Hydrogeology of East-Central Union County, Northeastern New Mexico

Open-file Report 555
Prepared for Northeastern Soil and Water Conservation District

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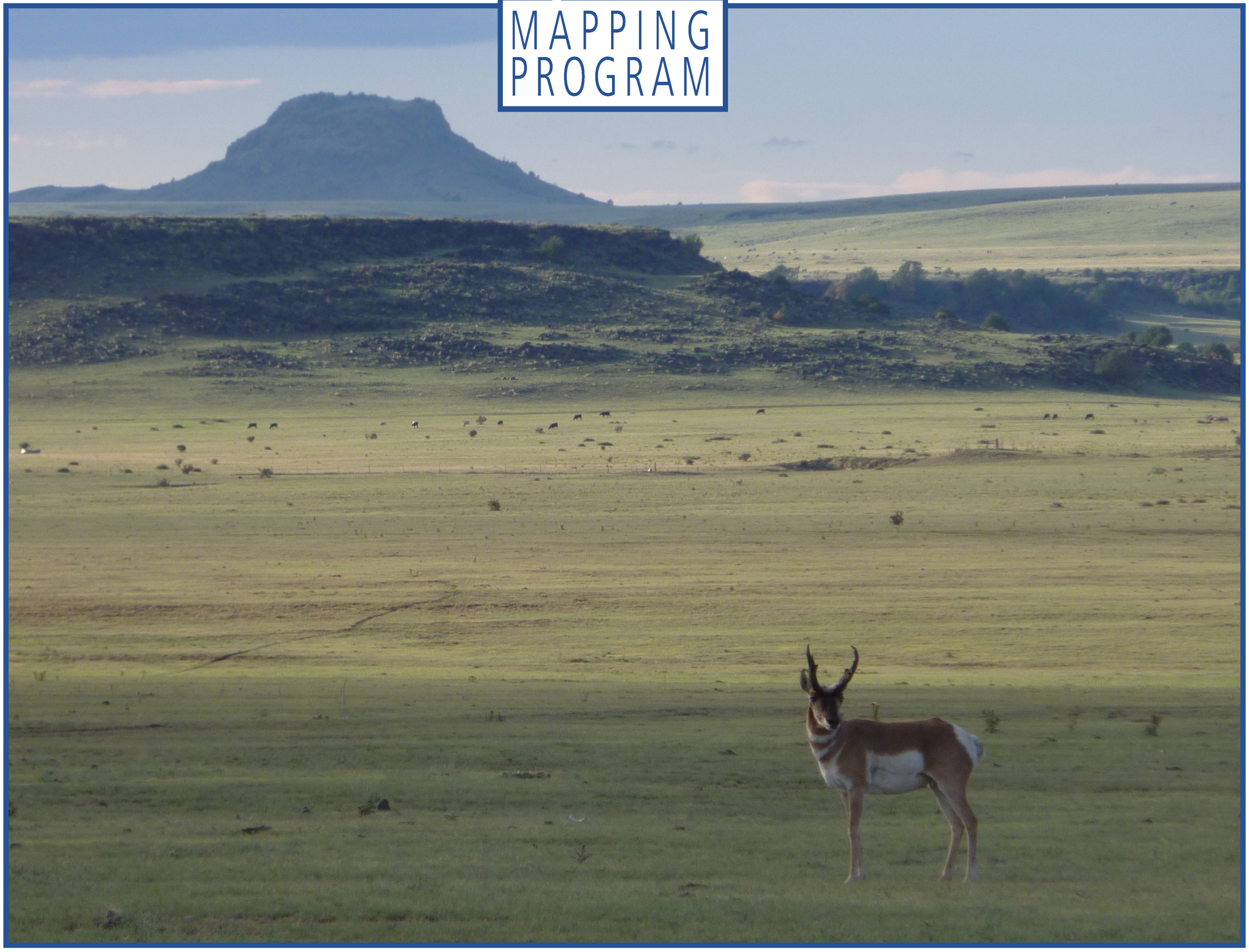
New Mexico Bureau
of Geology and
Mineral Resources

AQUIFER MAPPING PROGRAM

Geoffrey C. Rawling



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CONTENTS

Figures

Plates

Tables

Appendices

EXECUTIVE SUMMARY

The agricultural economy of Union County in northeastern New Mexico is highly dependent on groundwater. Ongoing drought, large new groundwater appropriations both within the county and in adjacent parts of Texas, and large water level declines in wells have led to concern amongst county residents over groundwater supplies. This report documents the finding of a hydrogeology study begun in 2010 to better understand the aquifers utilized in east-central Union County. The study covers 650 square miles and extends from north of Clayton to south of Sedan, and east to the state line. The study was jointly sponsored by Northeastern Soil and Water Conservation District (NESWCD) and the Aquifer Mapping Program of the New Mexico Bureau of Geology and Mineral Resources.

The goals of the study were to refine the existing geologic map of the area, describe the geologic framework of the aquifers that are utilized, describe present and historic water levels and trends over time, and utilize these data with geochemistry and age-dating techniques to understand the occurrence, age, and flowpaths of groundwater, and to identify the locations and processes of groundwater recharge.

The Ogallala Formation and upper Dakota Formation together vary from zero to several hundred feet in thickness and form a complex unconfined aquifer. Confinement increases with depth in the lower Dakota Formation and underlying formations. Shale layers form leaky confining beds amongst these units. Water level and saturated thickness declines from the mid 1950s to the present have been significant, and large portions of the Ogallala-Dakota aquifer have been dewatered. Water levels in deep wells largely recover after irrigation season ends, but the recoveries are superimposed on a long-term declining water-level trend. Groundwater extraction from all aquifers in the study area exceeds recharge

Tritium and ^{14}C analyses indicate that there is no significant recharge occurring to the sampled zones of the aquifer, consistent with the large and ongoing water level declines. Seepage velocity calculations are consistent with a recharge model in which the groundwater was recharged thousands of years ago, tens of miles west of the study area. Recharge occurred by rapid infiltration of playa lake waters and of precipitation on porous volcanic features, lava flows, and exposed bedrock of aquifer units. Recharge by these processes continues at present, but in insignificant amounts compared to groundwater extraction rates.

I. INTRODUCTION

Union County is the northeasternmost county in New Mexico. It is rural with an economy largely based on ranching and agriculture. Surface water resources are extremely limited, thus development of groundwater for livestock and irrigation is important and extensive. Concern has grown amongst county residents over recent large groundwater appropriations within the county and across the state line in Texas. These actions, along with general recognition of the increasing trend of groundwater use for irrigated agriculture, declines of water levels that have necessitated deepening or abandonment of wells, and repeated and persistent drought conditions since the early 1990s, have contributed to an increased awareness of the importance of groundwater resources to the economy and residents of the county. Specific concerns include the reliability of groundwater for the town of Clayton, and declining water levels in the Ogallala and Dakota Formation aquifers.

In 2010, the Northeastern Soil and Water Conservation District (NESWCD) asked the Aquifer Mapping Program of the New Mexico Bureau of Geology and Mineral Resources to conduct a groundwater assessment of Union County. Discussions between the two agencies resulted in a focused effort on the east-central portion of the county, covering the portions of the Seneca, Clayton, and Sedan 15-minute quadrangles within New Mexico, an area of about 650 square miles (Figure 1). This area includes the county seat of Clayton and much of the acreage of irrigated agriculture in the county.

This report documents the results of the study. The main goals were to:

1. Refine and update the existing geologic map (Baldwin and Muehlberger, 1959);
2. Produce subsurface geologic maps of the base elevation and thickness of both the Ogallala Formation and Dakota Formation;
3. Produce a subcrop geologic map of the base of the Ogallala Formation.
4. Produce a water table map and saturation maps for the Ogallala Formation and Dakota Formation.
5. Analyze a suite of water samples from representative wells for ion chemistry, trace metals, tritium and ^{14}C.

These data facilitated characterization of the aquifer system and allowed inferences to be drawn regarding groundwater flowpaths, groundwater residence time, and locations and timing of groundwater recharge.

