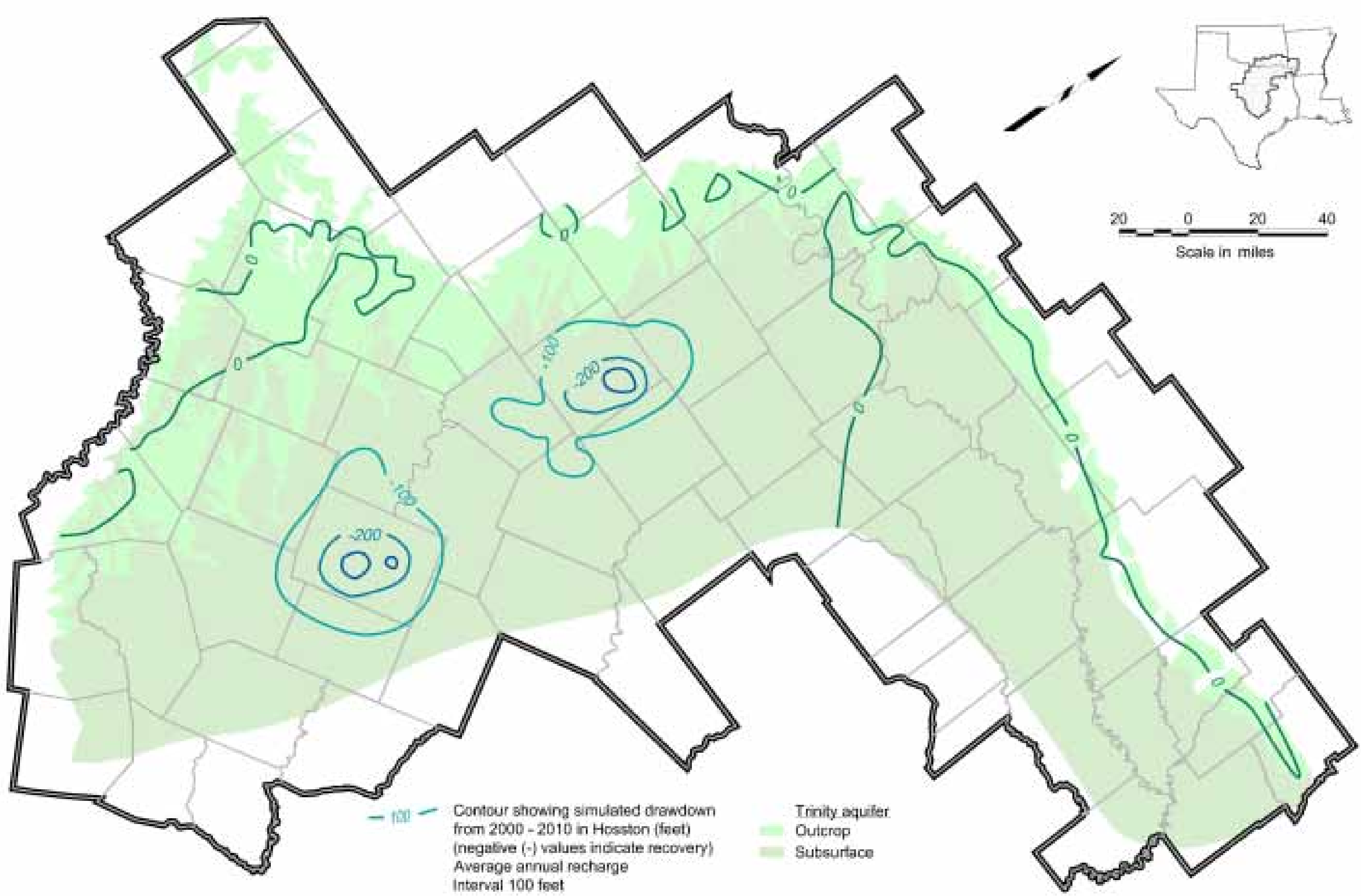



**Figure 10.66 Simulated Water Level Change From 2000 to 2010 for Layer 7 (Hosston) Assuming Average Annual Recharge**

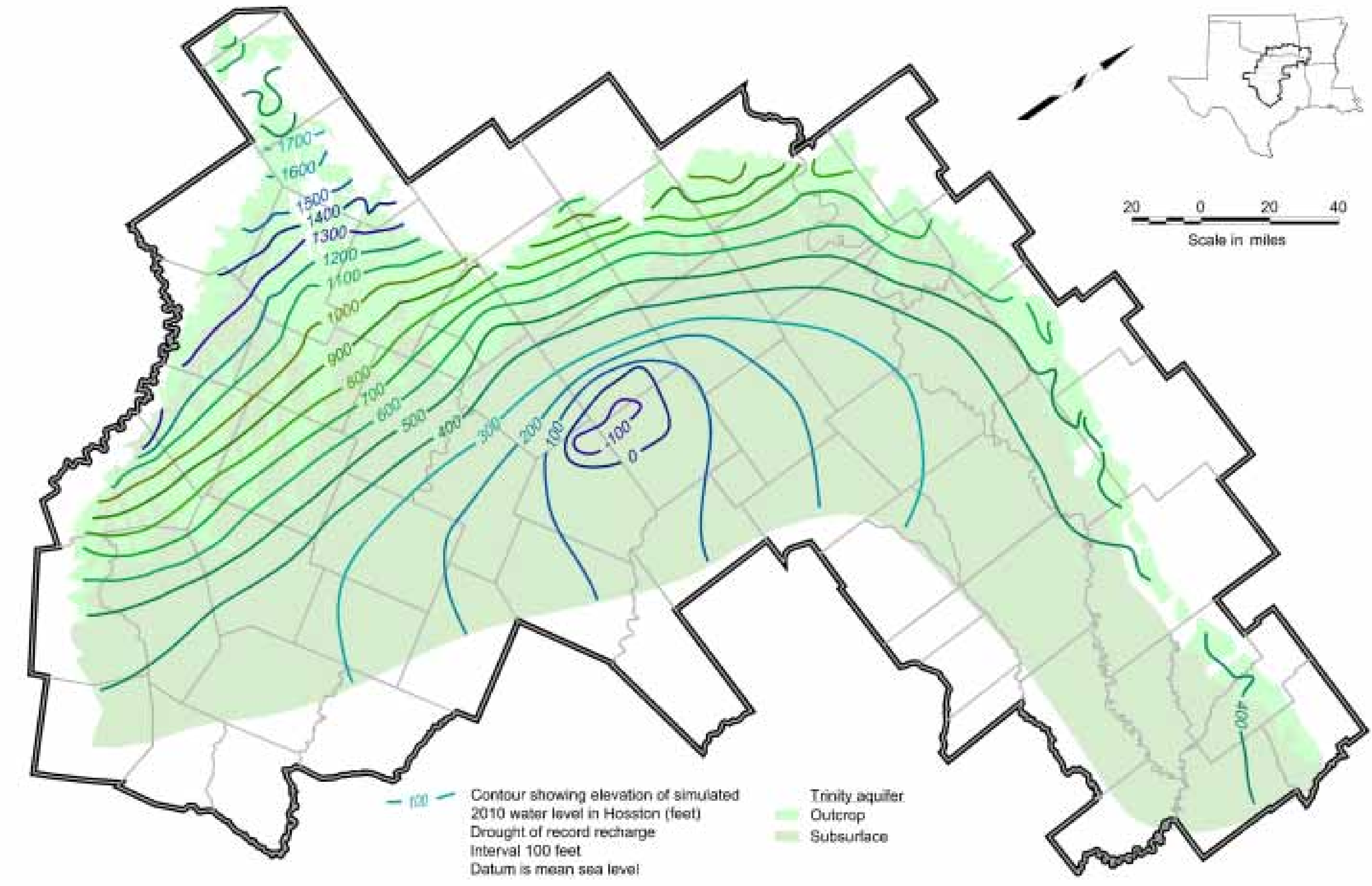



**Figure 10.67 Simulated 2010 Water Levels for Layer 7 (Hosston) Assuming Drought of Record Recharge Distribution**

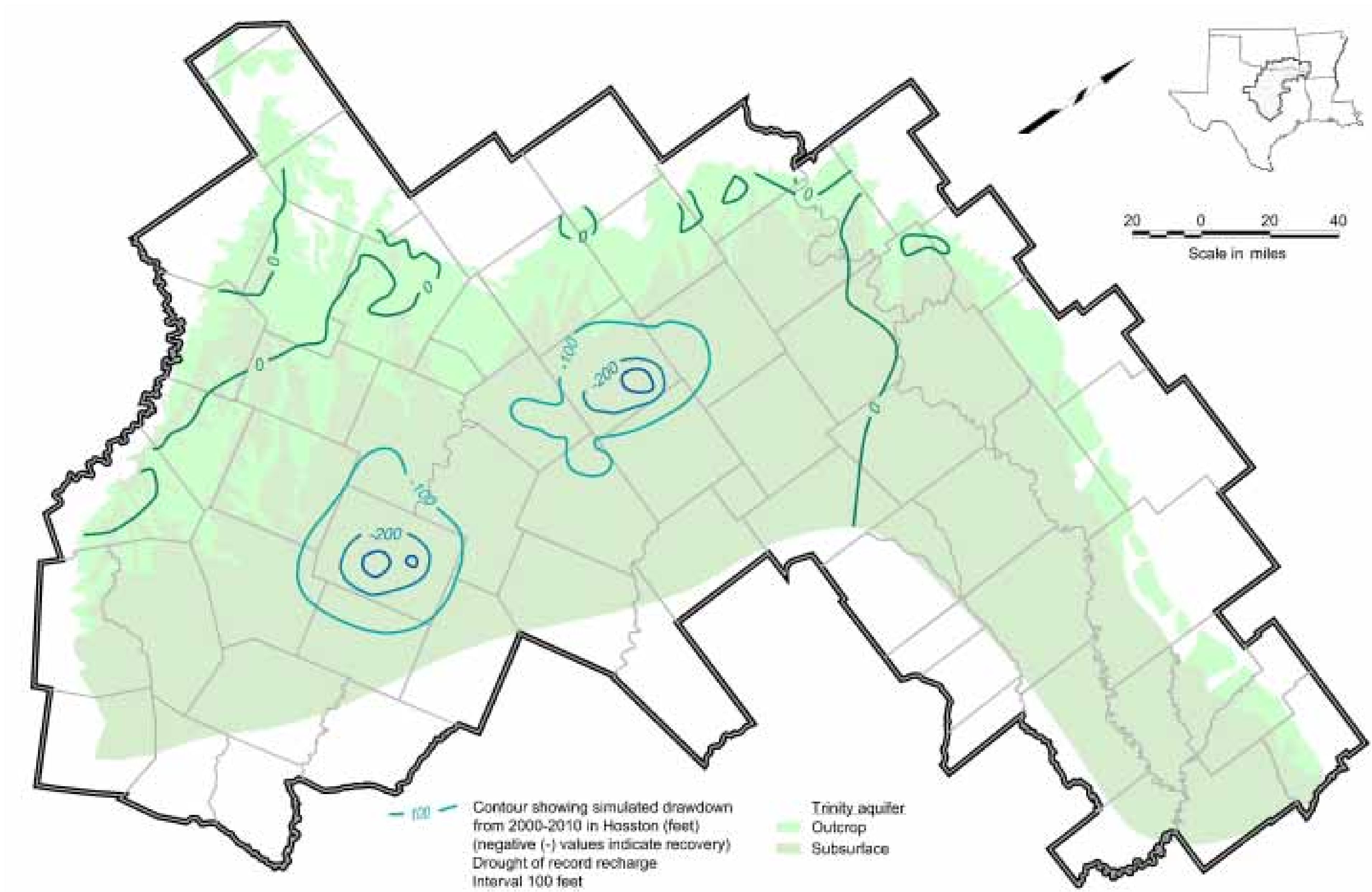



**Figure 10.68 Simulated Water Level Change From 2000 to 2010 for Layer 7 (Hosston) Assuming Drought of Record Recharge Distribution**

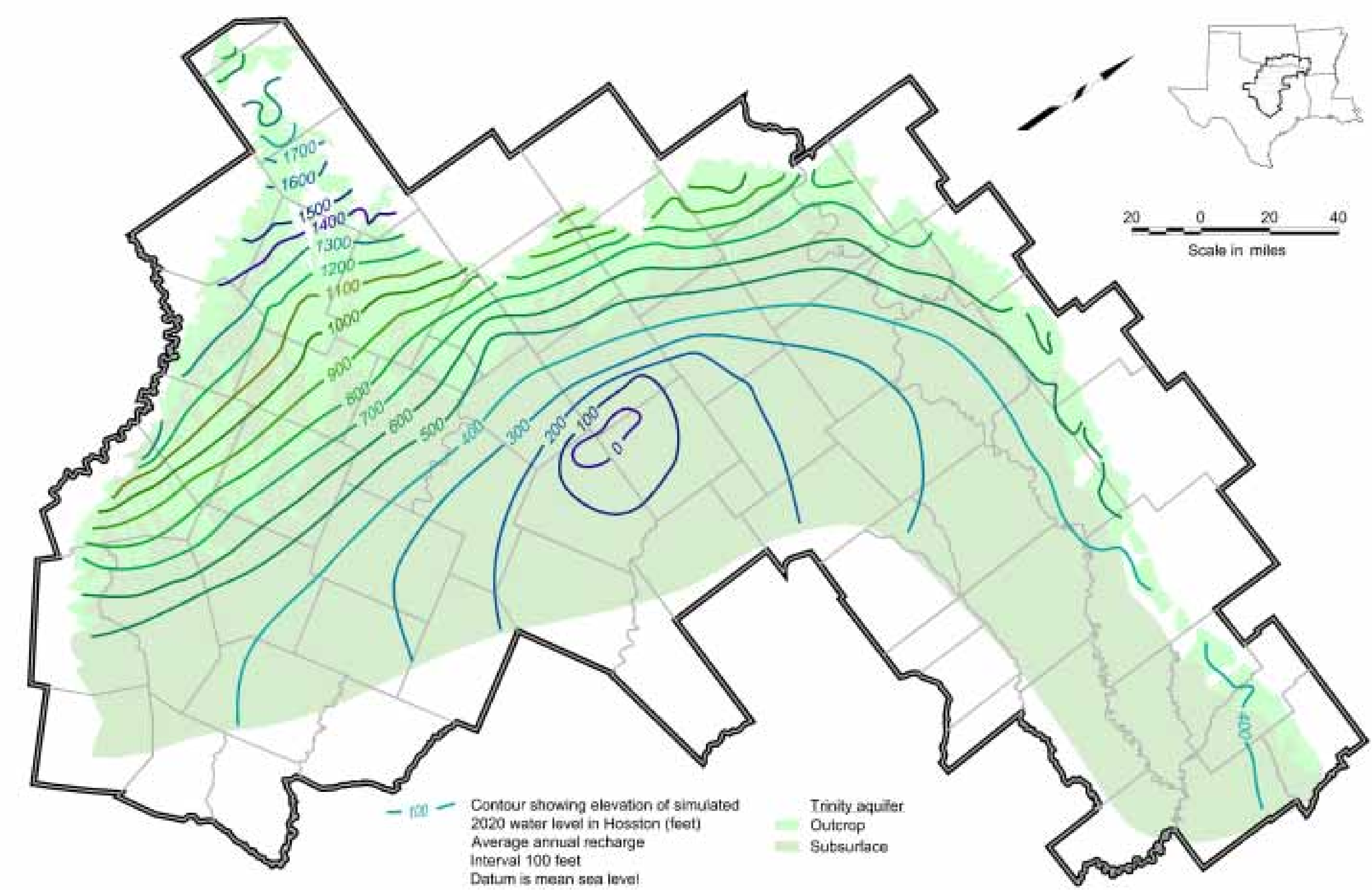



**Figure 10.69 Simulated 2020 Water Levels for Layer 7 (Hosston) Assuming Average Annual Recharge**

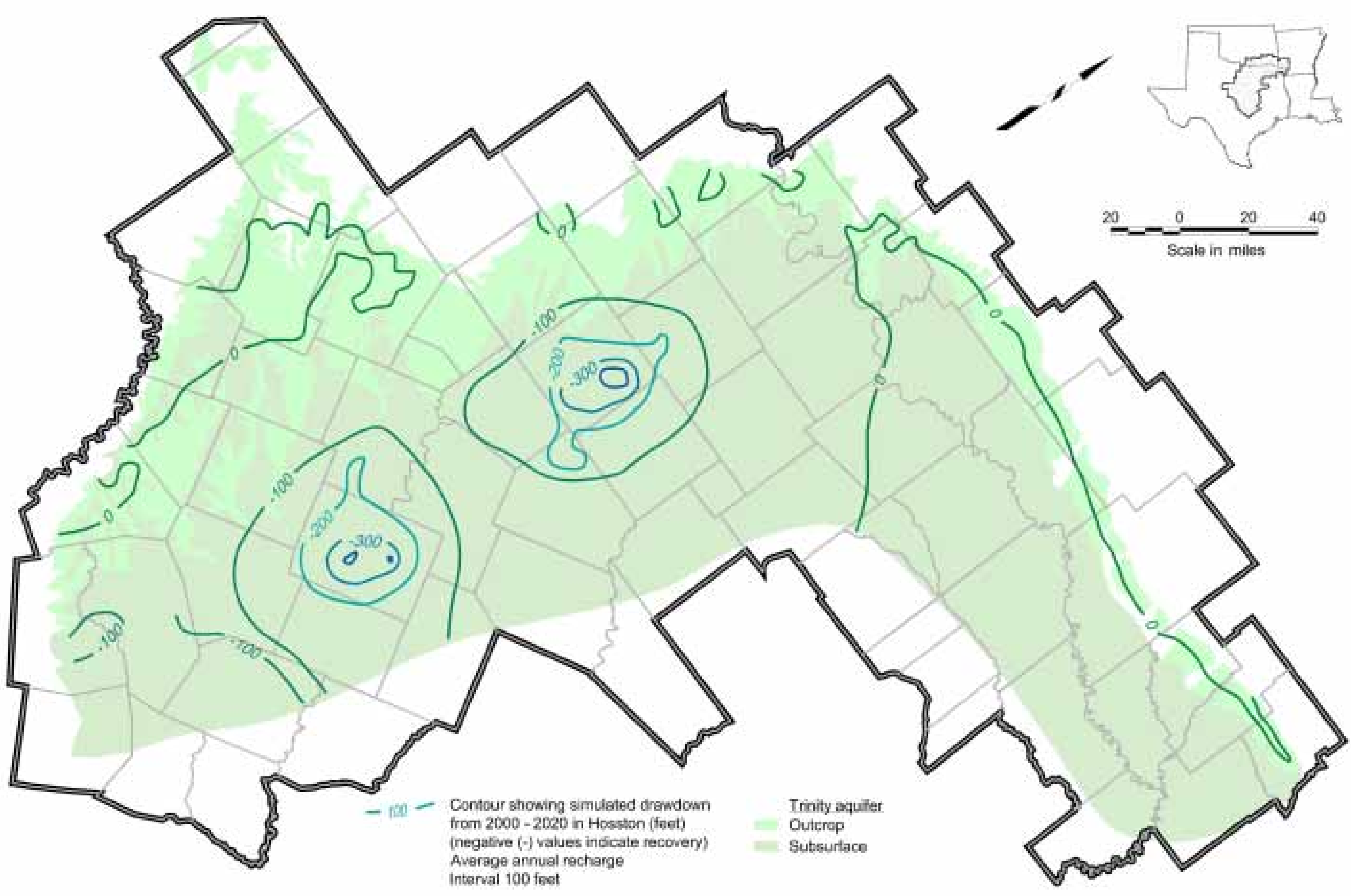



**Figure 10.70 Simulated Water Level Change From 2000 to 2020 for Layer 7 (Hosston) Assuming Average Annual Recharge**

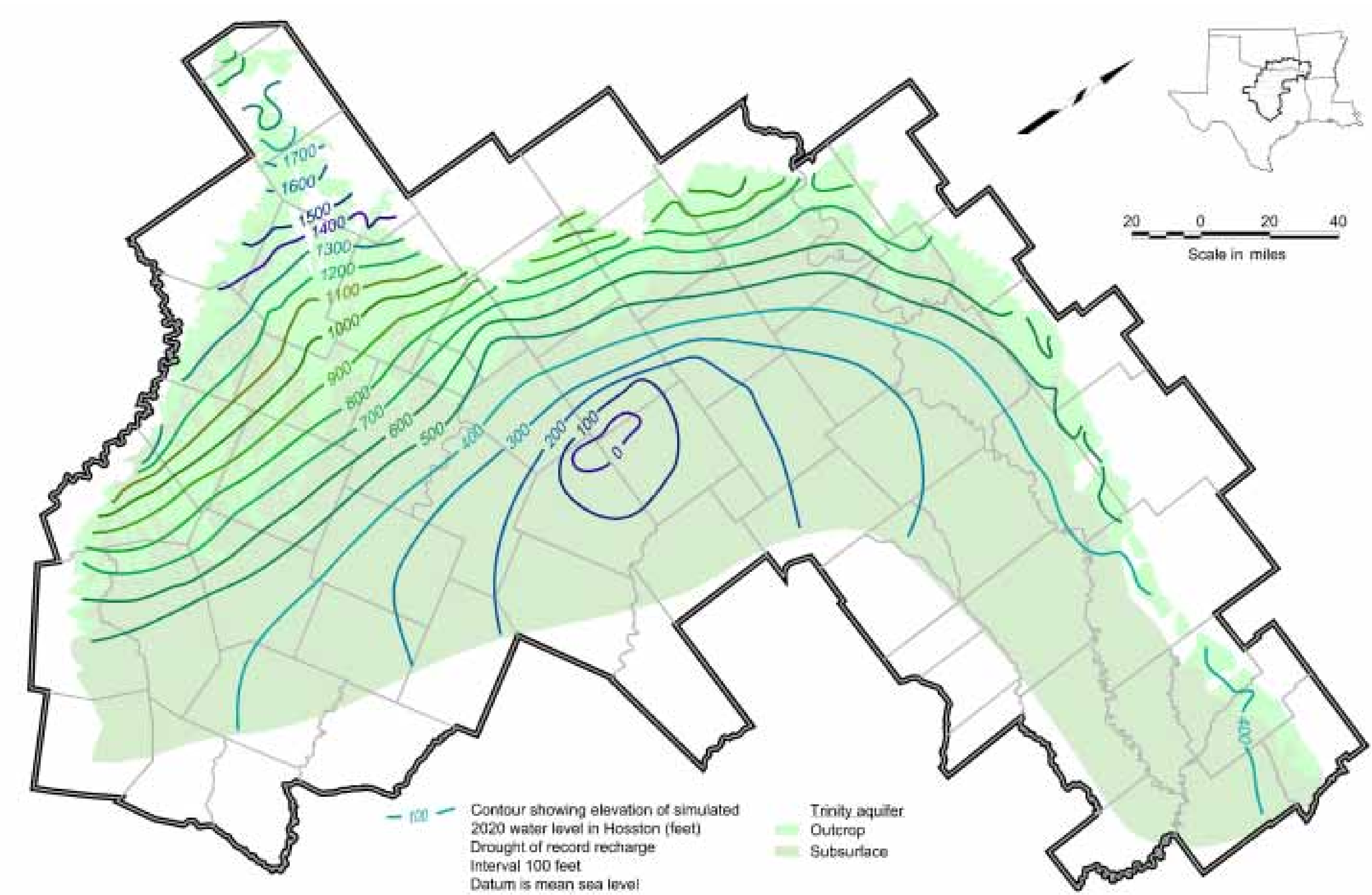



**Figure 10.71 Simulated 2020 Water Levels for Layer 7 (Hosston) Assuming Drought of Record Recharge Distribution**

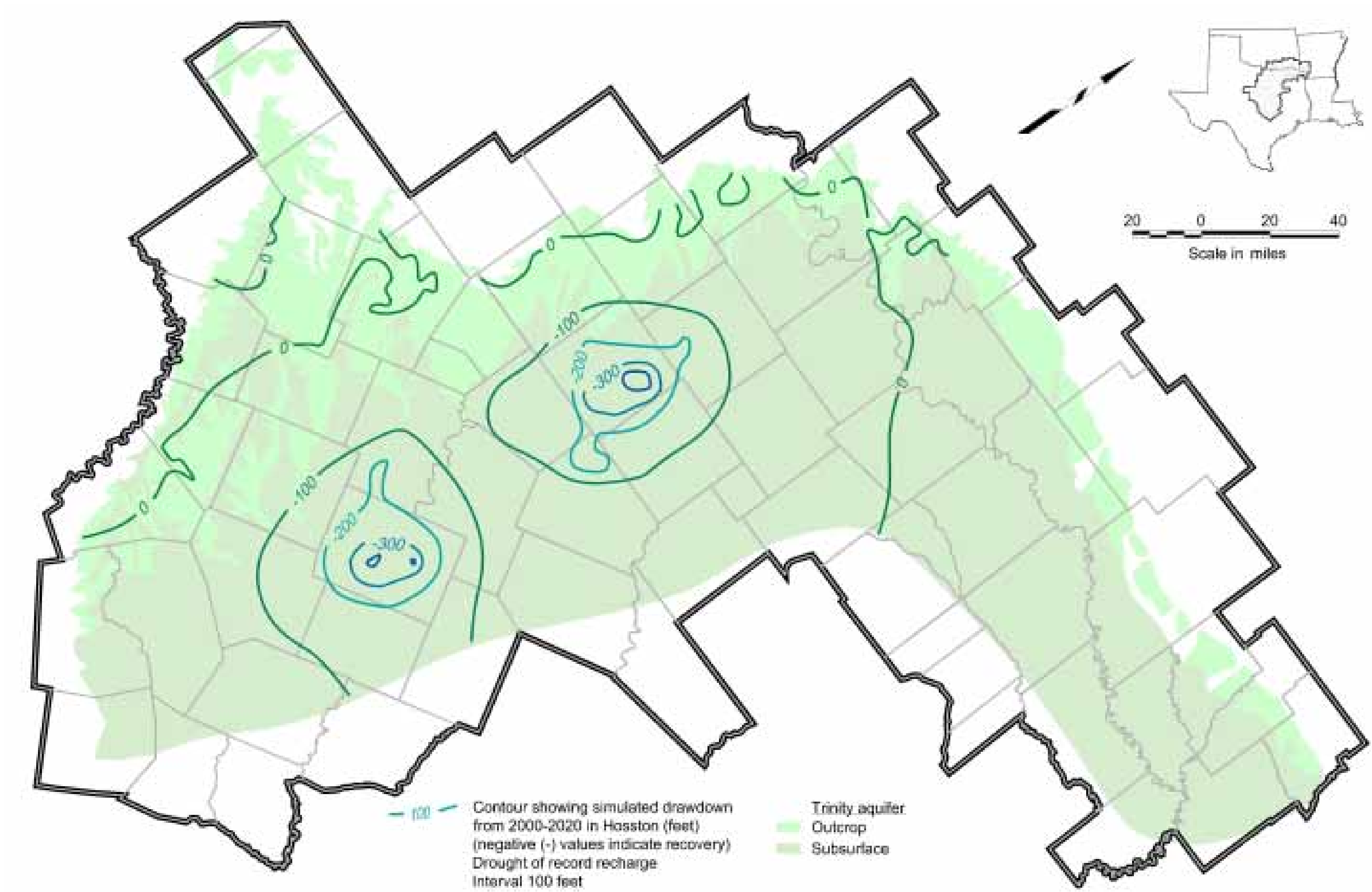



**Figure 10.72 Simulated Water Level Change From 2000 to 2020 for Layer 7 (Hosston) Assuming Drought of Record Recharge Distribution**