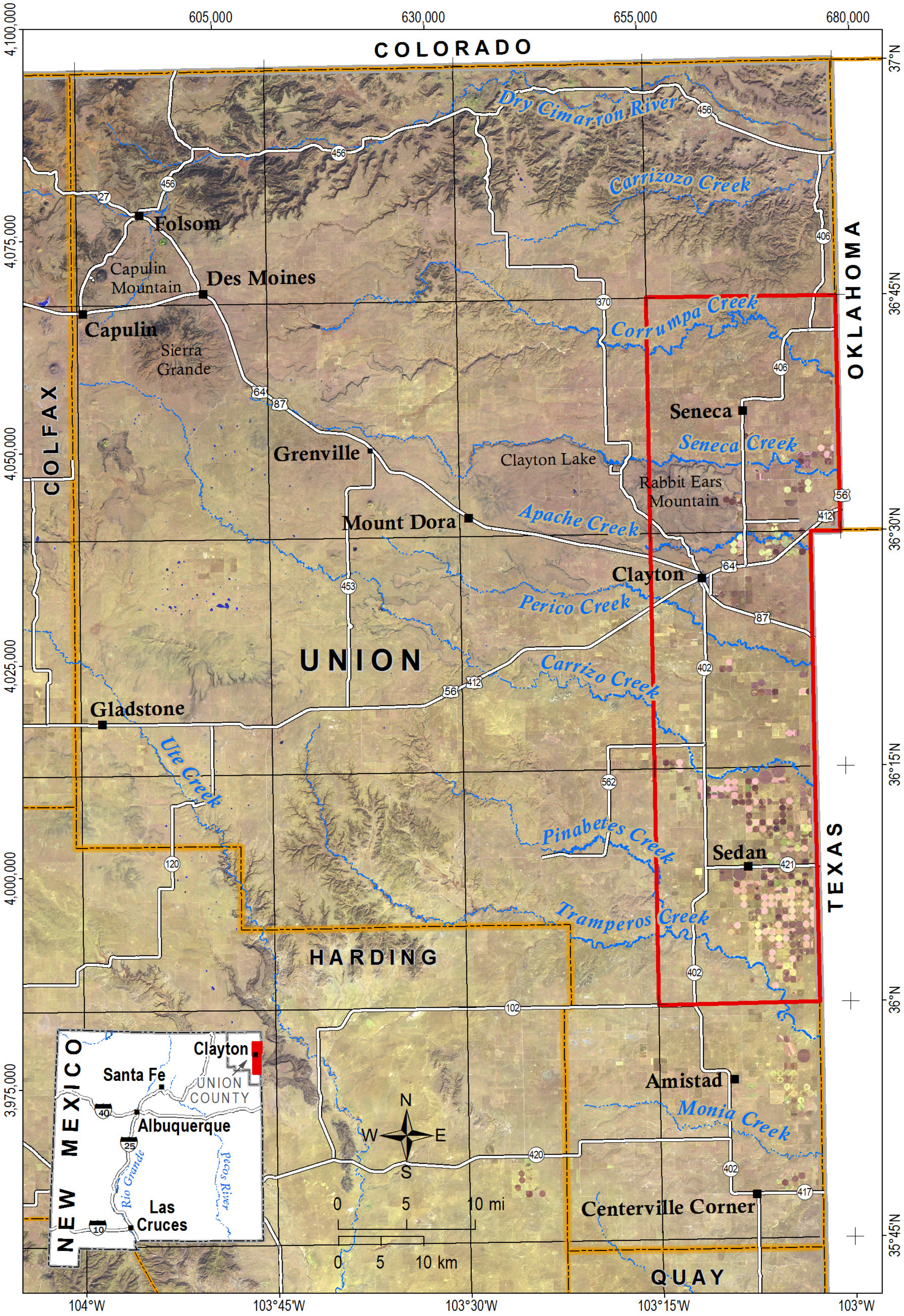


Figure 1–Location of the study area, outlined in red, in northeastern New Mexico. UTM coordinates are NAD83 datum.

II. PREVIOUS WORK

Geology

The seminal reference on the geology of Union County is Baldwin and Muehlberger (1959). Prior to their report there had been no detailed work on the general geology of the county or a countywide geologic map. The excellent map of Baldwin and Muehlberger (1959), which was incorporated into the geologic map of New Mexico (NMBGMR 2003), has required only minor revisions for this study, which mainly show a greater extent of bedrock exposures in stream valleys (Plate 1; Ziegler, 2011). The unpublished report by Lappala (1973) contains much subsurface data and geologic and hydrologic interpretation in the study area. However, it became available to the author after the present study was nearly complete and little of the basic data or interpretation could be included in this report.

Lucas et al. (1987a) documented the Triassic stratigraphy exposed in the Dry Cimarron valley. Mankin (1972) described the Jurassic stratigraphy in northeastern New Mexico. Kues and Lucas (1987) described the Cretaceous stratigraphy exposed in the Dry Cimarron valley. Pazzaglia and Hawley (2004) give an overview of the Ogallala Formation and Quaternary deposits in the county.

The volcanic rocks of the Raton-Clayton volcanic field have spurred much interest, with numerous studies addressing the age, distribution, and mineralogy and petrology of the volcanic rocks (e.g., Collins, 1949; Stobbe, 1949; Stormer, 1972a and b; Stroud, 1997). Aubele and Crumpler (2001) provide an overview of the volcanic field and a recent compilation of radiometric ages.

Hydrology

The geologic study of Baldwin and Muehlberger (1959) was conducted in the mid-1950s and was spurred by concerns over groundwater supplies around Clayton. Much of the hydrologic data these workers collected around Clayton was released as NMBMGR Circular 46 with discussion and analysis (Baldwin and Bushman, 1957). The complete data set of well data, water levels, and water chemistry for the whole county was published in 1967 (Cooper and Davis, 1967).

The US Geological Survey (USGS) has been collecting water levels from selected wells in Union County on an irregular basis since the late 1960s. These historical data are available from the National Water Information System (NWIS; <http://nwis.waterdata.usgs.gov/nm/nwis/gw>, accessed several times during the present study). Since 2007 these water level measurements have been conducted twice annually by the NESWCD.

Lappala (1973) conducted a detailed study of the geology and hydrology of the northeastern New Mexico and adjacent parts of Texas and Oklahoma. However, this report was never publicly released and was only recently rediscovered in the files of the New Mexico Office of the Sate Engineer (NMOSE).

There have been numerous studies of the hydrology of the Ogallala Formation and the High Plains aquifer, defined as the saturated sediments of both the Ogallala Formation and subjacent Cretaceous and older formations that contain potable water and are in hydraulic continuity with the Ogallala Formation (Gutentag et al., 1984). The present study area is within the west-central portion of the High Plains aquifer. Long-term research on the High Plains aquifer system by the USGS in the 1970s (e.g., Weeks et al., 1988; Luckey et al., 1981;

Weeks and Gutentag, 1981) provides geologic context and basic hydrologic data for the Ogallala Formation in the present study area.

Nativ and Smith (1987) and Nativ and Gutierrez (1989) studied the hydrogeology and geochemistry of the Ogallala and subjacent Cretaceous aquifers in the southern High Plains of New Mexico and Texas, south of the Canadian River.

Lucas and Hunt (1987) contains four papers pertaining to the hydrogeology of western Union and eastern Colfax and Harding counties (Kilmer, 1987; Trauger and Kelly, 1987; Trauger and Churan, 1987; Kelly, 1987). Kilmer (1987) provided ranges and average values for well yield, transmissivity, storage coefficient, and specific capacity for most of the geologic formations in the study area.

Reports by private consultants have been prepared for water rights applications and hearings before the NM Office of the State Engineer (e.g., Romero and Silver, 2009). These are generally proprietary and not readily available to the general public.

III. METHODS

Geology

Geologic field work was conducted by Ziegler Geologic Consulting with additional aerial photo interpretation and oversight by the author. The study area was not remapped in detail, rather reconnaissance field work, detailed description of outcrops, and interpretation of aerial photography were conducted to verify the location of important contacts and identify bedrock outcrops not shown on the regional map of Baldwin and Muehlberger (1959). Accurate 1:2400 scale topographic quadrangle maps did not exist when the previous mapping was completed, thus there were many inaccuracies in locations of geologic contacts that were rectified in this work. The field observations, and some local details mapped by Baldwin and Muehlberger on their original air photos that were not shown on their final geologic map due to scale issues, were digitally incorporated into the geologic map.