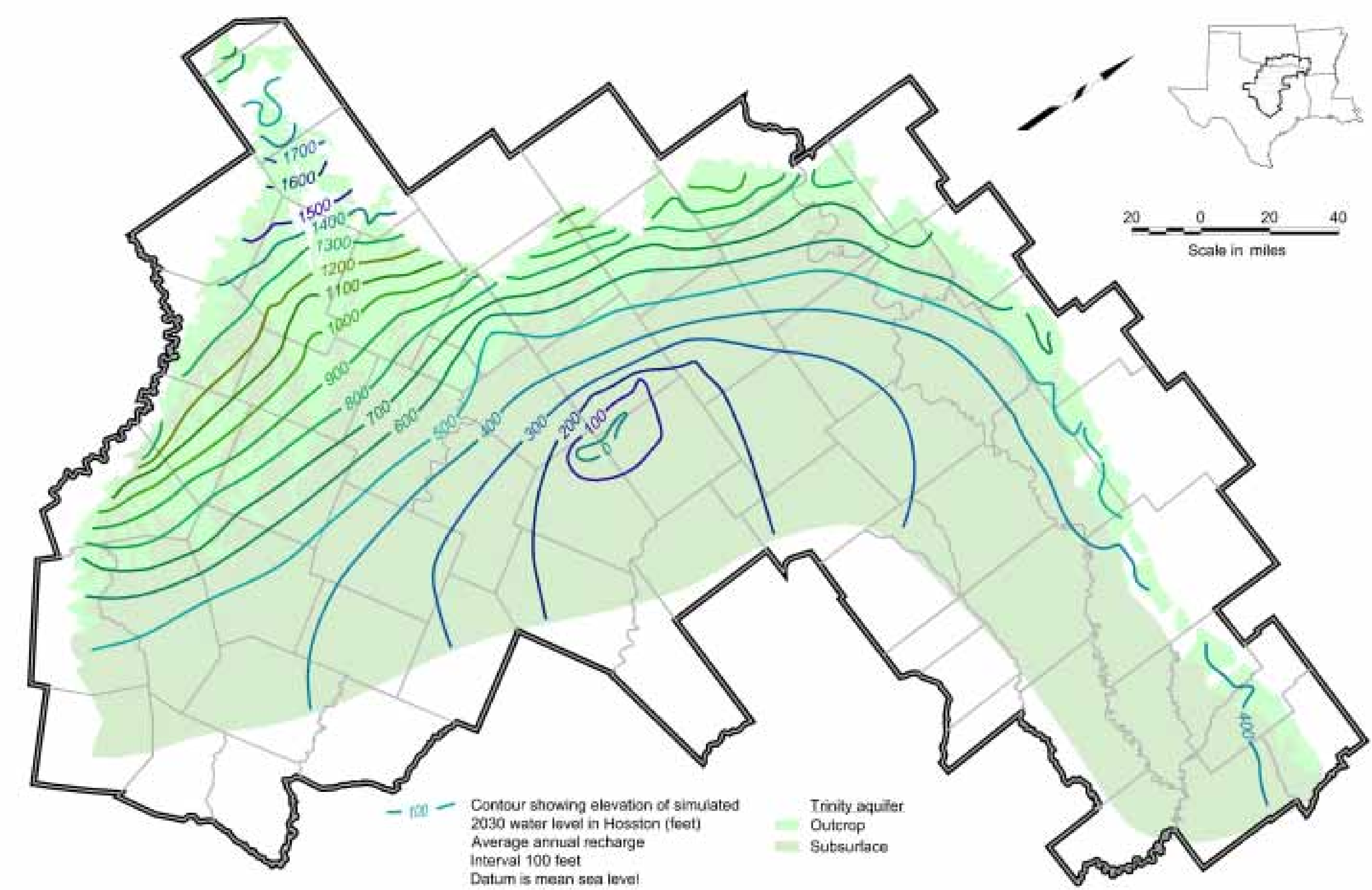



**Figure 10.73 Simulated 2030 Water Levels for Layer 7 (Hosston) Assuming Average Annual Recharge**

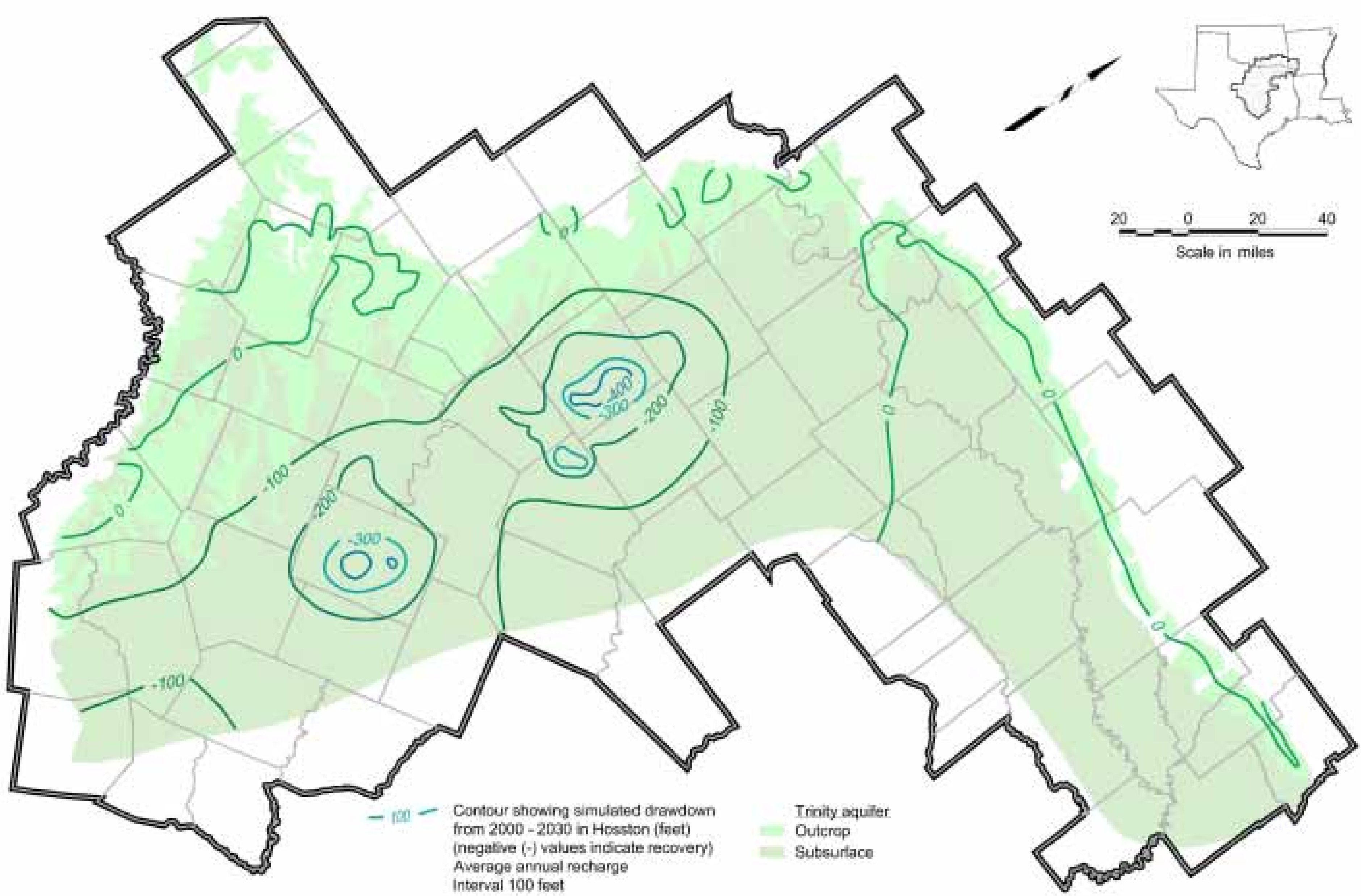



**Figure 10.74 Simulated Water Level Change From 2000 to 2030 for Layer 7 (Hosston) Assuming Average Annual Recharge**

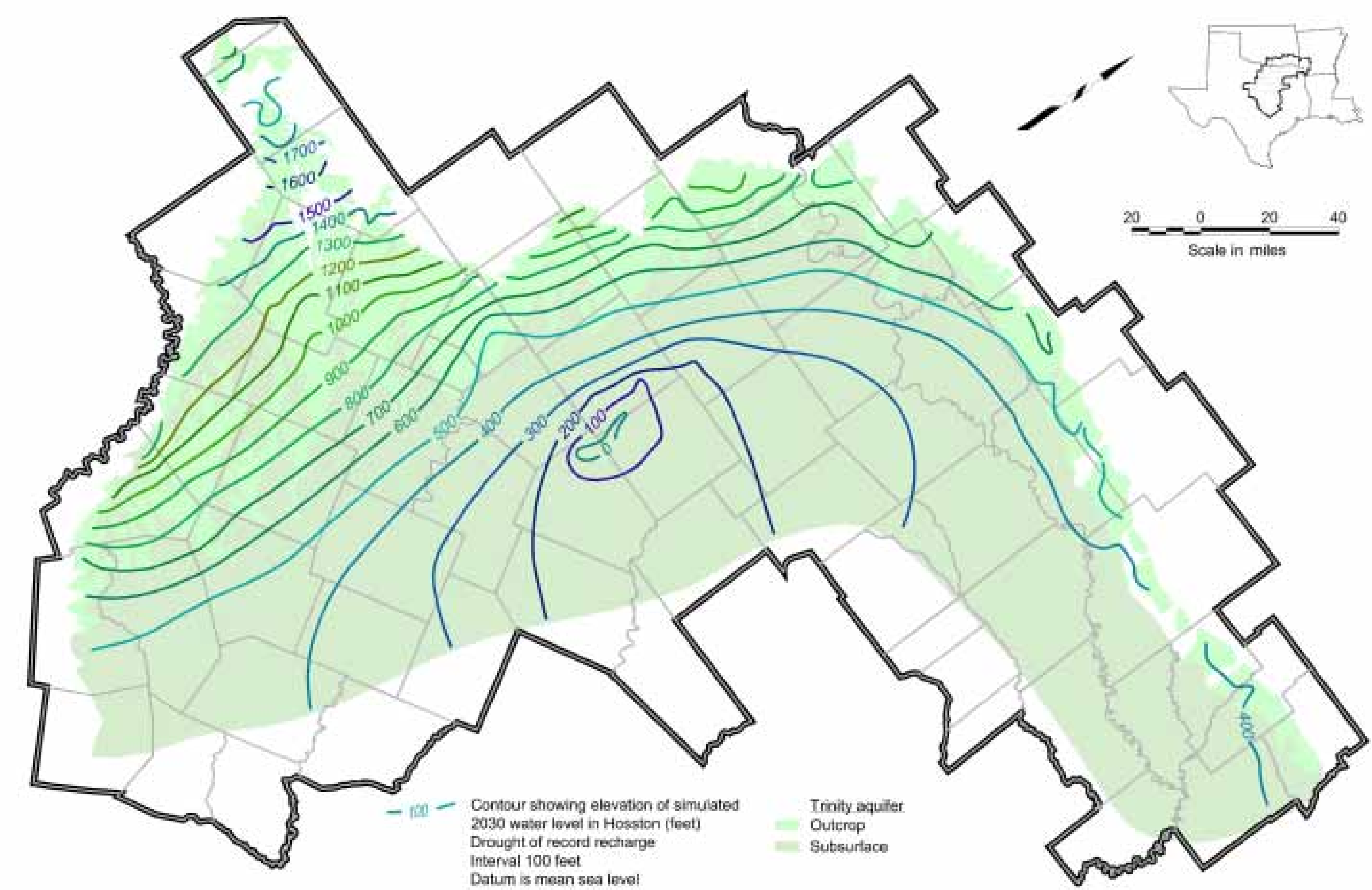



**Figure 10.75 Simulated 2030 Water Levels for Layer 7 (Hosston) Assuming Drought of Record Recharge Distribution**

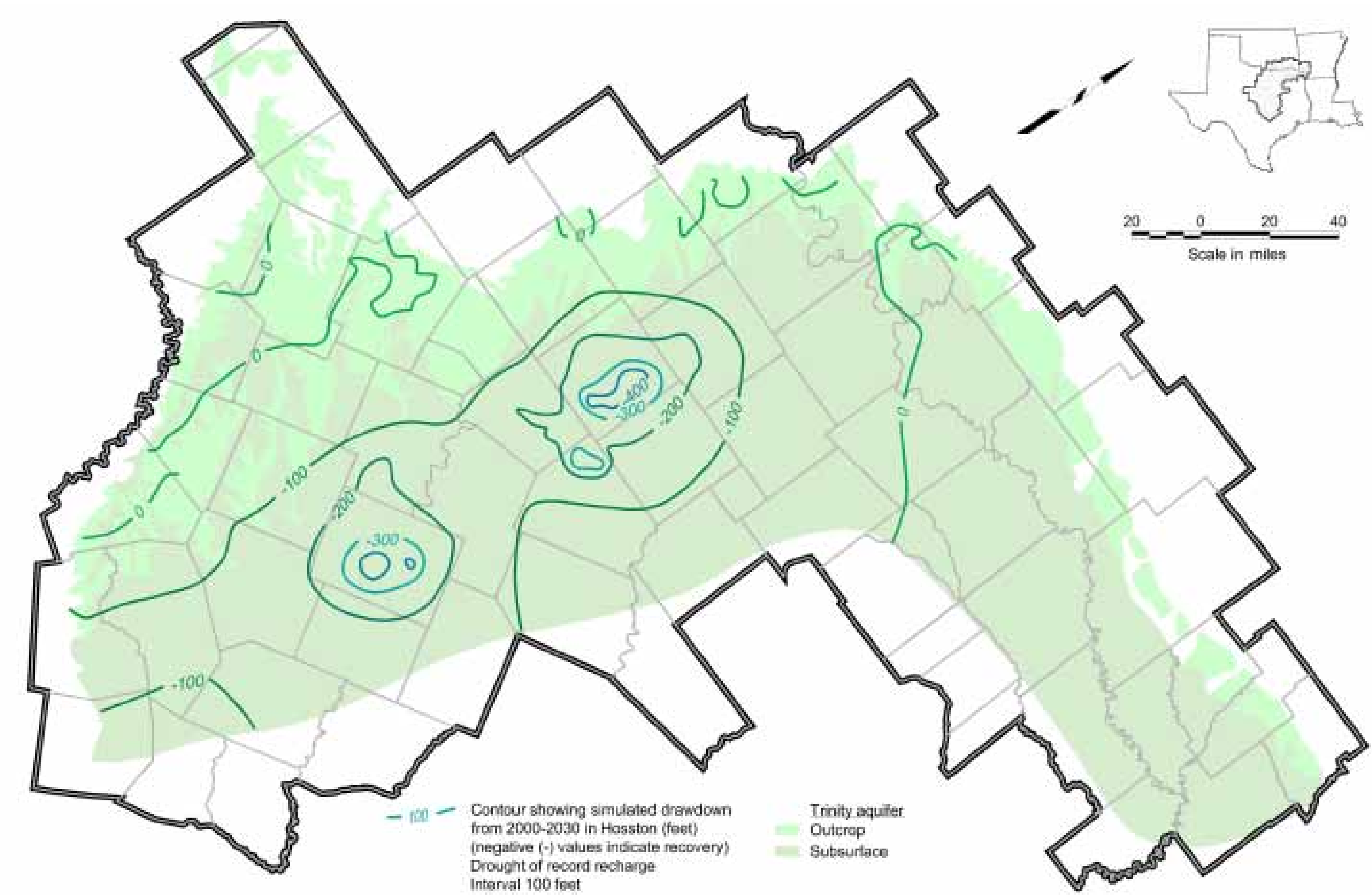



**Figure 10.76 Simulated Water Level Change From 2000 to 2030 for Layer 7 (Hosston) Assuming Drought of Record Recharge Distribution**

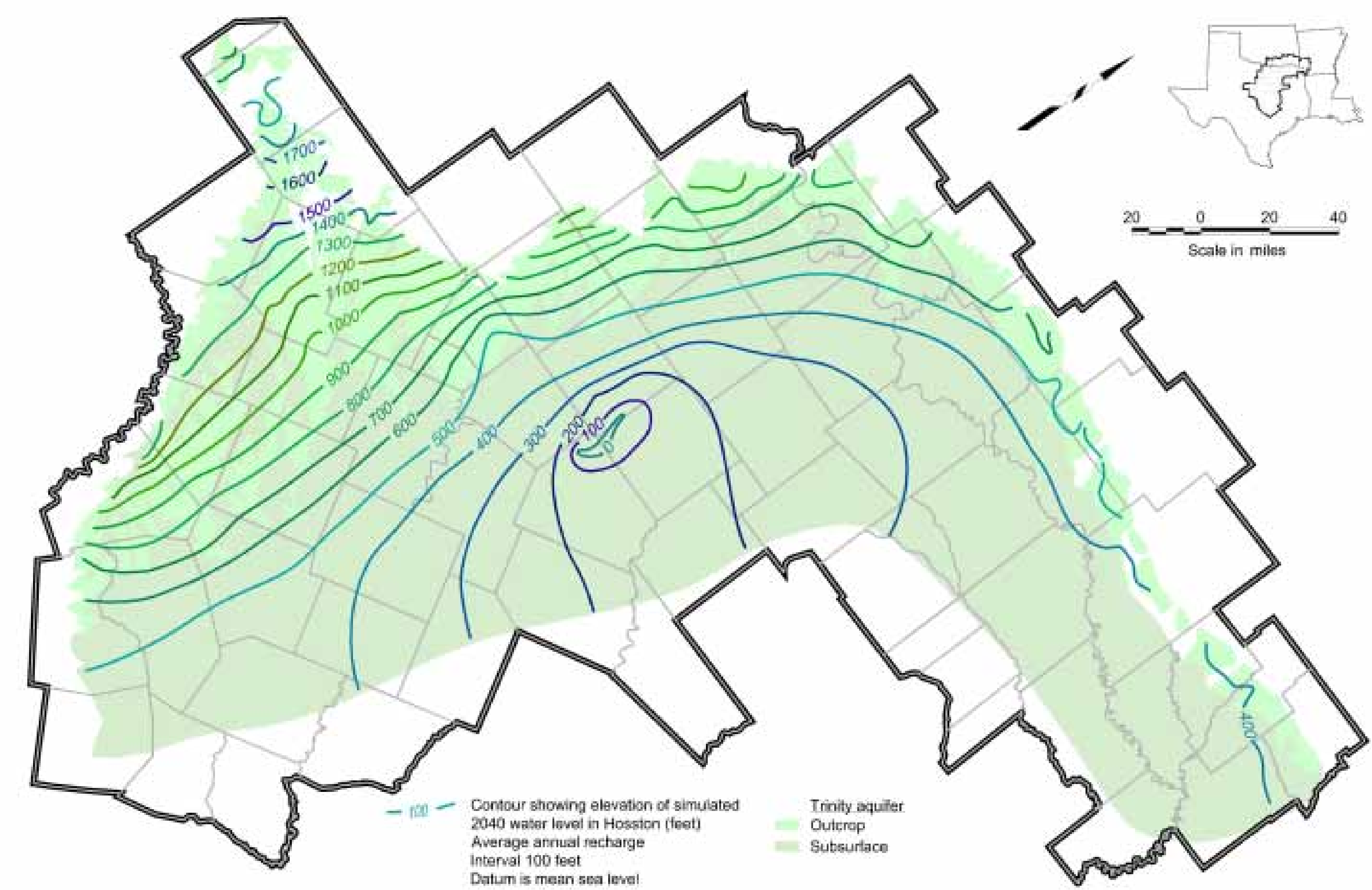



**Figure 10.77 Simulated 2040 Water Levels for Layer 7 (Hosston) Assuming Average Annual Recharge**

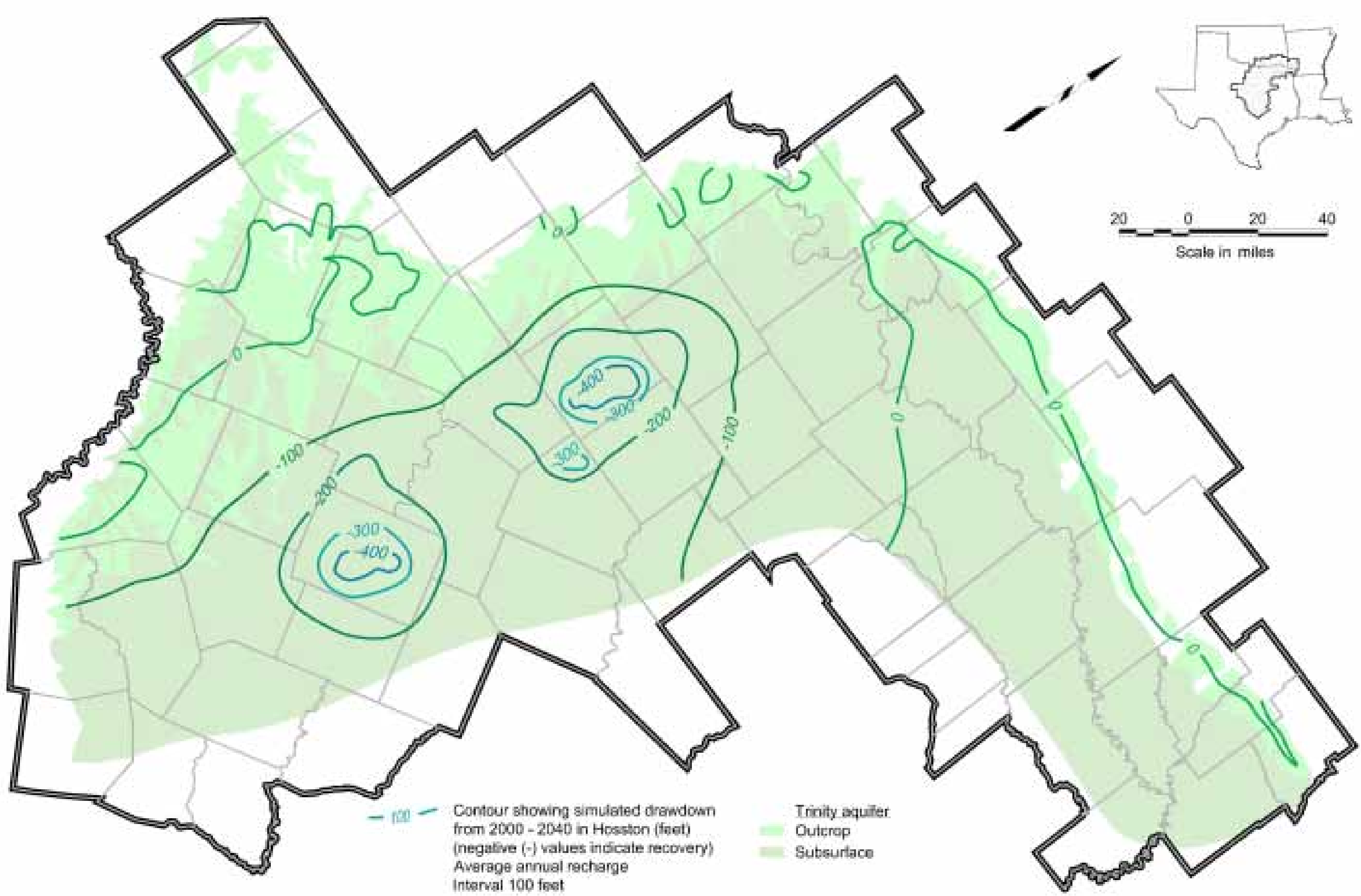



**Figure 10.78 Simulated Water Level Change From 2000 to 2040 for Layer 7 (Hosston) Assuming Average Annual Recharge**

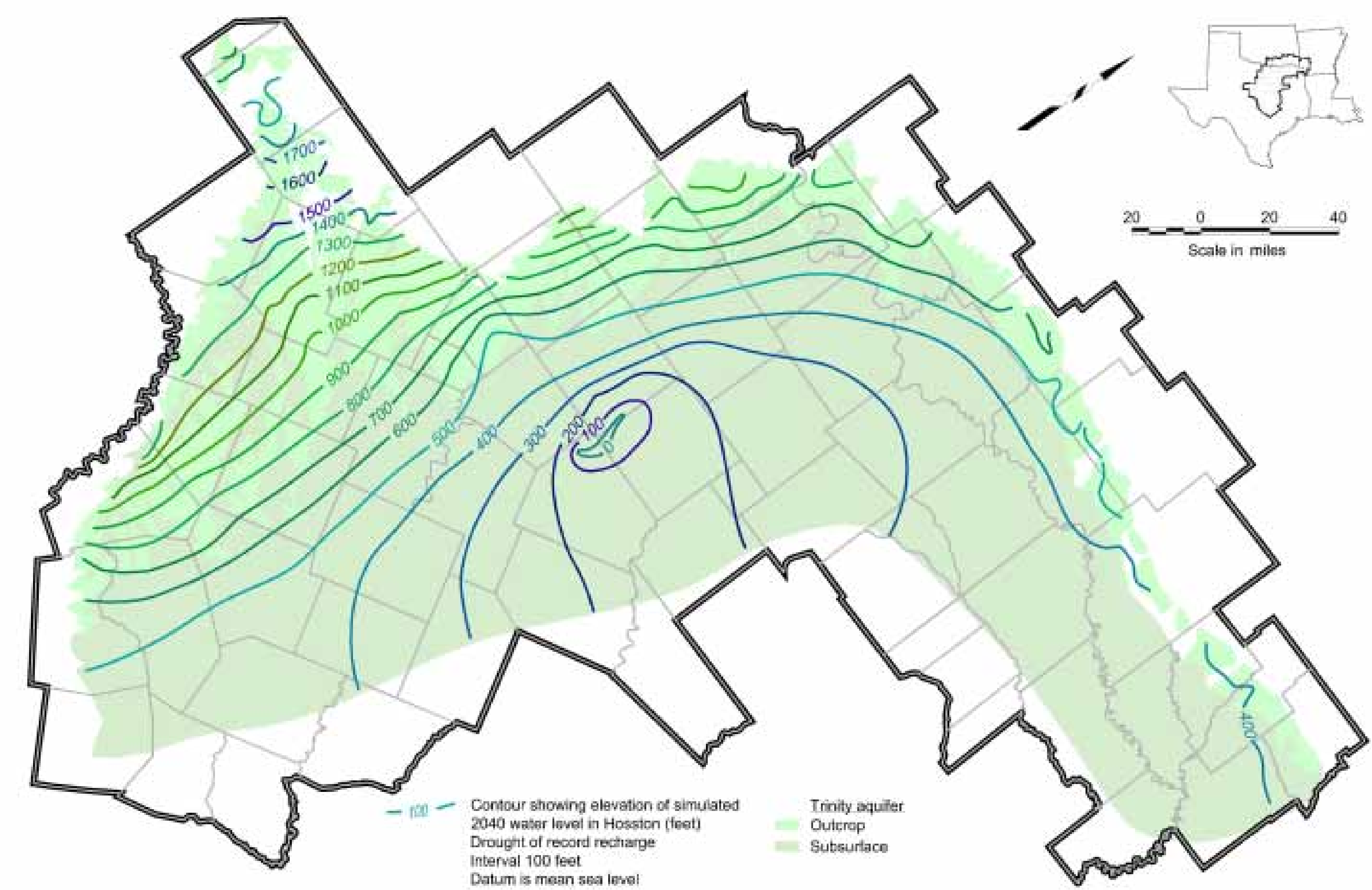



**Figure 10.79 Simulated 2040 Water Levels for Layer 7 (Hosston) Assuming Drought of Record Recharge Distribution**

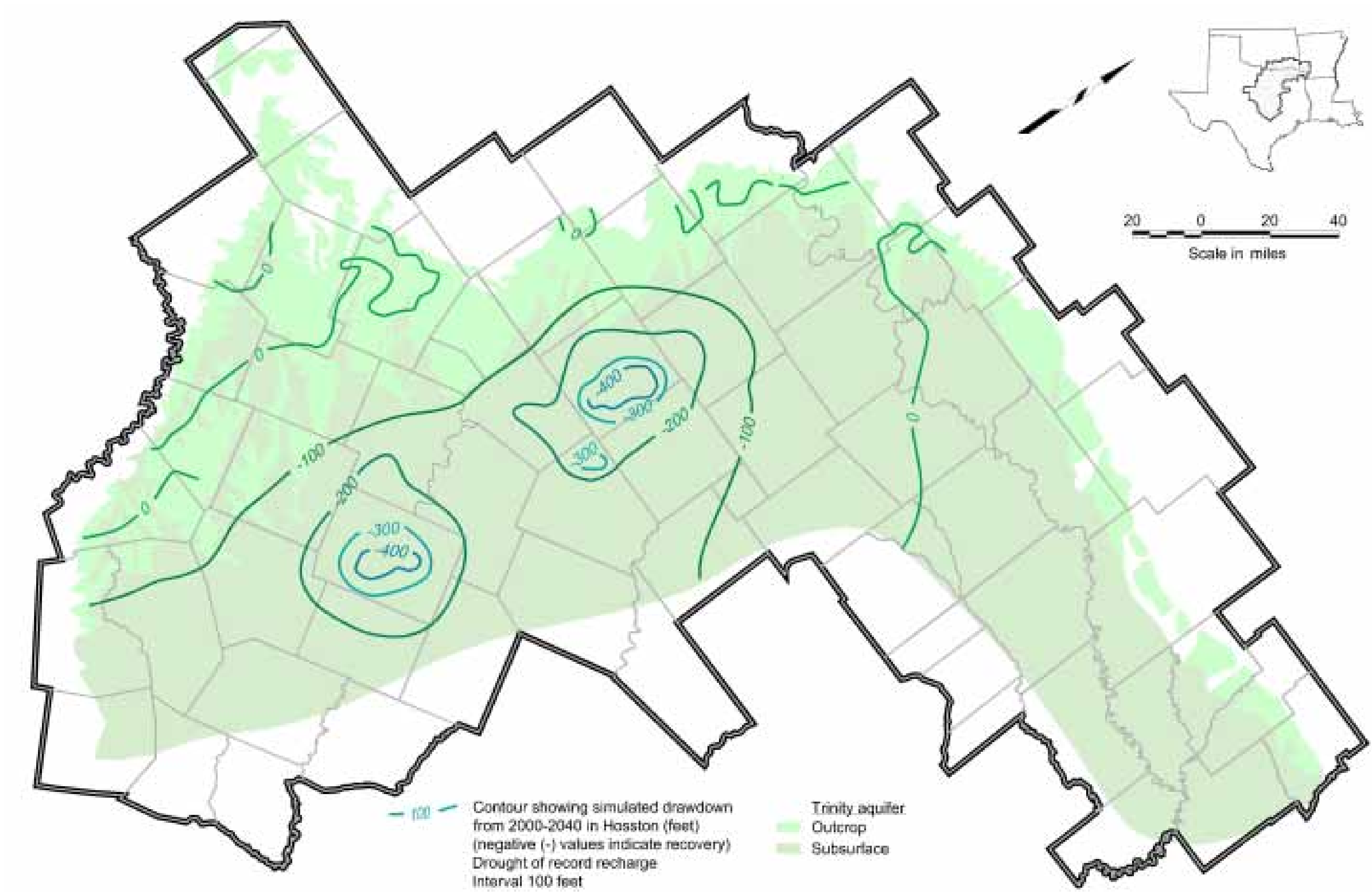



**Figure 10.80 Simulated Water Level Change From 2000 to 2040 for Layer 7 (Hosston) Assuming Drought of Record Recharge Distribution**

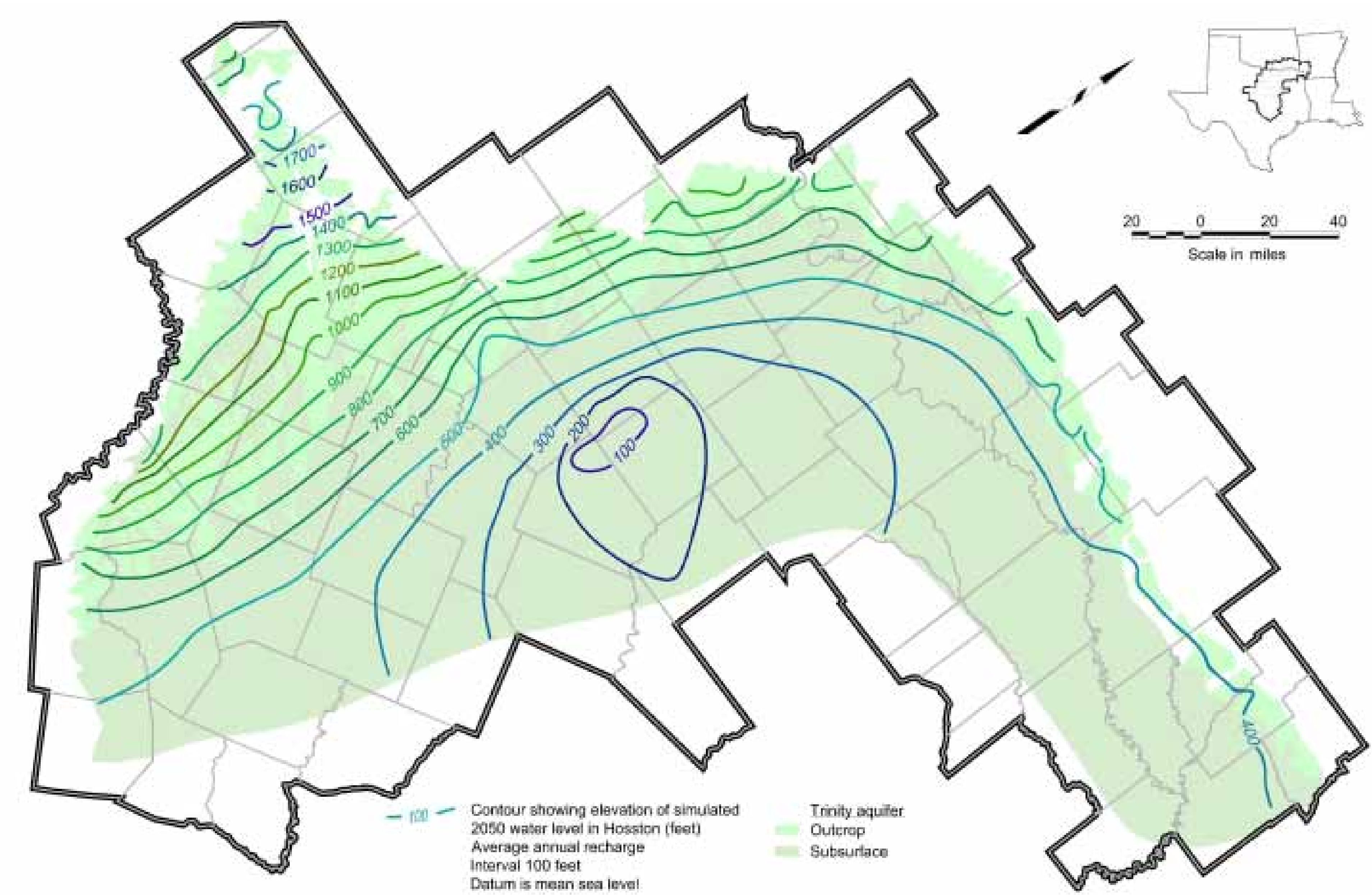



**Figure 10.81 Simulated 2050 Water Levels for Layer 7 (Hosston) Assuming Average Annual Recharge**

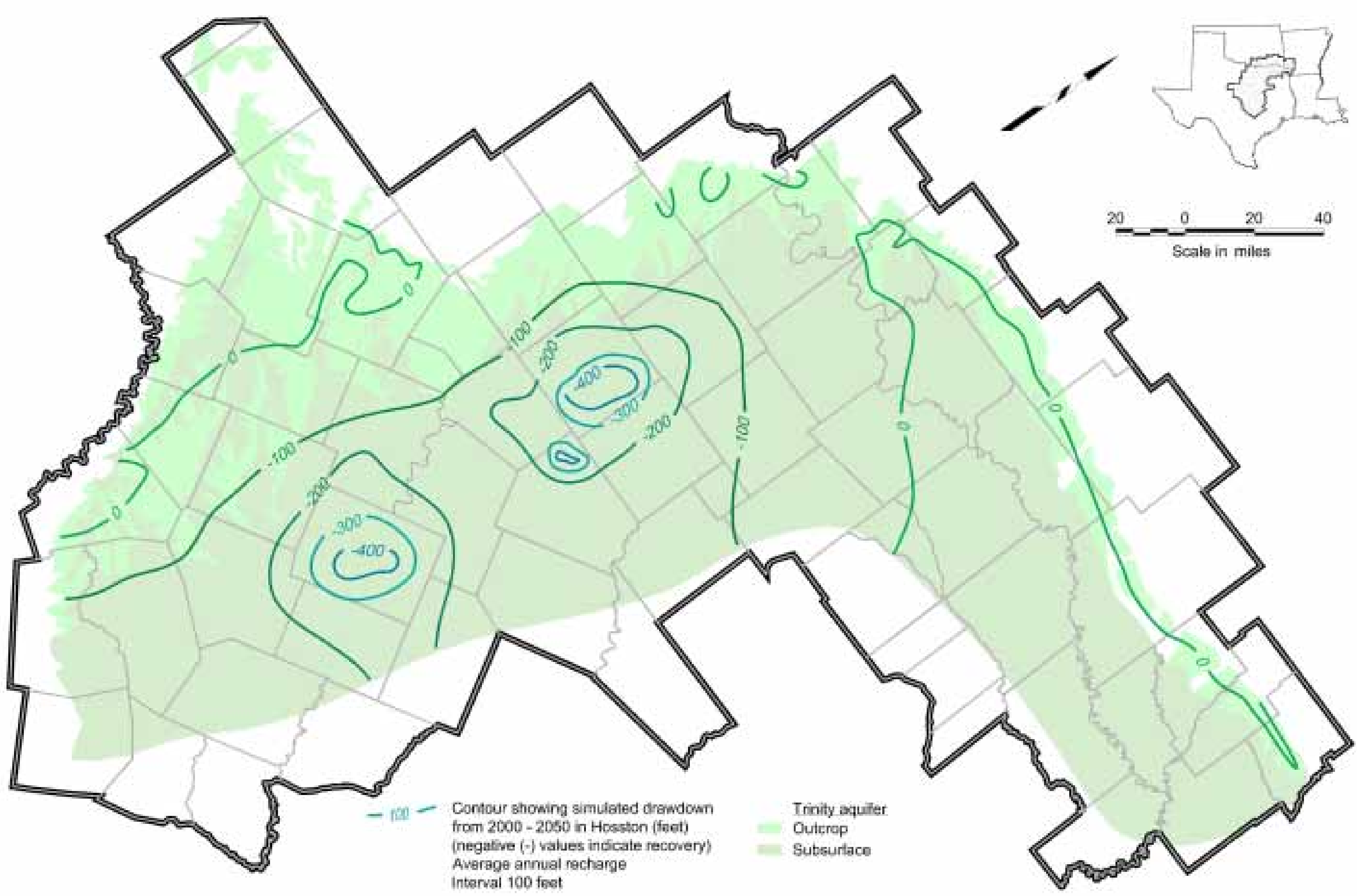



**Figure 10.82 Simulated Water Level Change From 2000 to 2050 for Layer 7 (Hosston) Assuming Average Annual Recharge**

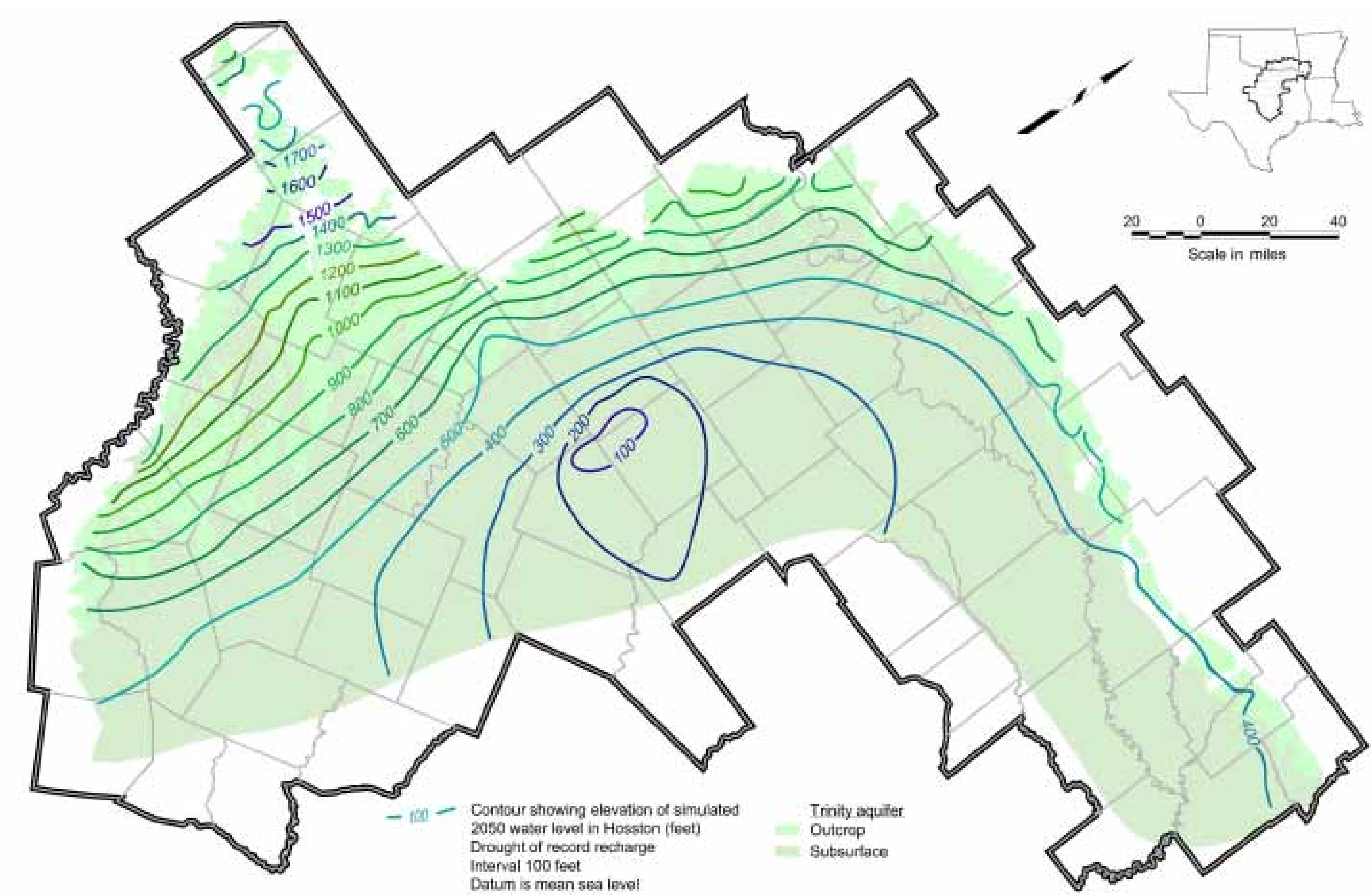



**Figure 10.83 Simulated 2050 Water Levels for Layer 7 (Hosston) Assuming Drought of Record Recharge Distribution**

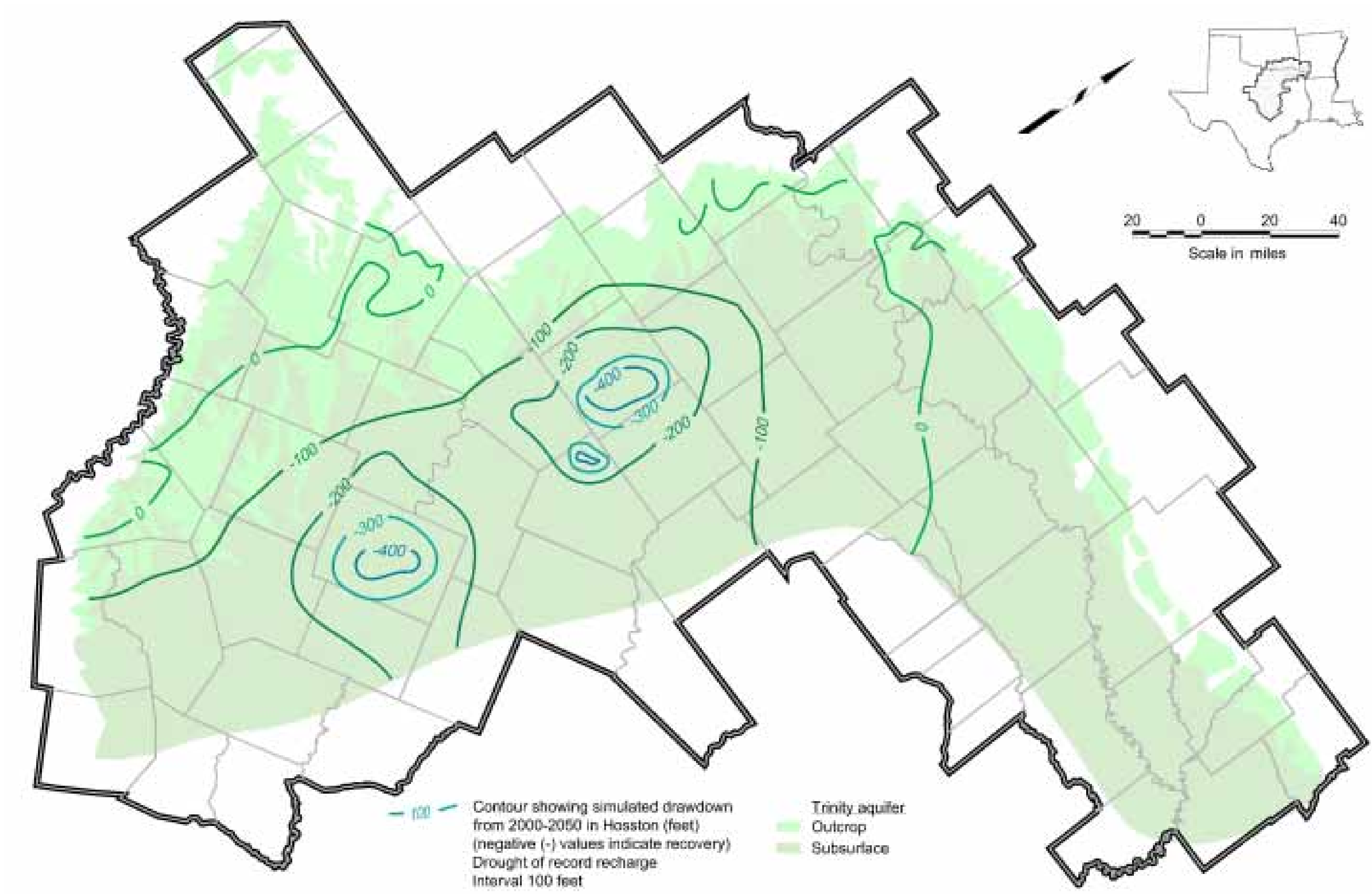



**Figure 10.84 Simulated Water Level Change From 2000 to 2050 for Layer 7 (Hosston) Assuming Drought of Record Recharge Distribution**

# 11.0 LIMITATIONS OF MODEL

This model is useful for evaluating the regional response of the Trinity/Woodbine aquifer to hydrologic stresses. It is recommended that it be used and results evaluated only by qualified groundwater professionals.