Available petroleum and water wells logs were examined. Compared to the number of water wells in the study area, the number of informative well logs is low, as the study area has only been part of an NMOSE declared groundwater basin since 2005. Ziegler (2011) reexamined well cuttings from five oil test wells and reviewed several water well logs across the study area and created descriptive and graphic logs of these data.

I used the tabulation of well information in Cooper and Davis (1967) of water well depths and formations of completion, well information in the USGS NWIS database for the county, subsurface contours presented in Baldwin and Bushman (1957) and Baldwin and Muehlberger (1959), and individual water and oil test well logs from the NMOSE and the NMBGMR to make several types of subsurface maps:

1. Structure contours on the base of the Ogallala Formation and younger deposits, undivided, and the base of Dakota Formation.
2. Isopach maps of the Ogallala and younger deposits, undivided, and the Dakota Formation ± the Graneros Shale.
3. A subcrop map of the geologic units present beneath the Ogallala Formation. This is essentially a generalized geologic map of the pre-Ogallala Formation land surface and includes the inferred extent of the Graneros Shale between the Dakota Formation and the Ogallala Formation.

For the various datasets of tabulated well data, I assumed that the well depth and location data were more accurate than the reported well head elevations because accurate topographic maps were not available at the time most of these data were collected. I recalculated all subsurface depths using elevations derived from a modern 10-meter DEM of the study area. This usually resulted in changes of tens of feet, and locally much larger, of reported subsurface elevations. These data were then used with the updated geologic map (Plate 1) to revise the subsurface contours in the Seneca and Clayton 15-minute quadrangles presented in Baldwin and Bushman (1957, figs. 6 and 8) and Baldwin and Muehlberger (1959, figure 14) and to create contours for the base of the Ogallala Formation in the Sedan 15-minute quadrangle. Additional details of the subsurface interpretations are discussed in the subsurface geology section and Appendix 1. Figure 2 shows the subsurface data points used in this study.

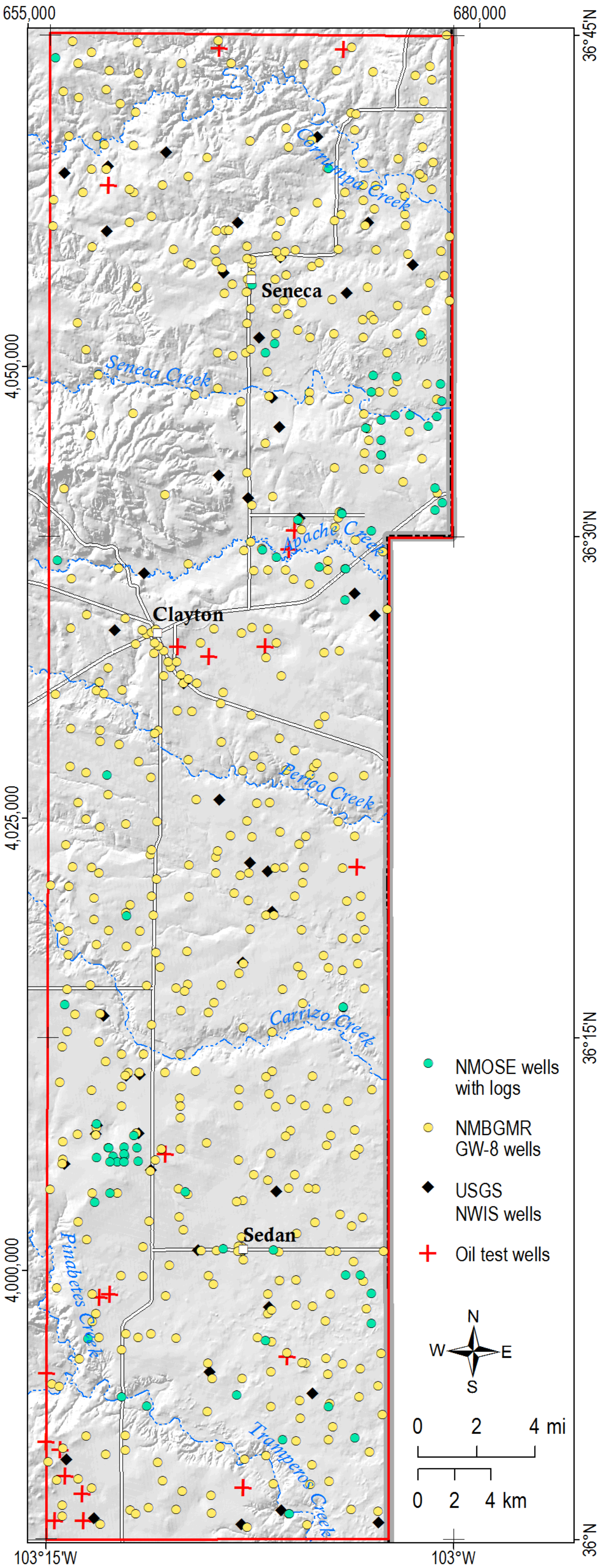


Figure 2–Inventory of subsurface data used for geologic interpretations. Oil test wells are from the NMBGMR petroleum database. NWIS wells are from the USGS National Water Information System database. NMOSE is the NM Office of the State Engineer. GW-8 wells are from NMBGMR Groundwater Report 8 (Cooper and Davis, 1967).

Hydrology

Water level data collection

Water-level measurements in wells were made by the author with a steel tape in conjunction with water sampling in September 2011. In several sampled wells water-level measurements were not possible due to the well head design. Continuous water level recorders were installed in four wells from March 2011 to December 2012 and programmed to collect data at one hour intervals. These wells were not equipped with pumps, thus the hourly data give a high-resolution picture of ambient water levels in the study area across two irrigation seasons. Water level data collected from wells by the USGS, the NESWCD, and this author from the late 1960s to the present allowed water level trends to be characterized in terms of well depth and formation.

Water level data contouring

I prepared a historic potentiometric surface map for the study area using the water well dataset from Cooper and Davis (1967). This dataset includes the data used by Baldwin and Bushman (1957) in the Clayton and Seneca quadrangles, and also includes water levels from the rest of Union County. Most of the data are from August, September, and October 1954 with fewer data from the 1960s. This map is representative of conditions during the mid-1950s when there was much less groundwater pumping for irrigation in the study area than at present (Lappala, 1973). As with the geologic data, I corrected the water-level elevations using surface elevations derived from a 10-meter DEM. I made depth-to-water and saturated thickness maps from the historic potentiometric surface map and the subsurface geologic maps. I also contoured the potentiometric surface elevation in the study area using winter 2011 water levels and calculated potentiometric surface changes and saturated thickness changes of the Ogallala and Dakota aquifers.

Water Chemistry

Sample collection

I collected sixteen water samples from wells within the study area. The sampled wells were chosen based on location, depth, the presence of a log, and ease of access. When sampling waters from wells, field parameters were recorded. As wells were purged, sampling was initiated once field parameters had stabilized. Temperature, specific conductance, pH, and dissolved oxygen (DO) were determined in the field with a portable meter (YSI Model 556 Multiprobe).The oxidation-reduction potential (ORP) was also recorded. The DO probe was calibrated onsite before sampling. The pH electrode was calibrated at the beginning of each sampling week against pH 7 and 10 buffers.

General ion and trace metal chemistry

Well and spring samples were collected using new, certified clean polypropylene containers after three repeated rinses. Samples for general ion chemistry analyses were collected using 250-ml polypropylene bottles. Water samples for trace metal chemistry were filtered onsite through an inline 0.45 µm filter into 125-ml polypropylene bottles and acidified to pH <2 using ultra-pure nitric acid. All chemistry samples were stored in an ice chest, transferred to the NMBGMR chemistry laboratory, and stored in a refrigerator until analyzed (within 1 week). Alkalinity (as mg/L HCO_3) was determined in the NMBGMR chemistry laboratory by titration within two weeks of sampling. Laboratory measurements of pH were performed with an Orion 420A meter, and conductivity using a YSI 3200 meter. A chemical analysis for anions (Cl, SO_4 and NO_3) was performed using a Dionex DX-600 ion chromatograph. Cations (Na, K, Ca, and Mg) were analyzed using a Perkin Elmer OPTIMA 5300 DV Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES). Trace metals were analyzed by Inductively Coupled Plasma Mass Spectroscopy (ICPMS) using an Agilent 7500 IS. The quality of the chemical analyses was carefully inspected by analyzing blanks, standards, duplicate samples, and checking ion balances. The ion balance errors for the analyses were generally within ±5%.