The relatively coarse cell size (one square mile) necessitates the averaging of spatial data and requires the introduction of many assumptions when constructing parameter datasets, precluding the accurate simulation of small-scale phenomenon. This includes spatial averaging of ground levels, aquifer hydraulic properties, evapotranspiration, and other hydrogeologic controls.

All regional groundwater systems incorporate rocks of varying hydraulic properties. However, several of the designated layers in the model are carbonate karst systems in some portions of the study area. Karst systems are typically characterized by extreme variations in hydraulic characteristics and often incorporate conduit flow that can significantly impact the flow dynamics of the groundwater system. The modeling approach used herein treats the karst systems as a more uniform porous media. As such, the modeled karstic systems represent estimated average conditions over regional-scale areas. Local, near-surface fractures can accept relatively larger amounts of recharge and facilitate short-term baseflow discharge. Such phenomena are beyond the resolution of this model.

The spatial averaging of ground level elevations assigned to outcrop cells also serves to smooth the topography input into the model, diminishing the hydraulic gradient between highlands and the streams, which in turn reduces the simulated baseflow. For this and a variety of other reasons, the model should not be used to assess groundwater-surface water interaction except in a very general manner. While surface-groundwater flow components are included in the water budget, they are very general in nature and more useful in indicating the approximate direction or magnitude of the groundwater-surface water flux than particular volumes or rates. In other words, the model should not be used to evaluate the specific or detailed impacts of pumpage on individual streams, rivers, or environments.

The model was not designed to be used for the estimation of individual well yields, nor the design of local well fields. Similarly, the model should not be used to determine the drawdown resulting from pumpage at a single location, in a well, or in areas where the local simulated water levels are likely distorted by model boundary effects or the relatively coarse discretization of the model grid.

Accurate reproduction of the complex internal stratification and structure of the individual hydrostratigraphic units was not possible in many areas because each of the individual hydrostratigraphic units was simulated utilizing a single MODFLOW layer. Faulting in the model domain was necessarily simplified. The displacement of model layers across fault boundaries was not modeled. In addition, hydraulic communication across the faults was estimated, as no detailed data were available. Therefore, the impact of these structural features on groundwater flow in these areas is only a simplification of actual flow.

Often, a lack of well completion data required that assumptions be made when attributing wells to individual model layers. These assumptions affect the distribution of calibration water level measurements, hydraulic parameters, pumpage, and water quality data. In addition, little information was available with respect to vertical communication between layers. As a result, the model may have some limitations with respect to predicted drawdowns in individual model layers, especially in areas where calibration information was scarce.

The Northern Trinity/Woodbine GAM is based on available data. Estimates of hydraulic parameters and aquifer geometry in some locations may not apply due to interpolation of values from nearby locations. In addition, the model should not be used to determine hydraulic parameters and aquifer geometry locally when more accurate and/or more recent information is available.

# 12.0 FUTURE IMPROVEMENTS

Groundwater flow models are only as accurate as the data used to develop the model. In addition, interpretation of simulation results is largely dependent upon the modeler's hydrologic understanding of the aquifer. While this model is an excellent tool for understanding historical change and estimating the future response of the aquifers to stresses, it should not be considered static. Rather, it should be updated and improved as often as required by the needs of the user(s). Some of the specific improvements that could be made to the model are summarized in this section.

In general, the structure provided in the model is more than adequate for regional assessments of aquifer response. However, refinement of the structural data in areas of extensive faulting and deformation would likely improve the accuracy of the simulations in a few local areas. This is particularly true in Grayson and Fannin Counties, and in the southern portion of the model in or near the Balcones Fault Zone. Additionally, model performance would likely benefit from the incorporation of site-specific information on the vertical and lateral hydraulic communication across fault zones in the study area.

Refinement of the historical pumpage input into the model may also improve model fit. Because Northern Trinity/Woodbine sediments are relatively non-transmissive, the distribution of wells heavily influences simulated water levels. For this reason, inappropriately reported and/or assigned historical pumpage not only skews calibration results, but also affects the estimation of future groundwater availability. Wells assigned the aquifer designations of "Trinity", "Antlers", "Twin Mountains", or "Travis Peak" are of special interest. These aquifer designations incorporate two or more of the individually modeled aquifers in the GAM, which allows for significant variation in the vertical distribution of pumpage from wells labeled as such. In some cases, well construction records report the thicknesses of the aquifers screened. However, reliable records are sparse and generally give little or no indication of the relative rates at which groundwater is withdrawn from each unit.

In many areas, the available knowledge and data pertaining to the Trinity/Woodbine (and aquifer systems in general) are sparse. Research into numerous topics would undoubtedly lead to insights into currently misunderstood aspects of groundwater hydrogeology. It is impossible to foretell with certainty which investigations will most advance our understanding of aquifer mechanics; however, with limited resources at our disposal, the ability to identify those avenues of study that are most likely to provide the most beneficial information is crucial.

In many areas, near-surface fluxes such as recharge, evapotranspiration, and discharge to springs, seeps, and streams can significantly influence local aquifer dynamics. However, the relative importance of these factors to regional groundwater availability is dependent upon the aquifer and the interval of study. In general, aquifers that are able to quickly accept recharge and subsequently transmit groundwater rapidly to discharge areas are more sensitive to near-surface fluxes. For example, karstic carbonate aquifers such as the Edwards aquifer in Central Texas can accept large volumes of recharge in small areas and over short intervals while simultaneously discharging groundwater to seeps, springs, and baseflow at relatively high rates. Because of this, water levels in the Edwards fluctuate rapidly in response to changes in climate within recharge areas, which in turn significantly affects the amount of groundwater available for use.

At the opposite end of the spectrum, the Trinity/Woodbine sediments accept recharge and allow discharge throughout a large area of outcrop but at relatively slow rates, resulting in a system that is comparatively stable and largely insensitive to changes in near-surface fluxes (see discussions in Sections 4.4.3, 4.5.3, and 9.1.3). This is demonstrated by the lack of coherent, historical water table declines in Trinity/Woodbine outcrop areas despite fluctuations in precipitation and widespread, sustained pumpage throughout the last 50 years. Sensitivity analyses of the calibrated model parameters also indicate that the water levels and water level drawdown throughout the aquifer are not appreciably affected by large changes in the amount of recharge. For this reason, additional research into the local rates and mechanisms of near-surface recharge and discharge from the Trinity/Woodbine would likely contribute little at this time toward the improvement of the model's ability to estimate the regional response of the aquifer system to pumpage. Additional studies regarding recharge and evapotranspiration could be conducted to attempt independent verification of the amounts of water entering the aquifer and discharging through natural vegetation. Therefore, recharge studies may provide better insights only on assessment of local site-specific recharge and natural discharge issues.

Conversely, investigations into the most basic aquifer properties and boundary conditions would likely do much to enhance the accuracy of regional groundwater availability evaluations. Confidence in the fundamental characteristics and behavior of an aquifer system not only allows for the improvement in the precision of water level predictions, but also facilitates the estimation the other fluxes that are either not directly measurable or are highly variable through space and time (e.g. baseflow, evapotranspiration, etc.). At present, the best method of characterizing the properties of an aquifer (and its associated boundary conditions) is by closely monitoring the water level response to pumpage. Although generally considered costly, several spatially distributed, large-volume, long-term aquifer tests conducted in wells penetrating individual Trinity/Woodbine aquifers would provide the most useful data concerning the real-world aquifer responses to applied pumpage.

# 13.0 CONCLUSIONS

This report provides documentation and simulation results for a predictive numerical groundwater flow model of the northern segment of the Northern Trinity/Woodbine aquifer system in Texas, Oklahoma and Arkansas. RWH&A was the prime contractor on the project. The work was conducted under a contract with the TWDB and provides the GAM for the subject aquifer. The model development, documentation, calibration, and simulations were developed using protocols specified by the TWDB and standard groundwater industry practices.

This model was developed as a tool to predict the regional response of the Northern Trinity/Woodbine aquifer system to groundwater stresses (primarily pumpage). The model predicts the aquifer's response by estimating the amount of drawdown or recovery that occurs in each model layer and the resulting changes in the water budget of the system. While this model is referred to as a groundwater availability model, it does not determine groundwater availability. The model is a useful tool, when properly utilized, for understanding the major hydrologic components that go into assessing groundwater availability. As such, this model should be considered as one of many tools available to groundwater conservation districts, regional water planning groups and other stakeholders.

Important conclusions resulting from development of the model and analysis of the simulation results include:

1) Artesian pressure declines of up to about 800 to 1,000 feet have occurred in major historical pumpage centers located in Dallas, Tarrant, and McLennan Counties.
2) Despite the large artesian declines recorded in downdip areas, outcrop water levels have remained relatively constant during the last 50 years, indicating that there has been little reduction in the amount of water in storage in the Northern Trinity/Woodbine system. From a practical standpoint, it is appropriate to conclude that there is essentially the same volume of water in the Northern Trinity/Woodbine aquifer as there was 50 years ago. Decreases in artesian storage or water table storage that have occurred are insignificant compared to the amount of water still present in the aquifer and the overall water budget of the aquifer.
3) The current model indicates that a large majority (~90%) of the current discharge from the aquifer is occurring through natural, near-surface mechanisms, primarily evapotranspiration and baseflow to streams, springs, and seeps, not pumpage. However, the percentage is dependent on the amount of recharge that is occurring. The actual amount of this natural discharge and recharge are difficult to measure directly, but

because of the large outcrop area and the stability of outcrop water levels it is reasonable to assume that a large percentage of the current recharge to the aquifers is being rejected through natural, near-surface mechanisms.

4) Analyses of the model results indicate that groundwater levels in the Northern Trinity/Woodbine system are not particularly sensitive to recharge, suggesting that the system is relatively resistant to drought conditions. This is consistent with the comparatively low transmissivities and large outcrop areas (e.g. specific yield storage) associated with the modeled aquifers.

5) Simulation of the aquifer response to future projected pumpage (based on the RWPG's and TWDB's pumpage estimates) shows a recovery of the artesian pressure in the Trinity/Woodbine of many hundreds of feet because of a predicted reduction in pumpage. While this is one possible use scenario, it is uncertain that future pumpage will decline by the amounts forecasted. Projected growth throughout the IH-35 corridor will likely exert pressure to continue use of the Trinity/Woodbine aquifers at existing, or possibly greater, levels in the future.

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Of course, this project could not be completed without the thorough dedication and concerted effort of the project team and its members. Unfortunately, we cannot thank all the individuals who so judiciously contributed their knowledge, time, and efforts. We would like to acknowledge some of those organizations and individuals who provided vital components of the work and their contributions.

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This report reflects the views of R.W. Harden & Associates, Inc. and should not be interpreted as necessarily representing the opinions, either expressed or implied, of HDR Engineering, Inc., Freese & Nichols, Inc., LBG-Guyton Associates, the United States Geological Survey, Dr. Joe Yelderman, or the Texas Water Development Board.

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The following is a list of the studies/tasks performed for the GAM project and the authors (in alphabetical order) associated with them:

***Project lead, geology, structure, hydrostratigraphy, literature review, model recharge estimates, evapotranspiration, discharge/pumpage assignment, conceptual model, model design/construction, model calibration/verification, predictive simulations, and reporting:*** R.W. Harden & Associates, Inc. (James Bené, Robert Harden, Brian Henkel, Ridge Kaiser, Kevin Spencer, Joel Zimmerman).

***Historical water levels and groundwater flow, water quality, previous recharge estimates, and aquifer hydraulic properties:*** LBG-Guyton Associates (Stuart Burton, Andrew Donnelly).

***Groundwater/surface water interaction:*** HDR Engineering, Inc. (David, O'Rourke, Kristine Shaw)

***Climatic data and stakeholder/RWPG interfacing:*** Freese & Nichols, Inc. (Stephanie Griffin, Stefan Schuster)

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# 16.0 APPENDIX 1: CONCEPUAL MODEL REPORT COMMENTS AND RESPONSES – TWDB MODELING STAFF

The following sections list the technical/administrative and editorial comments submitted by the Texas Water Development Board staff associated with the Northern Trinity/Woodbine GAM Conceptual Model Report. The responses to individual comments and suggestions are described in italics below each entry.

## 16.1 Conceptual Model Draft Report Technical/Administrative Comments

### 16.1.1 Section 2.0

1. Per Exhibit B, Attachment 1, Section 5.4: Figures required for the GAM report include a figure of the study area showing major towns and cities, county boundaries, major rivers and streams, major lakes, major roadways, location of the study area within Texas or any bordering states (if applicable), and the model boundaries. Figure 2.1 (page 2-2) incorporates county boundaries, location of the study area within Texas or any bordering states (if applicable), and the model boundaries. Please update this figure to include major towns and cities, major rivers and streams, major lakes, and major roadways. Please update legend to include solid black line as study area and reference additions noted above.

   ***Figure updated.***

2. Figure 2.2 (page 2-3): Please update legend to include solid green line as Trinity aquifer outcrop extent, explanation for dashed green line for downdip, solid blue line as Woodbine aquifer outcrop extent, and explanation for dashed blue line for downdip. Also if East Texas (Region I) is not part of the study area, please do not include and update text on page 2-1 accordingly.

   ***Figure updated.***

3. Figure 2.3 (page 2-4): Per Exhibit B, Attachment 1, Section 5.4, states the caption shall include reference sources for the basemap or the included information. According to http://www.twdb.state.tx.us/mapping/gisdata.htm , the latest GCD was updated September 1, 2003. It is advisable to reference date of GCD map update in caption. In addition, it appears the study area includes Robertson County, please include Brazos Valley GCD to the map, if applicable, and update text on page 2-1 accordingly.

   ***Figure updated.***

4. Figure 2.4 (page 2-5): Please update legend to include solid green line as Trinity aquifer outcrop extent, explanation for dashed green line for downdip, solid blue line as Woodbine aquifer outcrop extent, and explanation for dashed blue line for downdip. Please cross-reference or include TWDB basin designations to map (http://www.twdb.state.tx.us/mapping/gisdata.htm) and reference data source in caption per

Exhibit B, Attachment 1, Section 5.4, which states the caption shall include reference sources for the basemap or the included information.

***Figure updated.***

5. Section 2.1 (page 2-6): States the study region lies in portion of the Coastal Plains, Central Lowlands, and the Great Plains. Figure 2-5 (page 2-8) shows the study area in the North-Central Plains, Grand Prairie, Blackland Prairies, Interior Coastal Plains, and Edwards Plateau. Please adjust so text and figure agree. Please reference data source in caption per Exhibit B, Attachment 1, Section 5.4, which states the caption shall include reference sources for the basemap or the included information.

   ***Figure updated.***

6. Figure 2.5 (page 2-8), Figure 2.6 (page 2-9), Figure 2.7 (page 2-10), Figure 2.10 (page 2-13): Please include a legend that references solid green line/area as Trinity aquifer outcrop extent, explanation for dashed green line for downdip (or lighter green area), solid blue line/area as Woodbine aquifer outcrop extent, and explanation for dashed blue line for downdip (or lighter blue area). Please reference data source in caption per Exhibit B, Attachment 1, Section 5.4, which states the caption shall include reference sources for the basemap or the included information.

   ***Figure updated.***

7. Figure 2.7 (Page 2-10), Please show quads/control points for developing the contour lines for lake evaporation map.

   ***Figure updated.***

8. Figure 2.8 (page 2-11), Figure 2.11 (page 2-18), Figure 2.12 (page 2-19): Please reference data source in caption per Exhibit B, Attachment 1, Section 5.4, which states the caption shall include reference sources for the basemap or the included information. In addition, please correct spelling of Comachian in Figure 2.11 to Comanchean.

   ***Figure updated.***

9. Section 2.2 (pages 2-14 to 2-17): Per Exhibit B, Attachment 1, Section 3.1.2 states this section shall include a description of the important local and regional structure features in the study area. Please introduce the Luling-Mexia-Talco Fault Zone in this section and at a minimum refer to a more in-depth discussion in section 4.2.

   ***Included text introducing the major fault zones on page 2-17.***

10. Per Exhibit B, Attachment 1, section 3.1.2, states any available information on net-sand thickness maps and how they were developed shall also be presented in this section, as well as, several cross-sections throughout the study area. Please move net-sand thicknesses and geologic cross-section figures and text from Section 4 to Section 2.

    ***Moved text and figures from Section 4 to Section 2.***

### 16.1.2 <u>Section 4.0</u>

1. Explain in the structure section how the units (Travis Peak/Twin Mountain, Antlers etc.) that pinch out in the subsurface were treated in developing the structure surfaces. As discontinuous hydrostratigraphic units are in conflict with MODFLOW numerical requirement, a minimum thickness "dummy" layer is generally placed where a given hydrostratigraphic unit is absent. Has this procedure been followed?

   ***Added text Section 4 (page 4-1) describing the observation that the Glen Rose carbonates are not distinguishable on geophysical logs (pinches out) in the northern part of the study area, but there exists a clay-rich sediment interval between the Paluxy and Hensell in most cases. Because of this separation, there was no need to insert a "dummy" layer to account for the Glen Rose "pinch out". For areas where model layers represent aquifer units that no longer contain an appreciable amount of sand, reduced Kh values were applied to the model.***

2. Figure 4.2 (page 4-6): Please correct spelling of "Comachian" to "Comanchean" in Series column. Please add legend explaining tan model layers refers to confining units and blue model layers refer to aquifers.

   ***Correction made, and note added to bottom of diagram.***

3. Figures 4.3 to 4.7 (pages 4-7 to 4-11): Please add north arrow and scale in Index map box per Exhibit B, Attachment 1, Section 5.4.

   ***Figure updated.***

4. Figure 4.7 (page 4-11): Please re-label E to E' to E' to E or flip cross-section so that Index map and cross-section agree.

   ***Figure updated.***

5. Figure 4.10 (page 4-14): Is a duplicate of figure 4.9 (Elevation of the Base of the Woodbine). Please update report with figure showing the thickness of the Woodbine aquifer.

   ***Figure updated.***

6. Figures 4.35 through 4.38. Maintain uniform vertical scale on the hydrographs so that equal interval can refer to equal drawdown.

   ***Hydrographs with uniform scales inserted into figures.***

7. Figures 4.8 to 4.11 (pages 4-12 to 4-15): Please include in legend outcrop and downdip color designations used in the figures. Also please clarify notation in legend that states outcrop control points not shown. Figures appear to have some control points in the outcrop area, as well as, control points outside the Woodbine. This statement appears confusing and contradictory.

   ***Figure updated.***

8. Figures 4.12 to 4.23 (pages 4-16 to 4-27): Please include in legend outcrop and downdip color designations used in the figures. The two-tone designation of the outcrop area for the Trinity (Paluxy) appears confusing for Figures 4-12 to 4.14. Figure 4.15 (Net Sand for the Paluxy) appears to just show the extent of the Paluxy aquifer with one outcrop and a downdip color designation. Please clarify and for consistency please use the outline in Figure 4.15 for Figures 4.12 to 4.14 and update legend, as needed.

   ***Figure updated.***

9. Section 4.1 (page 4-2) states the sand thickness increases from less than 100 feet to about 600 feet (see Figure 4.11). Figure 4.11 show the maximum thickness of 400 feet. Please clarify and adjust appropriately.

   ***Text corrected to state a maximum thickness of 400 feet in the model area.***

10. Please note that when the contours in figures 4.12 and 4.13 are overlain, the Central Texas area does not agree with Figure 4.14, which indicates zero thickness in the same area. Please adjust so text and figures are in agreement.

    ***Figures corrected to show zero thickness in the Central Texas area.***

11. Per Exhibit B, Attachment 1, Section 3.1.4: The structure section should include discussion and figures relating to the top and bottom of each stratigraphic unit and layer thicknesses. Please move this information from Section 4.1 to Section 4.2. In addition, Exhibit B, Attachment 1, Section 3.1.4 states all information used to develop the structure surfaces shall be fully documented as to source, techniques, and quality. Please expand section 4.2 in the report with this information.

    ***Specified text was moved to Section 4.2. Text expanded in Section 4.2 to include structure documentation.***

12. Section 4.4.1 (page 4-38): States one criterion used for the development of the target water levels was selecting "publishable" data. Please verify if you also examined the remarks field and only selected blank, 1, or 01 records. Records that contain values greater than 1 indicates the well was being pumped, recently pumped, or some other circumstance which may have bearing if the water level is considered a static measurement (please see UM-50 for additional information: http://www.twdb.state.tx.us/publications/manuals/UM50%20Data%20Dictionary/um50.pdf )

    ***Text expanded to note that only water level records with remarks indicating "good measurements" were included in the study.***

13. Figures 4.30 to 4.32 (pages 4-40 to 4-42): Please update legend with aquifer color designations used in the figure.

    ***Figure updated.***

14. Section 4.4.3 (page 4-44) and Figure 4.38 (page 4-50): The text references Well 32-46-907 in Johnson County, however the hydrograph for this well is not included in Figure 4.38. Please

update Figure 4.38 with this hydrograph or attempt to tie the drawdown discussion to well 58-29-603, which also appears to have experienced a 200-foot drawdown since the 1940s.

***Text amended such that well 58-29-603 was tied into discussion.***

15. Section 4.5.1, Precipitation, (page 4-66): The text states the western portion of the study area averages 20 inches per year rainfall. Figure 2.10 (page 2-13) shows 30 inches per year of rainfall as the lowest contour. Please clarify and adjust so figure and text agree.

    ***Text modified to indicate a minimum of 30 inches per year of precipitation.***

16. Figure 4.54 (page 4-75): Please reference data source in caption per Exhibit B, Attachment 1, Section 5.4, which states the caption shall include reference sources for the basemap or the included information.

    ***Figure updated.***

17. Figure 4.56 (page 4-78): Per Exhibit B, Attachment 1, Section 5.4, please update figure with scale, north arrow, and legend. In addition please update caption with reference sources for the basemap or the included information.

    ***Figure updated.***

18. Per Exhibit B, Attachment 1, Section 3.1.7: Any specific or general information on streambed conductance shall be addressed including estimates and discussions for the information needed for the streamflow-routing package (streambed top and bottom, channel width and slope, and Manning's roughness coefficient). Please update section 4.6 with this discussion.

    ***Specified discussion is included in Section 4.6.5.***

19. Per Exhibit B, Attachment 1, Section 3.1.7: Information needed for the reservoir (lake) package shall be estimated and justified, for example reservoir conductance. Please update section 4.6.4 with this discussion.

    ***Specified discussion is included in Section 4.6.5***

20. Per Exhibit B, Attachment 1, Section 5.4, states the report should include basemaps of rural population densities and bar chart of yearly total historical and predicted groundwater usage. Please update report with these figures and include discussion in text.

    ***Specified text and figures are presented in Section 4.9.***

21. Table 4.13 (pages 4-112 to 4-113): Unable to match values listed. Please verify and clarify source of pumpage.

    ***Use data verified as correct. Table 4.13 includes only pumpage for the specified aquifer(s) within the active model area. Clarifying text added to Section 4.9.***

22. If Fig. 4.64 was provided by the TWDB, please provide a reference appropriately to indicate the data source.

    ***Reference inserted***

### 16.1.3 Section 5.0

1. Provide a block diagram that shows the model layers, types of model boundaries assigned, hydraulic interactions between units, and other hydrologic parameters to completely characterize how the flow system is conceptualized/simulated. For reference, please consult fig.50 of TWDB Report 353.

    ***Figures 8.1 and 9.1 included in report***

## 16.2 Conceptual Model Draft Report Editorial Comments

### 16.2.1 Abstract

1. Abstract does not summarize important elements of the report.

    ***Abstract modified to summarize the report elements.***

### 16.2.2 Section 2.0

1. Section 2.2 (page 2-15 and page 2-17): The last sentence in the first full paragraph page 2-15 and the first sentence on page 2-17 reference Klemt, 1975. The reference section lists Klemt and others, 1975. Please clarify and either add new citation in reference section or adjust reference in text as needed.

    ***Citation corrected.***

### 16.2.3 Section 3.0

1. Section 3.0 (page 3-1): The following citations are not listed in the reference section or may be cited in the reference section with co-authors: Taff (1893), Hill (1887), Hill (1891), Armstrong (1932), Klemt (1975), Klemt (1976), and Baker (1990). Please update either the reference section with the appropriate information or update the text indicating co-authors.

    ***Citations corrected and/or removed.***

### 16.2.4 Section 4.0

1. Section 4.1(page 4-3): The last sentence reference Klemt, 1975. The reference section lists Klemt and others, 1975. Please clarify and either add new citation in reference section or adjust reference in text as needed.

   ***Citation corrected.***

2. Section 4.4.4 (page 4-64): The first sentence reference Klemt, 1975. The reference section lists Klemt and others, 1975. Please clarify and either add new citation in reference section or adjust reference in text as needed.

   ***Citation corrected.***

3. Section 4.5 (page 4-65): The text references Table 4.5.1, however table and Table of Tables list this as Table 4.1. Please update text to Table 4.1.

   ***Text corrected.***

4. Table 4.1 (page 4-65): Table 4.1 cites the following references: Blunzter (1992), Kuniansky and Holligan (1994), Kuniansky (1989), Reeves (1967), and Reeves (1969). These are not listed in the reference section. Please update the reference section with full reference information.

   ***References added.***

5. Figure 4.51 (page 4-72): It is hard to distinguish Soil type A and Soil type B. Suggest a different color palette is used to distinguish between these soil classifications.

   ***Figure updated.***

6. Figure 4.53 (Page 4-74): It is hard to distinguish land uses. Suggest using a different color palette to distinguish between land use classifications. Please reference data source in caption per Exhibit B, Attachment 1, Section 5.4, which states the caption shall include reference sources for the basemap or the included information.

   ***Figure updated.***

7. Table 4.2 (page 4-77): Column "Average Flow into Trinity Outcrop" contains both comments and flow information. Suggest removing comments from this column and possibly adding another column with this information.

   ***Table modified as suggested.***

8. Section 4.6.2 (page 4-79): First sentence references Slade (2002). The reference section lists Slade and other, 2002. Please clarify and either add new citation in reference section or adjust reference in text as needed.

   ***Reference added.***

9. Section 4.6.2 (page 4-80): Last paragraph references Table 4.6.1. Please correct.

   ***Text corrected.***

10. Figure 4.64 (page 4-93): Water features blend into the outline used for the Woodbine. Please adjust figure. Please update legend to include features used in the figure.

    ***Figure updated.***

11. Section 4.8.1, Hensell section (page 4-103): This section cites Klemt, 1975 in two places. The reference section lists Klemt and others, 1975. Please clarify and either add new citation in reference section or adjust reference in text as needed.

    ***Citation corrected.***

12. Section 4.8.1, Hosston section (page 4-104): The last sentence states the Hosston transmissivity data has geometric mean of 8,62 $ft^2/d$. Please remove comma in 862 $ft^2/d$.

    ***Comma removed.***

### 16.2.5 <u>Section 6.0</u>

1. There are numerous references that have been referred to in the text but not cited in the reference list. Please ensure that this is addressed.

   ***Citations corrected.***

2. Please indent 2nd line of Baker (1960) reference.

   ***Reference format corrected.***

3. Section 6.0 (page 6-4): Please break reference for Holloway (1961) and Hayward (1978) so that Hayward, C., 1978 appears on separate line.

   ***Reference format corrected.***

4. Section 6.0 (page 6-5): Please correct spelling for Chowdhury in Mace and others (2000).

   ***Reference corrected.***

5. Section 6.0 (page 6-6): Please indent third line in Peckham and others (1963).

   ***Reference format corrected.***

# 17.0 APPENDIX 2: FINAL DRAFT REPORT COMMENTS AND RESPONSES – TWDB MODELING STAFF

The following sections list the technical/administrative and editorial comments submitted by the Texas Water Development Board staff associated with the Northern Trinity/Woodbine GAM Final Draft Report. The responses to individual comments and suggestions are described in italics below each entry.

## 17.1 Final Draft Report Technical/Administrative and Editorial Comments

### 17.1.1 Abstract

1. Please further revise the abstract to include important elements of the modeling effort. Please include information on 1) how recharge was modeled, 2) hydraulic conductivity of the aquifers, 3) fluxes in/out of the flow system, 4) level of fit between simulated and observed water-levels (RMS) during steady-state and transient runs, and 5) results from predictive runs.

   ***Text amended.***

### 17.1.2 Table Of Contents

1. No comments.

### 17.1.3 Section 1.0

1. No comments.

### 17.1.4 Section 2.0

1. Figure 2.2, please allow consistency in describing the legend: Region D, North East Texas, Region K Lower Colorado.

   ***Legend corrected.***

2. Figure 2.11, Please use correct spelling of Fredericksburg Group.

   ***Spelling corrected.***

3. Figures 2.15 and 2.17, Please change reference from Klemt, 1975 to Klemt et al., 1975.

   ***Reference modified.***

4. Per review comment from the Conceptual Draft Report, please re-label cross-section from E to E' to E' to E to match direction of traverse shown in the Index map.

***Cross-section modified.***

5. Figure 2.5. Fenneman and Johnson (1946) is not in the references.

   ***Reference added.***

6. Figure 2.6. It is not clear which USGS reference is intended. EROS data center and National Elevation Dataset are not in the reference section.

   ***Reference added.***

7. Figure 2.12 It is not clear which USGS reference is intended.

   ***Figure source modified.***

### 17.1.5 <u>Section 3.0</u>

1. Per Exhibit B, Attachment 1, Section 5.4, the 'Previous Work' section shall describe the previous modeling efforts in the aquifer and compare and contrast them to each other and the new modeling effort for GAM. Please expand this section to include a discussion that compares and contrasts the previous modeling efforts to each other and the new modeling effort for GAM. It would be helpful to include a figure showing the extents of each of the models, if possible.

   ***Text amended.***

2. Page 3-1. Baker (1960) is not in the references.

   ***Reference added.***

### 17.1.6 <u>Section 4.0</u>

1. Figure 4.2, please use the correct spelling of Comanchean and Fredericksburg.

   ***Spelling corrected.***

2. Per review comment from the Conceptual Draft Report, please update Figure 4.6 with a figure showing the total thickness of the Woodbine. Figures 4.5 (base of the Woodbine) and 4.6 (thickness of the Woodbine) are the same figure and do not support the discussion in the text (pages 4-7 and 4-8) of thicknesses of 600 feet with an average of 300 feet for the Woodbine aquifer.

   ***Corrected figure inserted.***

3. Please add Texas Cooperative Extension (2003) to Reference Section.

   ***Citation modified to: (Fipps, 2003).***

4. Page 4-30 mentions ‘the Woodbine’ in discussions for Table 4.8, which contains data for the Hosston aquifer layer. Please replace ‘Woodbine’ with ‘Hosston’ in the text.

   ***Text amended.***

5. Is the page after 4-39 intentionally blank?

   ***Page not blank in current document.***

6. Per Exhibit B, Attachment 1, section 3.1.5, the hydrographs will help define water-level declines and seasonal fluctuations throughout the model and will also serve as calibration targets. Please include a discussion if seasonal trends were observed in each of the aquifers.

   ***Text amended***

7. Page 4-64. Nordstrom (1983) is not in the references.

   ***Reference changed to Nordstrom (1982)***

8. Page 4-66 (Soil Permeability) references Figure 4.42 (Soil Permeabilities). The text states permeabilities in the study area ranges from 2 to 50 inches per hour. The legend in Figure 4.42 shows a range of 0.077000 to 0.100000 inches per hour. Please clarify units and adjust text or figure legend as needed.

   ***Figure legend corrected.***

9. Page 4-67 (Land use) references Figure 4.43 (Land Use). The text states “Herbaceous Planted” and “Non-natural Woody” are the dominant land use categories. Figure 4.43 shows very little “Non-natural Woody” land use in the study area. Please clarify and adjust as needed.

   ***Text amended.***

10. Page 4-68. Please include a full description of the factors by categories (land use, layer factor, permeability and rainfall) that were used to produce the recharge estimate. Inclusion of this information is essential for reproduction of recharge data sets.

    ***Text amended.***

11. Page 4-78, Figure 4.47. Please ensure that this figure is completely legible. Legends and station numbers could not be read.

    ***New figure inserted.***

12. Page 4-82, Figure 4.49. Please correct labeling of y-axis.

    ***Axis label corrected.***

13. Page 4-85 (Baseflow Studies), please verify if the final sentence on page 4-85 should read, ’The application of these values is described in section 4.6.6’.

***Text amended.***

14. Page 4-87, Figure 4-53. Please put consistent color code in legend for drainage area.

    ***Figure corrected.***

15. Figure 4.55. GAP not in references.

    ***Figure source modified.***

16. Section 4.6.5 (Stream Bed and Reservoir Bed Conductance) on page 4-91 references Figure B-2. Unable to locate figure B-2. Please either add this figure to the report or delete this reference.

    ***Reference deleted.***

17. Section 4.9 pages 4-112 to 4-113, Please verify if final sentence in Discharge section should read,' Table 4.21 and 4.22 list the total pumpage amounts by county for the Trinity and Woodbine respectively'.

    ***Text amended.***

18. Please reference Figures 4.73 (Rural Population Density 1990) and Figure 4.74 (Rural Population Density 2000) to discussion in section 4.9.2 (Rural Domestic Discharge).

    ***Figure references added.***

### 17.1.7 Section 5.0

1. No comments.

### 17.1.8 Section 6.0

1. Page 6-1. There is no reference for PMWIN.

    ***Reference added.***

2. Section 6.2 (Layers and Grid, page 6-2) Please update reference Haley et al.(1993) to Haley et al. (2000) to match Reference Section or adjust as needed.

    ***Reference updated.***

### 17.1.9 Section 7.0

1. Please expand discussion to include root mean square error between measured hydraulic head and simulated hydraulic head shall be less than 10 percent of the measured hydraulic head drop across the model or better. Also include discussion of sensitivity analysis. Per Exhibit

B, Attachment 1, Section 5.4, the modeling approach section shall describe the approach, philosophy, and focus for model calibration. Per Exhibit B, Attachment 1, Section 3.3, please discuss your strategy for addressing dewatered cells.

***Text amended.***

### 17.1.10 Section 8.0

1. No comments.

### 17.1.11 Section 9.0

1. Please update all figures (Figures 8.6 to 8.9) containing simulated vs. measured water levels to include simulated water-level values for the entire model area (active cells) and not only areas where there are measured values. Please include water-level contours for areas with steep declines in water levels. We suggest that areas with steep declines in water levels be represented in different colors than the rest.

   ***Figures updated.***

2. Figure 8.7. Please show water-level contours for areas with steep declines in water levels (water-level elevations of up to –250 feet in Tarrant County).

   ***Figure modified.***

3. Figure 8.8. Please show water-level contours for areas with steep decline in water levels (water-level elevations of up to –325 ft in Tarrant and Dallas counties).