Stable isotopes

The well waters were also analyzed for stable isotopes of oxygen-18 (^{18}O) and hydrogen-2 (deuterium, ^{2}H). Samples were collected in 25 mL amber glass bottles after three repeated rinses. No air bubbles were present in the samples, and bottles were kept from direct sunlight. Samples were stored at room temperature in sealed bottles until analysis at the New Mexico Institute of Mining and Technology, Department of Earth and Environmental Sciences stable isotope laboratory on a Picarro L1102-i Cavity Ringdown Spectrometer isotopic water liquid analyzer. Analytical uncertainties for $\delta^{2}H$ and $\delta^{18}O$ are typically less than 1 per mil (‰) and 0.1‰, respectively.

Carbon isotopes and tritium

A subset of the sampled well waters were analyzed for tritium (^{3}H) and carbon-14 (^{14}C) activity and $^{13}C/^{12}C$ ratios ($\delta^{13}C$) to determine groundwater age. Tritium samples were collected in two 500 mL polypropylene bottles after rinsing three times. The were shipped to the University of Miami Tritium Laboratory where they were analyzed by internal gas proportional counting with electrolytic enrichment. For these samples, a sampling protocol described at <www.rsmas.miami.edu/groups/tritium/advice-sampling-tritium.html> was followed. The enrichment step increases tritium concentrations in the sample about 60-fold through volume reduction, yielding lower detection limits. Accuracy of this low-level measurement is 0.10 tritium unit (TU) (0.3 pCi/L of water), or 3.0%, whichever is greater. The stated errors, typically 0.09 TU, are one standard deviation.

Water samples for carbon-dating were collected in one 1 L polypropylene bottle, after rinsing three times. Sampling procedures described at www.radiocarbon.com/groundwater.htm were used, with the exception of the addition of NaOH. Samples were kept chilled until shipment for analysis at Beta Analytic (www.radiocarbon.com). The ^{14}C activity and $^{13}C/^{12}C$ ratios of the water sample were derived from the dissolved inorganic carbon (DIC) by accelerator mass spectrometry. Measured $\delta^{13}C$ values were calculated relative to the PDB-1 standard. Results are reported as ^{14}C activity (in percent modern carbon, pMC) and as the apparent radiocarbon age (in radiocarbon years before present, RCYBP, where "present" = 1950 CE), with an uncertainty of one standard deviation.

No corrections for geochemical effects such as water-rock interaction have been completed, and the reported apparent ^{14}C ages do not precisely represent the residence time of the water within the aquifer. The ^{14}C activity and apparent ^{14}C age are used as a relational tool to interpret hydrologic differences between wells.

IV. CLIMATE AND PRECIPITATION

The study area has a semiarid continental climate. Precipitation in Clayton has averaged 15.2 inches per year from 1896 through 2011 (Trauger, 1987; data since 1987 from <http://www.prism.oregonstate.edu/>). This is typical for Union County and northeastern New Mexico as a whole (Trauger, 1987). Snowfall averages 23.2 inches (equivalent to approximately 2.3 inches of rain). Most precipitation falls between April and October during thunderstorms. These storms can be intense (e.g., Love, 2004), localized and short lived, and there is thus great spatial variation in precipitation across the study area during the rainy season. There can also be great year-to-year variations in totals, sometimes more than 100% of the yearly average (e.g., 1940–1941; Trauger, 1987). Average annual potential evaporation over the study area and all of northeast New Mexico is many times the average annual precipitation (Farnsworth and Thompson, 1982).

Precipitation in the southern High Plains was studied by Nativ and Riggio (1989, 1990). They determined that spring and summer precipitation moisture is derived dominantly from the Gulf of Mexico, whereas winter precipitation moisture is derived from the Pacific Ocean. Precipitation moisture in the late summer is derived from both source areas.

Several prolonged droughts have occurred during the period of record (1933–1940, 1951–1958, 1973–1980). The period from 2001 through 2011 has had only three years with precipitation at or above the long term average of 15 inches, with 2011 ranking as the sixth driest year on record in Clayton (9.68 inches).

V. GEOLOGY

Regional physiography

Union County and the present study area lie within the southern High Plains physiographic province that encompasses much of New Mexico east of the Central Mountain chain (Figure 1; Pazzaglia and Hawley, 2004). The landscape is characterized by rolling plains and nearly level plateaus dissected by valleys, arroyos, and canyons of the Canadian and Dry Cimarron River drainages. Other than the main stem streams, these drainages are usually dry except during periods of heavy precipitation. Prominent in the landscape are cinder cones (e.g., Capulin Mountain and Rabbit Ears Mountain) and shield volcanoes (e.g. Sierra Grande) of the Raton-Clayton volcanic field. Lava flows from the volcanoes of this field form most of the broad uplands and plateaus of Northeast New Mexico (Pazzaglia and Hawley, 2004). The town of Clayton sits on the level upland surface formed by one of these lava flows at an elevation of 5,056 feet. Elevations within the county range from a high of 8,713 feet on Sierra Grande to a low of 4,200 feet where the Dry Cimarron River exits the state. Elevations within the study area range from 6,048 feet on Rabbit Ears Mountain to 4,346 feet.

Regional geology and geologic history

A variety of Mesozoic sedimentary and Cenozoic sedimentary and volcanic rocks are present in Union County (Figures 3 and 4 and Plate 1). An understanding of the rock types and their history is important for characterizing the aquifers within the study area. Muehlberger et al. (2005) is a good beginning reference to the geology of this region of New Mexico.

The oldest rocks exposed within Union County are Triassic in age and are only exposed in the valley of the Dry Cimarron River north of the study area (Baldwin and Muehlburger, 1959; Lucas et al., 1987a). These rocks are red to purple, brown, and green in color as is typical of Triassic rocks across the southwestern U.S. They are sandstones, siltstones and minor limestones and conglomerates deposited by streams flowing eastward from the ancestral Rocky Mountains in a floodplain environment.

The Triassic rocks are overlain with angular unconformity by a Jurrassic rock sequence composed of the Entrada Sandstone, the Bell Ranch Formation, and the Morrison Formation. The angular unconformity can be clearly seen in several buttes within the valley of the Dry Cimarron River (Lucas et al., 1987a) and indicates a period of uplift, tilting and erosion of the Triassic rocks prior to the deposition of the Jurassic rocks. The Entrada Sandstone is a clean quartz sandstone that was deposited as dunes. It is a locally important aquifer in Union County. The overlying Bell Ranch Formation is siltstone that was probably deposited as lake-bottom sediment. The Morrison Formation caps the Jurrassic sequence and is composed of interbedded mudstone and siltstone with locally thick sandstone beds (Figures 3 and 4). It was deposited by sluggish streams on the floodplains of a vast river system (Baldwin and Muehlberger, 1959). The Morrison Formation sandstone beds are locally important aquifers in Union County.