   ***Figure modified.***

4. Figure 8.9. Please show water-level contours for areas with steep declines in water levels (water-level elevations of up to –850 ft in Tarrant and Dallas counties).

   ***Figure modified.***

5. Per Exhibit B, Attachment 1, Section 5.4, final figures shall include several hydrographs demonstrating the sensitivity of water-level fluctuations to changes in important hydrologic properties of the model.

   ***Figures added.***

### 17.1.12 Section 10.0

1. Per Exhibit B, Attachment 1, Section 5.4, final figures shall include saturated thicknesses for 2010, 2020, 2030, 2040, and 2050 for average recharge conditions.

   ***Figures added.***

2. Table 10.2, please check the water budget numbers for 2050. From the model runs, we obtain a storage value of 220,943 ac-ft/yr compared to 207,657 ac-ft/yr reported, ET is –949,459 ac-ft/yr compared to –951,621 ac-ft/yr reported, and Stream flow is -39,370 ac-ft/yr compared to –37,105 ac-ft/yr reported.

   ***Water budgets recalculated and inserted in Table 10.2 following model pumpage update.***

3. Is the page 10-9 intentionally left blank? Also, Page 10-5 (Figure 10.1) starts after Page 10-9 (Table 10.2). Please correct pagination.

   ***Blanks and pagination corrected.***

### 17.1.13 <u>Section 11.0</u>

1. Page 11-1, Para 2: Please provide specific reasons why pumpage effects on streams cannot be determined using the model.

   ***Text amended.***

2. Page 11-1, Para 3: Please rewrite to "…. nor the design of local well fields". Please remove ".. or in close proximity of well fields".

   ***Text amended.***

3. Page 11-2: Please rewrite "Estimates of hydraulic parameters and aquifer geometry should not be assumed to be applicable to specific sites or locations" to "Estimates of hydraulic parameters and aquifer geometry in some locations may not directly apply due to interpolation of values from nearby locations"

   ***Text amended.***

### 17.1.14 <u>Section 12.0</u>

1. Suggest adding additional pump tests in areas with limited information. Additional studies on recharge, possibly age-dating, and ET.

   ***Text amended.***

### 17.1.15 <u>Section 13.0</u>

1. No comments.

### 17.1.16 <u>Section 14.0</u>

1. No comments.

### 17.1.17 <u>Section 15.0</u>

1. Please adjust format for Baker, E.T., Jr., 1960, Geology and ground-water resources of Grayson County.

   ***Format adjusted.***

2. Please assign journal name and volume number for Canadell and others (1996).

   ***Reference updated.***

3. Please put page numbers for LBG-Guyton and Associates (2003).

   ***Reference updated.***

4. Please provide year of publication for Texas Parks and Wildlife reference.

   ***Reference updated.***

5. Page 15-3. Hayward (1978) is out of order.

   ***Order corrected.***

6. Page 15-5. Both Reeves references are out of order

   ***Order corrected.***

### 17.1.18 <u>Public Review Comments:</u>

1. No comments.

### 17.1.19 <u>Model Files And New Report Comments:</u>

1. PMWIN Water budget module for calibration/verification period could not be run.

   ***Unable to reproduce problem. Model files rewritten.***

2. TWDB staff extracted pumpage from the input model files and compared the summed results at the county level to the raw pumpage summed at the county level. While not all of the historic raw pumpage categories were aquifer-specific, we expect the summed pumpage in the model for a specific county to either match the raw data or be less than the estimates for the entire county. Since the predictive dataset contained only aquifer specific data even though the aquifer may not cover an entire county, the comparison between the well.dat file and raw data should match reasonably well, if not exactly. One observation is that the pumpage files for calibration/verification period appear to be shifted by one year in almost all of the counties reviewed.

   ***Analysis revealed no shift in historical pumpage.***

3. Please review the pumpage files used in the model, adjust as needed, and/or provide a detailed table outlining stress periods to dates so users can easily extract various pumpage datasets from the well.dat files by year/stress periods. In addition, we observed pumpage in the predictive well.dat files were considerably less than the raw pumpage provided in approximately 80 percent of the counties in the study area (see Figures 6-10 as samples of our QA analyses). Please review, clarify, and if needed adjust the pumpage in all of the study area to more reasonably match the data provided.

   ***Predictive pumpage recompiled and input into model.***

4. Please provide a "read me" file that makes it clear that MODFLOW version MODFLOW96+INTERFACE TO MT3DMS must be used to allow the model to run correctly in PMWIN5.3. The readme file should include any other instructions that are necessary to run the model. Also, please indicate the necessary MODFLOW executable file.

   ***"Readme" text files constructed and included with model files.***

5. Please provide a .dxf file of the boundary of the active model area.

   ***Dxf files depicting the active model boundaries constructed and included.***

6. It is assumed that the 20 stress periods in the transient calibration/verification model correspond to 1/1/1980 through 12/31/1999. If correct, please place this information in a readme file.

   ***Information included in "readme" text files included with model files.***

7. It is assumed that the 50 stress periods in the 2050 average recharge model correspond to 1/1/2000 through 12/31/2049. If correct, please place this information in a readme file.

   ***Information included in "readme" text files included with model files.***

8. In checking the water budget, a difference was found between the predictive model average recharge and drought of record stream leakage totals given in Table 10.1 and the totals computed from TWDB check runs. Please explain why there is approximately a 4% difference for the average recharge and approximately a 6% difference for the predictive drought of record runs. The text should be amended with a new budget table if the current one is incorrect. New PMWIN model files should be provided if necessary to correct this problem. Otherwise, the text should be amended to explain this discrepancy.

   ***Analysis of budget outputs confirms stream leakages are as listed in Table 10.1 when using PMPro or PMWin 5.2 or earlier. Only PMWin version 5.3 produces the increased leakage values mentioned. A note stating the existence of the budget differences in version 5.3 was added to the "readme" text files supplied with the PMWin model files.***

9. The calibration/verification model will not run due to an apparent incompatibility between PMWIN5.3 and PMWIN pro 7.0 used by Harden. The incompatibility causes extraneous real numbers to be placed in the stream table. They have values on the order of 1.0E-30, which

prevents the model from running. Please correct this and provide new PMWIN files that will run without having to edit the stream table.

***Model files recompiled using version 5.3.***

10. The initial head in layers 3, 5, and 7 for the calibration verification model matches the 1980 head given in Figures 8.7, 8.8, and 8.9, respectively. Please explain why the initial head in layer one for the calibration verification model does not match the 1980 head distribution given in Figure 8.6. Add a revised figure and/or text if necessary.

    ***Figure 8.6 corrected.***

11. What is the source of the initial layer heads for the steady state/transitional model? The initial heads do not match the predevelopment heads given in Figures 4.20 through 4.22. Please add some discussion and/or figures in Section 8 to document the initial heads.

    ***Discussion added to Section 7 "Modeling Approach".***

12. There seems to be a discrepancy in the metadata files regarding the projections for the N. Trinity GAM. In contours.met and points.met, the horizontal datum is given as the North American Datum of 1983. In structure.met, Cal_WL.met, Woodbine Water Quality.met and Strin_GAM.met the horizontal datum is given as the North American Datum of 1927. Also, the latitude of projection origin, 31.15 degrees, is incorrect in structure.met, Cal_WL.met, Woodbine Water Quality.met and Strin_GAM.met. It should be 31.25 degrees. Please search for and correct this discrepancy in all metadata files.

    ***All metadata files corrected.***

13. This comment is in regard to mismatching of layers, contours, and wells between source files and text figures. In other words, some text figures ascribed to one layer occur in the source files as a different layer. Additionally, source file identifications suggest that on some text figures wells may belong to one layer and contours to a different layer. In order to match source files with text figures and to correctly label each text figure, we need positive identifications of which contours and which wells belong to which model layers.

    ***The MS Access database "Figures.mdb" is included with the source drawings and supplies detailed information pertaining to the data used to construct individual figure elements.***

14. Please provide the source of the following figures in the Final Draft report: 2.1, 2.2, 4.20-4.22, 4.25-4.28, 4.41, 4.48-4.51, 4.54, 4.74, 4.75.

    ***Source annotations inserted.***

15. There is an error in Figures 4.10 and 4.13. They are the same contours. The legend in Figure 4-13 (Elevation of the top of the Hosston) is for the elevation of the top of the Hensell. Please provide corrected figures.

    ***Correct figure (4.13) inserted.***

16. There is an error in Figures 4.11 and 4.14. They are the same contours. The legend in Figure 4.14 (Elevation of the base of the Hosston) is for the elevation of the base of the Hensell. Please provide corrected figures.

    ***Correct figure (4.14) inserted.***

17. There is an error in Figures 9.8 and 9.9. They are the same contours. Please send corrected figures.

    ***Correct figure (9.9) inserted.***

18. There is a discernable difference between Figures 10.31 and 10.35 simulated 2030 and 2040 water levels in the Paluxy for average recharge conditions. However, there is no difference between figures 10.35 and 10.39 simulated 2040 and 2050 water levels in the Paluxy for average recharge conditions. They are the same contours. Please verify and provide correct figures as needed.

    ***Figure contours verified as correct. The slight change in water levels simulated between 2040 and 2050 is not discernable given the contour interval selected.***

19. Figure 10.44 is for the saturated thickness of the Hensell according to the caption. The Hosston is mentioned in the legend. Please correct and verify that the contours are correct for the Hensell. If not, please provide corrected figure.

    ***Correct figure (10.44) inserted.***

20. Reference for USGS Center of Biological Informatics GAP Analysis Program. Please provide a full reference.

    ***Figure source citation and reference updated.***

21. Reference for USGS collected Landuse/Landcover datasets. Please provide sufficient information to be able to locate source of data in Figure 4.43.

    ***Figure source citation and reference updated.***

22. Figure 4.41. U.S. Geological Survey is not in the references.

    ***Figure source citation updated.***

23. In Appendix 2, under 17.1.6, the comment numbers start with 3 instead of with 1. Please correct this and provide revised pages.

    ***Numbering corrected.***

# 18.0 APPENDIX 3: FINAL DRAFT REPORT COMMENTS AND RESPONSES – GAM SUBCONTRACTORS

The following sections list the technical and editorial comments submitted by select subcontractors (HDR Engineering, Inc., LBG-Guyton Associated, Freese & Nichols, Inc.) associated with the Northern Trinity/Woodbine GAM. The responses to individual comments and suggestions are described in italics below each entry.

## 18.1 General Comments

1. We would like to request an additional run for the Trinity and Woodbine GAMs to better reflect the possible Region C groundwater demands on the two aquifers. We are suggesting the following changes be added to the model and rerun for the years 2010 through 2050 (units shown below in acre-feet): Trinity GAM: Collin County – 2,500; Cooke County – 7,000; Dallas County – 5,000; Denton County – 6,000; Ellis County – 2,000; Grayson County – 3,000; Parker County – 4,000; Tarrant County – 6,500; Wise County – 3,400. Woodbine GAM: Collin County – 2,000; Cooke County – 123; Denton County – 1,400; Ellis County – 3,200; Grayson County – 7,000.

   ***Not in project scope.***

2. Why is Freestone County missing from Table 4.21?

   ***Freestone County is not within the active model footprint.***

3. The term "data" is sometimes treated as singular and other times as plural in the report. We suggest treating the term as plural throughout the report.

   ***Treatment of "data" standardized to plural throughout the report.***

4. Units should be spelled out in the text of the report, such as feet and acre. Also, the "/" should be replaced with the word "per" in the text of the report.

   ***Units spelled out at first usage throughout report.***

5. The term "however" is misused to connect two sentences together throughout the report. The proper use of the term would be to either put a semicolon prior to the word followed by a comma or simply placing a period before the term and beginning the next sentence with "However,". Page 3-2, last paragraph, first sentence is an example of such an occurrence. For example: "aquifer; however, the…" or "aquifer. However, the…".

   ***Usage of "however" amended throughout report.***

6. The term "pinches-out" does not need to be hyphenated.

   ***Hyphens removed from "pinches out" throughout report.***

7. The figures ought to be inserted facing the same direction so that the reader does not have to rotate the report to see the figures on facing pages.

***The use of both landscape and portrait layouts in the report requires the current orientation of the figures.***

8. The addition of landmarks to the geologic maps would be helpful, such as the outline of Dallas, Fort Worth, Waco, Austin, and Texarkana.

   ***Landmarks included in figures where readability is not degraded by the insertion of landmarks.***

9. The result maps in Section 10 are inconsistent with the text of that section.

   ***Section 10 rewritten.***

10. The maps in Section 10 dealing with simulated water level changes should include interval markings at 25' or 50' spacing.

    ***Consistency preferred in order to facilitate comparison between aquifer units.***

11. Why are the following reservoirs not included (* Indicates that the lake may be too small to include in the model): Lake Amon G Carter*, Lake Athens*, Lake Bardwell, Lake Bonham*, Lake Bridgeport, Cedar Creek Reservoir, Coffee Mill Lake*, Cooper Lake, Lake Crook*, Lake Cypress Springs, Ellison Creek Lake*, Forest Grove Lake*, Lake Hugo (Oklahoma), Joe Pool Lake, Lake Lavon, Lake Limestone, Lake Mexia*, Lake Mineral Wells*, Moss Lake*, Mountain Creek Lake*, Navarro Mills Reservoir, Lake Noona*, Lake Palestine, Pat Mayse Lake*, Randell Lake*, Lake Ray Hubbard, Richland-Chambers Reservoir, Lake Tawakoni, Lake Texoma, Valley Lake*, Lake Waxahachie*, Welsh Lake*, Wright Patman Lake.

    ***The reservoirs do not intersect the aquifer outcrop areas or the reservoirs are too small for inclusion in the model.***

## 18.2 Specific Comments

### 18.2.1 Abstract

1. Page xii; Last Paragraph- Suggest adding "in response to a projected decrease in pumpage from these aquifers" to the end of the second sentence.

   ***Text amended.***

2. Page xii, the first complete paragraph states that "Construction of the 100-year model was necessary because extensive pumpage…" Was this really due to pumpage or to artesian flow? Should the phrase "pumpage in" be replaced with "use of"?

   ***Text amended.***

### 18.2.2 Section 1.0

1. Page 1-2 First Paragraph: Suggest changing "will likely result" to "may result" in the last sentence.

***Text amended.***

### 18.2.3 <u>Section 2.0:</u>

1. Suggest adding a discussion on the scope and detail for the model area that is in Oklahoma. In general, it's there but it is ignored. We suggest a brief 'approach/scoping' statement early on in the report regarding this part of the model.

   ***The discussions concerning the Oklahoma portion of the model are consistent with those presented for other low-use areas of the model.***

2. Page 2-2 Figure 2-1: Somewhere in the report you should include a basic study area outline with county names included, as well as smaller towns, etc. Counties are referred to by name later in the report, there should be a map somewhere in the report showing county names.

   ***Figure 2.2 added.***

3. According to the Texas Water Development Board, Region C has two groundwater districts: Neches-Trinity Valleys Groundwater Conservation District and Mid-East Texas Groundwater Conservation District. Only the Neches-Trinity Valleys GCD is shown in Figure 2.3. The Mid-East Texas GCD is located in Freestone County.

   ***The Mid-East GCD is not within the active model footprint.***

4. Pages 2-3,4,5,9 Figures 2.2, 2.3, 2.4, 2.6: Suggest removing Woodbine and Trinity outlines on figures like this. They add information that isn't needed in the figure, and in some cases they make the figure too busy. In Figure 2.4 the lined outlines of the Trinity and Woodbine make it more difficult to see the river basins, which are the whole point of the figure. This comment applies to figures throughout the report. Also, suggest rotating and enlarging the study area, as was done in Figure 2.8. Figure 2.8 is a good example of how much better some of these figures look without the aquifer outlines. Outlines in Figure 2.6 are especially distracting because they are so heavy.

   ***Outlines add needed spatial reference to aquifer outcrop zones.***

5. Page 2-7, first line: "23 in/yr." should read "23 inches."

   ***Text amended.***

6. Figure 2.7 and Sections 2.1 and 4.7: The reference to lake evaporation is inconsistent. In sect. 2.1, the term "avg annual gross surface lake evap rate' is used; fig 2.7 uses " avg annual net lake surface evapo from 1960-2000; and sect 4.7 uses "lake evaporation". They all seem to be the same parameter, i.e., avg annual net.

   ***All references changed to "average annual gross lake evaporation".***

7. Page 2-8 Figure 2.5: Suggest removing outlines. In figures like this, perhaps either include the rectangular study area outline, or the outline of the counties that are included. The outcrop outline that is included is especially "busy".

***Outlines add needed spatial reference to aquifer outcrop zones.***

8. Figure 2.9: the legend is unclear. Suggest the following labels: Red Dot = Rainfall Station Used for Study and Averaged in Charts; Blue dot = Rainfall Station Used for Study.

   ***Legend modified.***

9. Pages 2-10, 13 Figures 2.7, 2.10: Suggest removing the Trinity and Woodbine shading and coloring in the contours. Figure 2.8 on the next page looks much better without the aquifer outlines on it.

   ***Outlines add needed spatial reference to aquifer outcrop zones.***

10. Page 2-15 Second Paragraph: Suggest adding "where the Glen Rose pinches out"at the end of the second sentence.

    ***Text amendment not preferred.***

11. Page 2-15, first complete paragraph, fourth line: the comma is not needed between "Paluxy merges with and generally becomes…"

    ***Comma removed.***

12. Section 2.2: should the section be organized such that the Trinity is discussed in detail followed by the Woodbine being discussed in detail?

    ***Description order modified.***

13. Page 2-25 Figure 2.18: For all Woodbine figures, suggest not coloring in the Trinity outline.

    ***Outlines add spatial reference to aquifer footprint.***

14. Page 2-26: Figure 2.19: Two comments. On this figure, Paluxy color in figure does not match legend. For all Paluxy figures, why was Paluxy differentiated when this was not done for Hensell and Hosston? In fact, in Hensell and Hosston, the Paluxy portion of the outcrop is included in their outcrop outlines.

    ***Figure corrected.***

### 18.2.4 <u>Section 4.0:</u>

1. It would be helpful to the reader to know how the thickness was calculated. Was is be subtracting surfaces or contouring picks from the geophysical logs?

   ***Text added to section 4.2 describing methodology.***

2. Page 4-4 Last Paragraph: The Luling-Mexia-Talco fault zone is an important component defining the study area, yet it is really not shown in any figure. It is included in Figure 4.3, but it is hard to see in this figure with all of the other structural components being shown. For something as important as the feature defining the downdip limit of the model, I think a separate figure might be added showing the faults in the fault zone and where the downdip boundary of the model area is with respect to the fault zone.