The Jurassic rocks are overlain by Cretaceous rocks of the Lytle Sandstone, Glencairn Formation, Dakota Formation, and Graneros Shale. The nomenclature of the Cretaceous rocks in this area is complex and can easily lead to confusion. The Lytle Sandstone and Glencairn Formation of Lucas et al. (1987b) are equivalent to the Purgatorie Formation of Baldwin and Muehlberger (1959). The Purgatorie name will be used in this study. The Dakota *group* encompasses the Purgatorie Formation plus the overlying Dakota *Formation* (Figure 3; Baldwin and Muehlberger, 1959). All of these rocks were deposited in environments adjacent to or within the Cretaceous interior seaway, a shallow continental sea that covered much of what is now New Mexico during the Cretaceous period. As the extent of the sea waxed and waned over time, the shoreline moved great distances laterally, and thus many different depositional environments are represented in the vertical succession of rocks. The interbedded sandstones, siltstones, shales and minor coal of the Dakota and Purgatorie Formations were deposited in beaches, river channels, and swamps adjacent to the sea. Fossiliferous sandstones, shales and limestones of the Purgatorie Formation and Graneros Shale were deposited in deep water beneath the sea (Figures 3 and 4). Cretaceous rocks younger than the Graneros Shale - the Greenhorn Limestone, Carlisle Shale, and the Niobrara Formation - are only present in the northwest corner of the county, outside of the present study area (Baldwin and Muehlberger, 1959). All of the Cretaceous sandstones are important aquifers in Union County.

Following the deposition of the Cretaceous rocks, there was a long period of regional uplift and erosion that saw the retreat of the Cretaceous

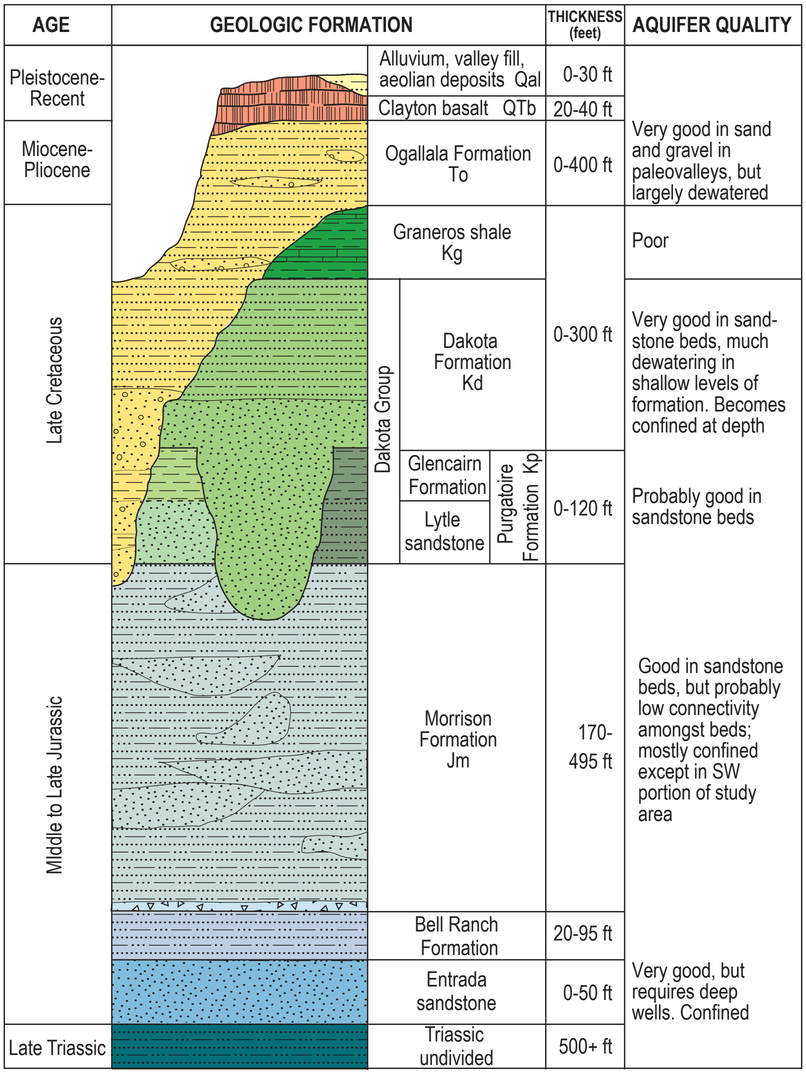


Figure 3–Schematic stratigraphic column of geologic units present in the study area.

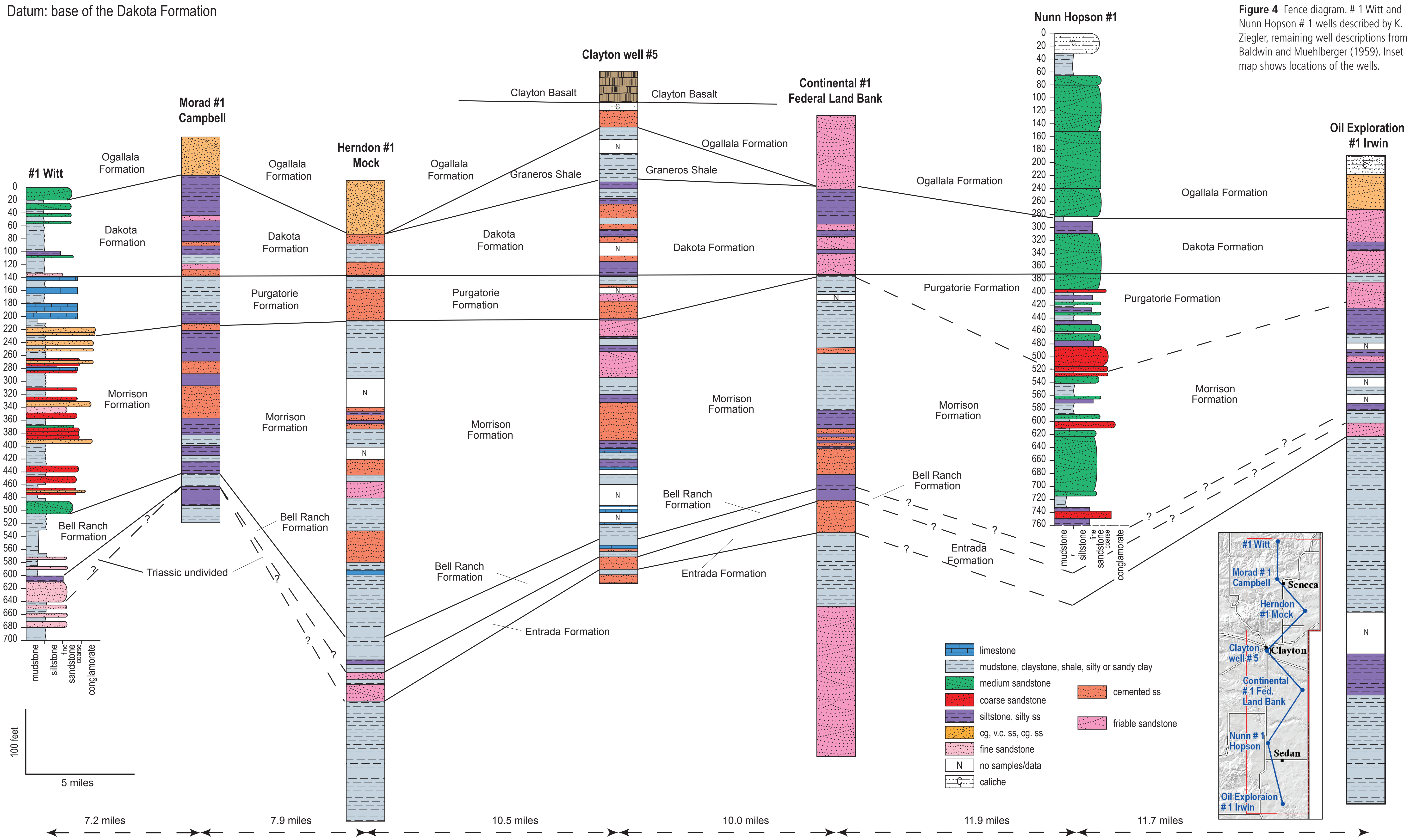


Figure 4–Fence diagram. # 1 Witt and Nunn Hopson # 1 wells described by K. Ziegler, remaining well descriptions from Baldwin and Muehlberger (1959). Inset map shows locations of the wells.

Seaway from the continental interior and the uplift of the Rocky Mountains in a mountain building event known as the Laramide Orogeny. The landscape was eroded by streams flowing roughly west to east. Most of the Cretaceous shales were eroded and in many places rivers cut down into the sandstones of the Dakota Group and in a few places into the Jurassic rocks. The resulting landscape had several hundred feet of relief between the river valleys and intervening uplands.

Eventually the abundant detritus washed east from the Rocky Mountains became so voluminous that streams ceased eroding and began to deposit sediment in present day Union County. The stream channels filled first and eventually sediment accumulated across the landscape in a broad sheet. This occurred from late Miocene to early Pliocene time and the resulting deposits are known as the Ogallala Formation (Frye et al., 1978, Pazzaglia and Hawley, 2004). The Ogallala is a vertically and laterally complex rock unit composed of conglomerate, sandstone and siltstone. It generally has conglomerate and coarse sandstone at the base of channels scoured into the underlying rocks and finer-grained aeolian sediments on the paleo-upland surfaces (Gustavson and Winkler, 1988). The Ogallala Formation is an important aquifer throughout its 174,000 square mile extent across eight states of the western high plains, including northeast New Mexico.

The basalt lava flows and the volcanic vents at Rabbit Ear Mountain are 2.5 to 3 million years old (Luedke and Smith, 1978; Aubele and Crumpler, 2001). They postdate the deposition of the Ogallala Formation and were deposited on top of it. Other volcanoes and lavas of the Raton-Clayton volcanic field west of the study area are up to 9 million years old and were erupted coevally with the deposition of the Ogallala Formation (Luedke and Smith, 1978; Aubele and Crumpler, 2001).

Throughout much of the time of deposition of the Ogallala Formation, and to the present day, the climate of northeast New Mexio has been arid to subhumid. This is shown by the multiple buried calcic soils and the distinctive calcic soil zone (the "caprock") at the top of the Ogallala Formation. These "caliché" deposits indicate landscape stability for thousands of years or longer. The major drainages in the present study area (Figure 1) have eroded through the caprock, and these valleys are floored with younger, generally unlithified, fluvial and aeolian sediments (Plate 1). Much of the upland surfaces in the county, whether underlain by basalt or the Ogalalla Formation, are also covered by aeolian deposits comprised of sand sheets and small dunes (Plate 1; Pazzaglia and Hawley, 2004).

Geology of the study area – surface exposures

The geology of the study area is shown in Plate 1. Apart from the volcanic rocks, bedrock exposures are rare, occurring only in the floors and along the walls of stream valleys and arroyos (Plate 1). Most of the study area is composed of uplands underlain by Ogallala Formation with its caprock caliche, or basalt flows. Both are mantled by thin aeolian deposits. Fairly large exposures of Dakota Formation sandstones are present along the north side of Corrumpa Creek north of Seneca (Plate 1). Valley sideslopes along this drainage have only a thin cover of alluvial and colluvial sediment over Dakota Formation bedrock. More Dakota Formation exposures are present north of Rabbit Ears Mountain along Seneca Creek, just east of the famous outcrops of dinosaur tracks at Clayton Lake. Throughout the rest of the study area sparse outcrops of Dakota Formation sandstones and the overlying Graneros Shale are scattered along most of the major drainages (Plate 1).

The Cretaceous Purgatoire Formation and underlying Jurassic Morrison Formation are only exposed along Tramperos Creek at the southwest corner of the map area. A thin layer of Dakota Formation sandstone caps the outcrops here. This area appears to be an exposure of an east-trending anticlinal structure that brings the Jurassic rocks to a greater elevation than anywhere else in the study area. The Morrison Formation sandstones present here are atypical of the Morrison Formation elsewhere in the county and are similar to those of the overlying Dakota Formation. They constitute a distinctive unit that was mapped to the west along Tramperos Creek by Baldwin and Muehlberger (1959).

The valley west and southwest of Clayton contains the only extensive exposures of the Ogallala Formation in the study area. Other smaller exposures are present along Perico Creek, Carrizo Creek, and Tramperos Creek.

Geology of the study area - subsurface and structure

Figures 4 through 9 illustrate major aspects of the subsurface geology of the study area. I defined the top of the Ogallala Formation beneath the basalt flows by creating an approximately planar surface connecting the base of the exposed basalt outcrops (Plate 1). The combined thickness of the Ogallala Formation and younger Quaternary surficial deposits was determined by subtracting the surface defined by the structure contours on the base of the Ogallala Formation from this simulated “pre-basalt” ground surface. (Figures 5 and 6), as they cannot be reliably distinguished on well logs, and there is no hydrologic reason to distinguish them. The Quaternary deposits are rarely saturated and few wells are completed in them.

Most water well logs and tabulated well information list only “Cretaceous” or “Dakota” as the formation of completion. The base of the Dakota Formation is a persistent sandstone bed that is usually identifiable in the field and in wells and thus makes a good reference horizon (Figure 4; Baldwin and Muehlberger, 1959; pages 56–58). I contoured the base of the Dakota Formation assuming that this sandstone was identified correctly in the examined wells; this is probably not always the case. This introduces elevation and thickness errors, but I believe they are on the order of a few tens of feet at most and do not invalidate the geologic or hydrologic conclusions presented herein. I calculated the combined thickness of the Dakota Formation ± Graneros Shale as the elevation difference between the base of the Dakota Formation and the base of the Ogallala Formation and Quaternary deposits, undivided (Figures 7 and 8).

The Graneros Shale is present locally between the Dakota Formation and the Ogallala Formation but there are insufficient well data to map out its extent and thickness with any accuracy. I inferred its extent and thickness using the method described in Appendix 1. The extent of the Graneros Shale so determined is presented in Figure 9 along with the mapped outcrops of the unit for comparison. I do not consider the calculated Graneros Shale thicknesses to be reliable, and the correlation of the mapped outcrops with the inferred extent is poor. However, for hydrologic purposes, the presence of only a few feet of shale may be sufficient to partition aquifers. Figure 9 is an interpreted subcrop map at the base of the Ogallala Formation, essentially a geologic map of the land surface at the time of the onset of Ogallala deposition.

I did not attempt to map out the extent of the Cretaceous rocks below the Dakota Formation. The Purgatorie Formation (composed of the Glencairn Formation and Lytle Sandstone; Figure 3) is lithologically similar to the rocks of the Dakota Formation (interbedded sandstones and shales) so it is not unreasonable hydrologically to treat these formations together. As noted above, it is probable that some of well data used in this study conflate and mis-identify these different rock units. Few if any wells are completed in the Graneros Shale. For the above reasons and for simplicity, I will use the generic term “Dakota Formation” in the hydrologic discussions that follow in this report, with the understanding that locally, underlying Cretaceous rocks may be included.

The contoured base of the Dakota Formation is deepest northeast of Sedan and shallowest in the northwest corner of the study area (Figure 7). The base contours vary smoothly compared to the base of the Ogallala Formation (Figure 5). This is in part an artifact of there being fewer data points available for contouring the base of