***Fault color and thickness modified in Figure 4.3.***

3. Wrong graphic is used (Figure 4.6), i.e., base is used, not thickness.

   ***Correct graphic inserted.***

4. Section 4.3, first paragraph, first sentence: suggest replacing "…was evaluated as an aid…" with "…was evaluated to aid…".

   ***Text amended.***

5. Page 4-22, last paragraph: improper use of the term "however."

   ***Usage corrected.***

6. Section 4.3.1, first sentence: To what does the term "screening levels" refer? Maybe replace that term with "water quality standards"?

   ***Text amended.***

7. Page 4-23, second paragraph, second sentence: add a comma between "established" and "levels".

   ***Correct punctuation currently observed.***

8. Page 4-23, third paragraph, third sentence: the term "ration" should be "ratio".

   ***Text amended.***

9. Table 4.1, third column: add a comma to the number "1,000" for TDS.

   ***Comma added.***

10. Table 4.3, third column: add a comma to the number "1,000" for TDS.

    ***Comma added***

11. Page 4-30, fourth line: improper use of the term "however".

    ***Usage corrected.***

12. Table 4.7, second column: add commas as appropriate.

    ***Commas added.***

13. Page 4-30, last paragraph, first sentence: Replace "Woodbine" with "Hosston".

    ***Text amended.***

14. Table 4.8, second column: add commas as appropriate.

    ***Commas added.***

15. Figures 4.16, 4.17, 4.18, and 4.19: add description to the legend by adding "Fresh", "Slightly Saline", "Moderately Saline", and "Very Saline" next to the range of the TDS levels.

***Legends modified.***

16. Page 4-38, first paragraph: improper use of the term "however".

    ***Usage corrected.***

17. Figure 4.15: Green has been used for negative contours elsewhere. Should the layers of positive numbers be in a different color?

    ***Contour color scheme used is consistent throughout report.***

18. Pages 4-44 and 45 Figures 4.23, 24: Suggest adding "in outcrop wells" to the figure titles.

    ***Titles modified.***

19. Figure 4.28: Hydrograph for well 32-09-901 is labeled as a Paluxy well in the Hosston/Trin figure.

    ***New hydrograph inserted in figure.***

20. Tables 4.1 and 4.2: A statement in the text is needs as to the population of samples used in the statistics. Are all samples from all wells used, or is each well represented with only one (latest) sample?

    ***Text added to section describing methodology.***

21. Page 4-32 Figure 4.16: Suggest adding "Fresh", "Slightly Saline", "Moderately Saline", and "Saline" in the legend after the TDS ranges.

    ***Legend modified.***

22. Page 4-50 Third Paragraph: Suggest rewording start of second sentence from "In 1980" to "As seen in Figure 4.35".

    ***Text amended.***

23. Figure 4.42: The units in the figure are from 0.077 to 0.10 inches per hour, yet the text states that a typical range is near 0.0 to 50 inches per year. Consistency is needed.

    ***Legend corrected.***

24. Section 4.5.3, near end: There seems to be a change in terminology in the text where "recharge factor" is used yet the equation uses "layer factor". Are these the same parameter?

    ***Clarifying text added to section.***

25. Section 4.5.3: A discussion on the development of each of the three factors is needed. The method may have some transfer value for other modelers, or it may need to be defended to skeptics.

    ***Clarifying text added to section.***

26. Page 4-98 Figure 4.57: Unsure of exact meaning or use of "ET Distribution Factor". I assume that the factor is unitless, but exactly how was it used to determine ET parameters.

    ***Clarifying text added to section.***

27. Figure 4.46: The figure title 'Recharge Potential' is inconsistent with text (pg 4-68) and figure legend/data.

    ***Figure title changed to "Estimated Potential Recharge Rate".***

28. Page 4-66, fourth paragraph: improper use of the term "however".

    ***Usage corrected.***

29. Table 4.10: Title of second column is unclear. Is the title referring to flow into the aquifer or flow on land? Add comma to 1,060 cfs in second column. Remove third column.Put gage names in the comment column (instead of gage numbers).

    ***Column title modified. Comma added. Current table format preferred.***

30. Figure 4.8: yellow lines in graphs are hard to read.

    ***Current colors found to be legible and are preferred.***

31. Pages 4-78, 81, 90 Figures 4.47, 4.48, 4.54: Figure needs to be cleaned up. Color shading for Trinity and Woodbine are not consistent with rest of document. Text is hard to read and lines are not sharp. If this figure is an image file (.TIF, .BMP, .JPG, etc) suggest pulling into an image editing program (Photoshop or equivalent) and using the "sharpen" tool, which may significantly improve the sharpness issues seen in figures such as this.

    ***Figures modified.***

32. Page 4-80, 2nd para: The call out of Figure 4.50 is given as 4.59.

    ***Text amended.***

33. Page 4-83, second paragraph, first sentence: replace "…their applicability to determining…" with "…their applicability for determining…"

    ***Text amended.***

34. Page 4-82 Figure 4.49: Fix y-axis label on upper graph.

    ***Axis corrected.***

35. Page 4-85, 2nd para: The call out of Table 4.12 is given as 4.11.

    ***Text amended.***

36. Table 4.12, pg. 4-85: Suggest presenting streamflow/baseflow data in cfs rather than cfd. Cfs is more commonly used and easier for lay people to relate to.

***Table units changed to "cfs".***

37. Table 4.13: Rename "Spillway Elevation" as "Top of Conservation Pool". Add "Lake" to the end of "Squaw Creek". Third column: round units to the nearest tenth. Fourth column: add commas as appropriate. Entries of 682 and 676 for Eagle Mountain Lake are incorrect. Entry of 724 for Benbrook Lake is incorrect. Remove the line between notes b and c.

    ***Current terminology preferred. "Lake" added to "Squaw Creek", Units rounded. Commas added. Entries are correctly cited from dataset used. Line removed.***

38. Figure 4.54: text has poor quality.

    ***Text quality acceptable.***

39. Page 4-92, second paragraph, first sentence: add an apostrophe after gages. ("… the two gages' measuring points."

    ***Apostrophe added.***

40. Page 4-92, second paragraph, last sentence: reorder "time lag" as "lag time".

    ***Text amended.***

41. Page 4-93, fourth paragraph, last sentence: remove the word "an" before the term "annual stress periods".

    ***Text amended.***

42. Pg. 4-92-93: When discussing the limits of the method with respect to Darcy's law, I have a graphic I developed for a presentation that you may feel free to use if you see fit. It's attached at the end.

    ***Figure 4.55 inserted.***

43. Page 4-95, last sentence second to last word: replace "to" with the word "for".

    ***Text amended.***

44. Page 4-105, should the term "geometric mean" be explained? We are not familiar with it.

    ***Explanation readily available in standard texts.***

45. Page 4-111, third line: the superscripted 4 belongs to the number on the second line. The entire number should be presented on one line.

    ***Text amended.***

46. Page 4-112 Second Paragraph: You might indicate that the apparent lack of springs in many of the counties in the study area is because these counties were not covered in Brune (1981). A similar note on Figure 4.69 might be appropriate. Also, the correct citation is Brune (1981), which was reprinted in 2002.

***Spring locations determined from both the TWDB groundwater/well database and Brune, 2002.***

47. Figures 4.69 and 4.71: the yellow dots are too light to show up on the figure.

    ***Dot color changed.***

48. Page 4-112 Third Paragraph: Suggest changing "expelled" to "discharged" in the first sentence.

    ***Text amended.***

49. Page 4-113, 1st para: The call out of Table 4.22 is given as 4.21.

    ***Text amended.***

50. Tables 4.21 and 4.22 (1): A distinction between historical and projected pumpage for the year 2000 is badly needed. One would expect it to be historical, however, it appears to come from projection tables. HDR suggests adding a header across the columns that is labeled Historical and Projected.

    ***Note added to tables.***

51. Tables 4.21 and 4.22 (2): The pumping tables published by the Central Carrizo-Wilcox GAM that breaks out the pumping be category have been extremely helpful in the Regional Water Planning process. HDR strongly suggests including a set of tables with the pumpage tabulated by category, aquifer, and county. This could go into an appendix.

    ***Not within project scope.***

52. Pages 4-122 to 124 Tables 4.21 and 4.22: Suggest renaming tables to "Historical and Projected Trinity Groundwater Pumpage (ac-ft/yr), currently they have slightly different names. Also suggest adding totals, and perhaps totals by state, at the bottom of the table.

    ***Table names modified.***

53. Table 4.21: Why is Freestone County not included in the table?

    ***Freestone County is not within the active model footprint.***

54. Table 4.22: Why is Freestone County missing? Why is Wise County listed as part of Oklahoma?

    ***Freestone County is not within the active model footprint. Wise County moved to Texas portion of table.***

## 18.2.5 <u>Section 5.0</u>

1. Page 5-1 Third Paragraph: Suggest changing "likely minimal" to "assumed to be minimal" in the first sentence.

    ***Text amended.***

2. Page 5-2 Second Paragraph: Suggest adding another way that water level declines have not been observed in outcrops. "4) aquifer properties have limited the propagation of declines away from pumping centers." Also, you indicate that there is not a significant reduction in the volume of water in storage in the Trinity/Woodbine system. While this is true when evaluating the study area in total, and also when comparing the amount remaining in unconfined storage in these units, I might elaborate to indicate that in major pumping centers there has been a significant reduction in artesian storage in these aquifers.

   ***Paragraph correct as written. While the relatively low transmissivities of the Trinity/Woodbine aquifers undoubtedly restrict the lateral extent of stress induced cones of depression, the addition of "aquifer properties have limited the propagation of declines away from pumping centers" is not preferred in the context of this paragraph because: 1) there has been significant, historical pumpage in outcrop areas, and 2) historical water level measurements suggest that the major cones of depression created in the Trinity/Woodbine aquifers during the last century did extend up to outcrop zones in many areas but did not result in coherent declines in water table levels. While there has been a significant reduction in artesian storage near major pumping centers, the volume of groundwater removed from storage is small in relation to the total water in storage in the system.***

3. Figure 5.1: What does "(Small?)" mean for vertical and horizontal leakage?

   ***"(Small?)" removed from figures.***

## 18.2.6 <u>Section 6.0</u>

1. Page 6-1 Second Paragraph: As indicated above, the faults digitized should be shown in a separate figure and referenced in this paragraph.

   ***Text added to section describing faults and Horizontal Flow Barrier Package.***

2. Page 6-1 Section 6.2 First Paragraph: No mention is made of the boundaries that are not outcrop or the fault zone. There is a western boundary in Arkansas and a southern boundary.

   ***Description included in Section 6.4.***

3. Section 6.0, last sentence: move comma from after "simulations" to after "and".

   ***Comma moved.***

4. Section 6.1, first paragraph, second sentence: break this into two sentences "…20 years. Its popularity is primarily…".

   ***Text amended.***

5. Page 6-3, first paragraph: If there is a physical explanation, please add it.

   ***Text amended.***

6. Page 6-6 Figure 6.1: There is a color-shading problem in the Eastland/Callahan County area. Dark green appears out of place and is not present in the legend.

***Figure corrected.***

### 18.2.7 Section 7.0:

1. The reader needs to be told the length of the stress periods and the period for each of the simulations in this section. There is a great lack of clarity in the simulation periods. It appears that the calibration period is 10 years and from 1/1/1980 to 12/31/1989, yet its called 1980-1990 which is a 11-year period. Then, is the 12/31/1989 calibration results compared with year 2000 data? The same applies for the verification period. The lack of clarity is greatest in the transition from the calibration/verification period to the predictive period. Where does the year 2000 (1/1/2000 to 12/31/2000) fit? Is it in both simulations? I don't think so. Is the predictive simulation from 1//1/2000 to 12/31/2050, a 51-year period? Or, does the simulation end in 12/31/2049 for a 50 year simulation. Sufficient clarification probably can be made with a new subsection in section 7.0.

   ***Clarifying text added to section.***

2. Page 7-1, last paragraph: in Region C, these were not predicted pumpages but availability based on previous TWDB data.

   ***Text amended.***

### 18.2.8 Section 8.0

1. Page 8-1 First paragraph: Change "Section 6" in first sentence to "Section 7". Also, I suggest elaborating on exactly what was done in the "steady-state" simulation. This paragraph implies that the "steady-state/transitional" model incorporated a reverse extrapolation of 1980 pumpage, but does not describe a non-pumping, pre-pumpage phase of this model. Later in this section are figures (8.1), text, and tables all indicating a true "steady-state" model, without pumpage, and this is somewhat confusing based on what is written in the first paragraph on Page 8-1. Is there an extended non-pumping stress period? If so, was it run to steady-state or how long was it? Suggest changing "engaged" to "included" in the second to last sentence. Also, the last sentence in the first paragraph, which refers to Section 9, should read "transient simulation" not "transitional simulation".

   ***Text amended in Section 8.***

2. Figure 8.2: The 0.0 coutour line does not seem reasonable.

   ***Figure modified.***

3. Table 8.2 – Water Budget: This is strictly your call on style but we've found that clients find water budgets much more understandable if presented graphically, as in the example in the attached jpg file inserted at the end of this document.

   ***Not within project scope.***

4. Page 8-9 Last Paragraph:- Suggest changing "volumes" to "effects" in last sentence.

***Text modified.***

5. Page 8-15; Figure 8.13- Move the y-axis to X = -1000 feet.

   ***No change necessary (Y-Axis currently at position specified).***

6. Figure 8.15 – Simulated vs. Estimated Baseflow: Suggest displaying this figure in cfs, a more understandable unit for surface water discussions.

   ***Units of cubic feet per day used in order to maintain consistency with model water budget output.***

### 18.2.9 <u>Section 9.0</u>

1. Section 9.1.1, 2nd para: The part of the sentence reading "residual values ranging about 53.3 feet from smallest…to greatest…" is awkward and 53.3 is not readily determined from the tables. Suggest rewriting.

   ***Text amended.***

2. Page 9-15 Fourth Paragraph: Suggest changing "by 1990" to "in 1990". The use of "by" implies a consistent change or trend, which is not the case with precipitation.

   ***Text amended.***

3. Section 9.1.3: Information is needed as to when (1990 or 2000) comparison of results were made.

   ***Clarifying text added.***

4. Page 9-2, last paragraph: spell out RMS and identify it before using the acronym.

   ***Text amended.***

5. Tables 9.1 and 9.2: What do ABS and RMS stand for? They are not described in the text.

   ***Text amended.***

6. Page 9-3, first paragraph: The term "conversely" is being used inappropriately as a conjunction. Try rephrasing as "…measured water level. Conversely, points below…"

   ***Text amended.***

7. Figures 9.10, 9.11, 9.12, and 9.13: Each figure needs a key. Which is historical and which is simulated?

   ***Keys added.***

8. Tables 9.2 and 9.3: add explanation of "ET" and "GHB" to the notes attached to the table.

   ***Notes added.***

9. Page 9-29, list of twelve parameters: add symbols in parentheses following each item.

   ***Symbols added.***

10. Page 9-29, last paragraph, second sentence: refers to "conductivity" but the item listed in number 7 refers to "conductance". Which is correct?

    ***Text amended.***

11. Page 9-29, last paragraph: write out the terms for Kv, ET, HFB, Sy, and GHB.

    ***Terms written in preceding list.***

12. Figures 9.32 thru 9.41: replace yellow lines with another color that can be seen.

    ***Line color legible and preferred.***

13. Pages 9-30-34 Figures 9.33-41: Suggest changing "Down" to "-" and "Up" to "+".

    ***Current terminology preferred.***

## 18.2.10 Section 10.0

1. Page 10-2, first paragraph, last sentence: should "hydrograph" be "hyetograph"?

   ***Text amended.***

2. Section 10.2, first paragraph: as mentioned earlier, these were not predicted pumpages in Region C but availability based on previous TWDB data.

   ***Text amended.***

3. Section 10.2, 2nd para: There is no section 8.4. This paragraph should be consistent with the sensitivity presentation.

   ***Text amended.***

4. Page 10-3, Section 10.2.1, third line: add a "d' to the word "increase" to read as "…due to the increased pumpage over…"

   ***Text amended.***

5. Page 10-3, Section 10.2.2, fourth line: 290 feet is not shown in Figure 10.22.

   ***Text amended.***

6. Page 10-4, Section 10.2.3: 400 feet is not shown in Figure 10.58.

   ***Text amended.***

7. Page 10-5, Section 10.2.4: 880 feet, 500 feet and 540 feet are not shown in Figure 10.78. Maximum of 400 feet is shown in Figure 10.78.

*Text amended.*

8. Even numbered figures from Figure 10.2-10.80 should have intervals of 25 feet or 50 feet.

   ***Consistency of contour intervals facilitates comparison with other aquifer units.***

9. Section 10.2, last para: The call out of Table 4.20 and 4.21 should be 4.21 and 4.22.

   ***Text amended.***

### 18.2.11 Section 11.0

1. Page 11-1, middle of the page: “then” should be “than” and “yields” should be “fields”.

   ***Text amended.***

2. Page 11-1 Second Paragraph: Suggest adding “and the model should not be used to simulate small-scale (local) groundwater flow” at the end of the third sentence.

   ***Text amended.***

3. Page 11-1 Fifth Paragraph: Suggest adding “and may include conduit flow which may have significant impact on regional flow dynamics in the aquifer” at the end of the third sentence.

   ***Text amended.***

### 18.2.12 Section 12.0

1. Page 12-1 Third Paragraph: Suggest adding “Pumpage is a critical component of any groundwater model which, unlike most other components, is capable of being quantified very precisely. Imprecise pumpage should not be a source of error for a groundwater model, although it commonly is. Any additional information on pumping rates and locations will greatly help improve the model” at the end of the paragraph.

   ***Addition is not necessary/redundant.***

2. Page 12-1, last paragraph, third line: add a comma after zones.

   ***Comma added.***

### 18.2.13 Section 13.0

1. Page 13-1 Number (3): You might indicate that the 90% estimate for discharge refers to the outcrop areas and not in the downdip areas, where nearly all of the discharge is to wells.

   ***Text amended.***

2. Page 13-2, item 5: as mentioned earlier, these were not predicted pumpages in Region C but availability based on previous TWDB data.

***Text amended.***

### 18.2.14 Section 14.0

3. Page 14-1, third paragraph, third line: “judicially” should be replaced with “judiciously”.

    ***Text amended.***