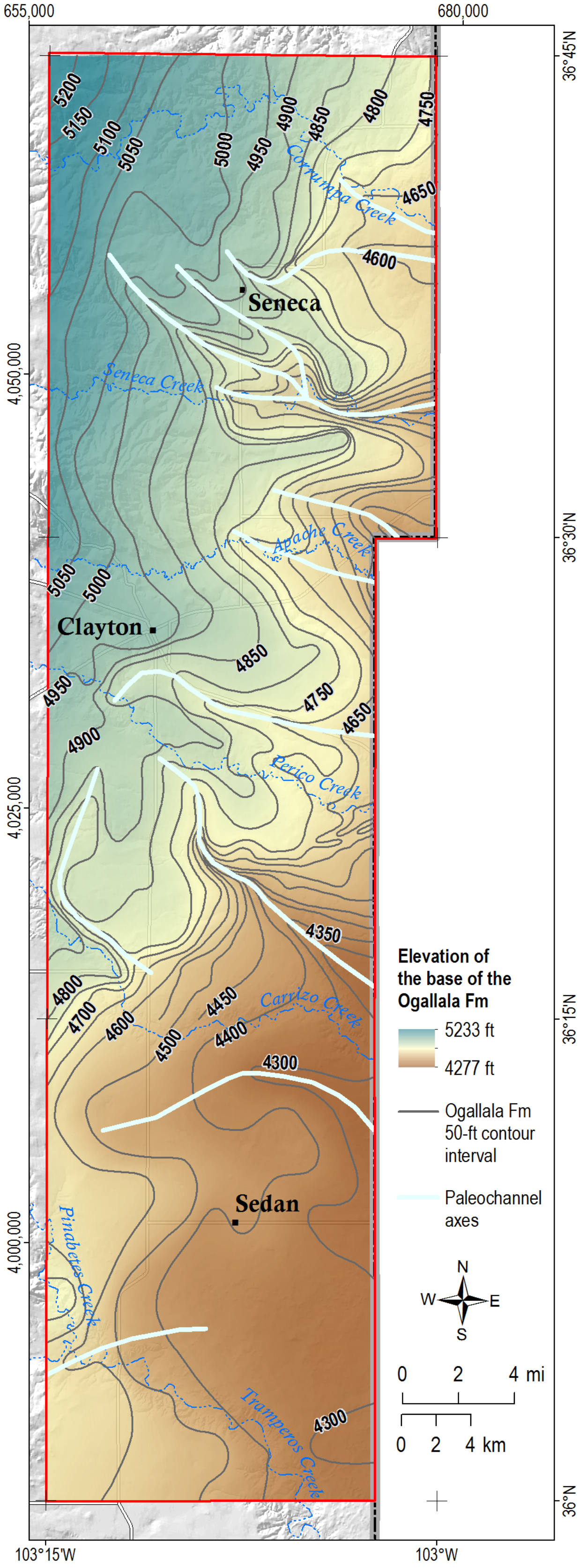


Figure 5–Elevation of the base of the Ogallala Formation. Elevations are projected through areas where the formation is absent. Blue lines are axes of paleochannels eroded into the underlying strata.

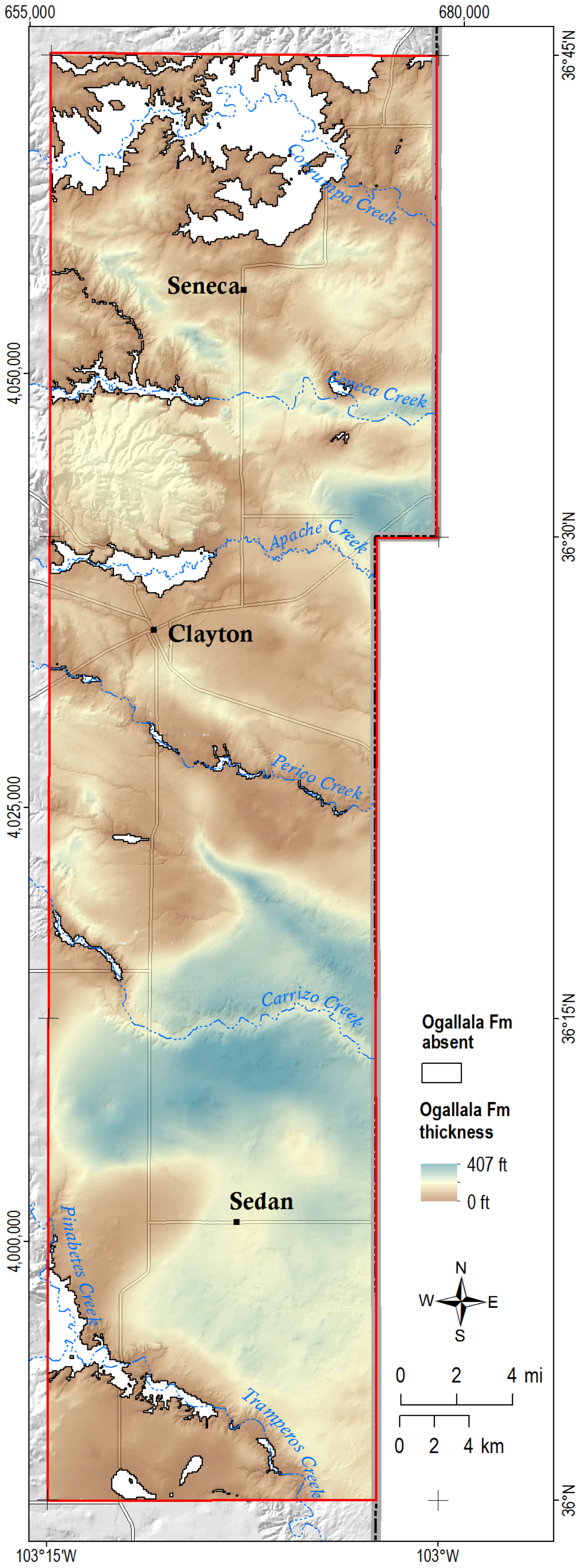


Figure 6–Extent and thickness of the Ogallala Formation.

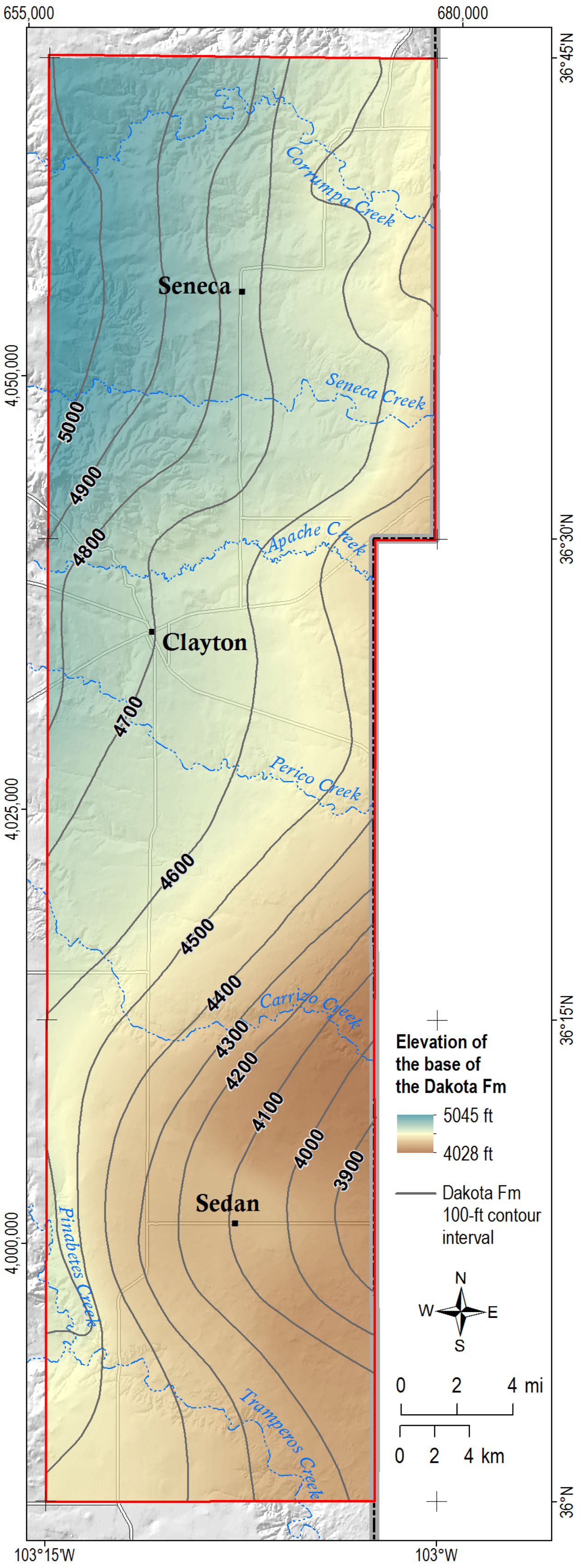


Figure 7–Elevation of the base of the Dakota Formation. Elevations are projected through areas where the formation is absent.

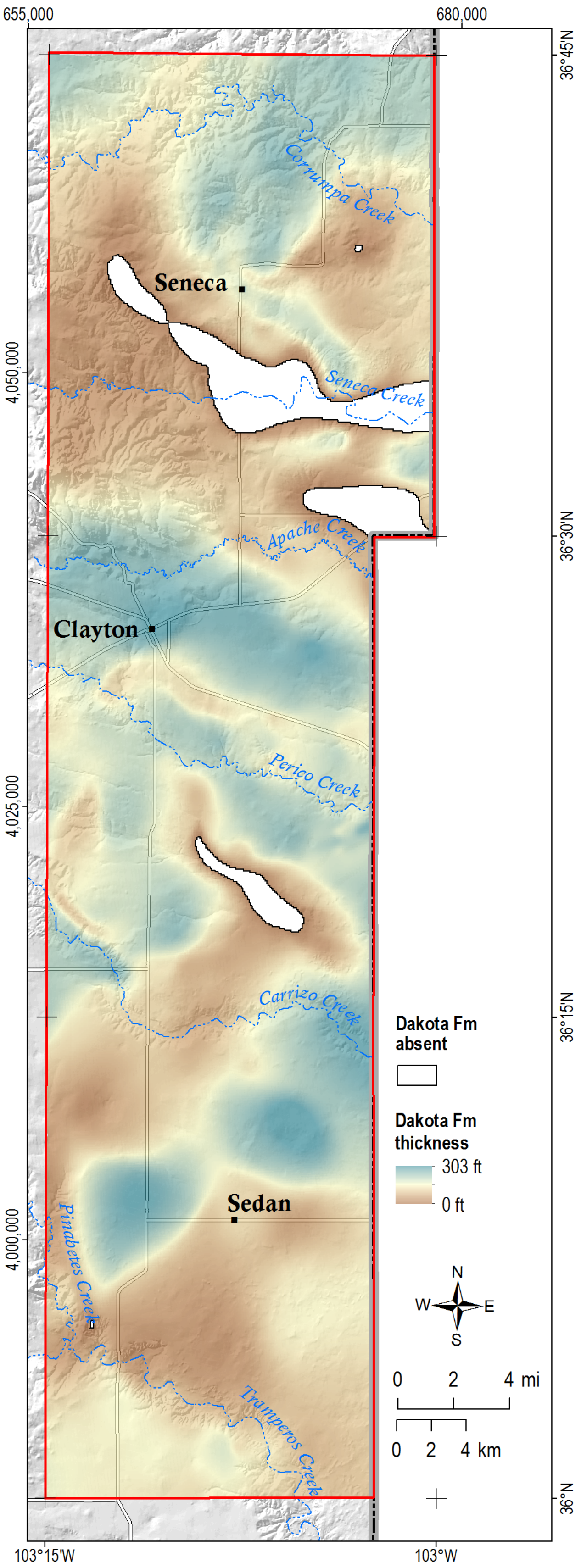


Figure 8–Extent and thickness of the Dakota formation ± Graneros shale, combined

the Dakota Formation. There are several elongated areas where the Dakota Formation is not present (areas of zero thickness; Figure 8). Here the Ogallala Formation rests on Jurassic rocks (Figure 9). In these areas, channels were eroded through the Cretaceous section by streams that deposited the Ogallala Formation. Comparison of the thickness contours and the base elevation contours reveals that most of the spatial variation in thickness is controlled by patterns of pre-Ogallala erosion. The exception is the deep basin northeast of Sedan. The maximum thickness is 303 feet.

The base of the Ogallala Formation shows a paleo-highland in the northwest quadrant of the study area partly dissected by southeast trending channels and a low, relatively flat basin in the southeast quadrant. Several paleochannels at the base of the formation can be seen in the base contours (Figure 5). The Ogallala Formation has been completely eroded to varying degrees along the western extents of all the major drainages in the study area (Figure 6). Cretaceous and Jurassic bedrock is exposed or mantled with thin Quaternary deposits in these areas. The Ogallala Formation is thickest north of Sedan at about 400 feet.

There is no compelling evidence from the subsurface data for faulting in the study area and no significant faults are exposed at the surface. Lappala (1973) mapped several normal faults in the subsurface at the base of the Dakota Formation along Apache Creek north of Clayton, but this interpretation is questionable to the author. The exposures of Jurassic rocks along Tramperos Creek in the southwest corner of the study area (Plate 1) are the easternmost exposures of a large area of Jurassic rocks that extend far to the west (Baldwin and Muehlberger, 1959; NMBGMR, 2003) along the Tramperos Creek drainage. This area is a structural high and is the nose of an easterly or southeasterly plunging anticline or arch. It is roughly coincident with the eastern extent of the Bravo Dome, which is a buried Pennslvanian – Permian age uplift that is now the site of a producing carbon dioxide gas field (Broadhead, 1987).

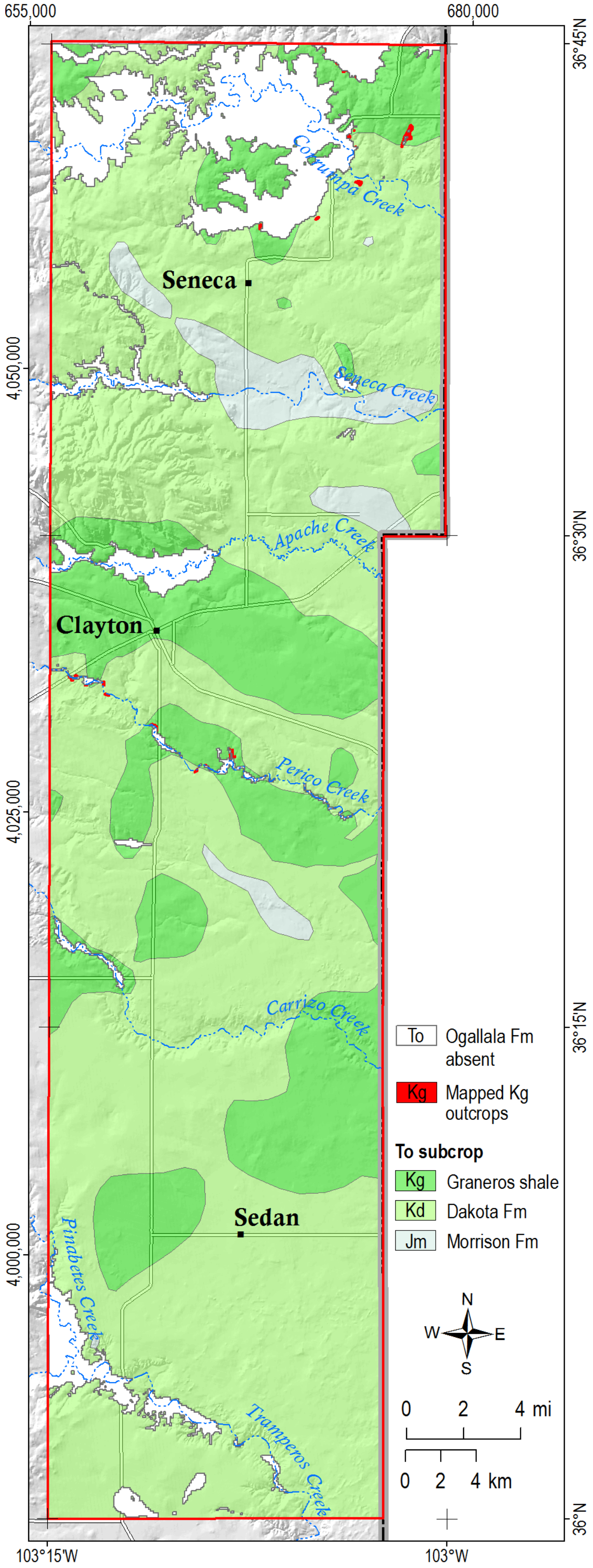


Figure 9–Inferred geologic subcrop at the base of the Ogallala Formation. Mapped outcrops of the Graneros Shale (Kg) are shown for comparison with the inferred subsurface extent. See text and Appendix 1 for discussion.

VI. HYDROLOGY

Geologic controls

An understanding of the basic geology of the study area allows numerous inferences to be drawn about groundwater occurrence. The subsurface geology consists of vertically stratified sandstone beds from several formations with intervening shale, siltstone, and minor coal layers (Figures 3 and 4), all with an overall gentle dip to the east (Figure 7). Beds should be fairly continuous and homogeneous laterally within the Cretaceous units given their shoreline depositional environment. Channel sandstones and floodplain mudstones of the Morrison Formation should show more lateral heterogeneity. The most hydraulically conductive sands and gravels of the Ogallala Formation are at the base and along the paleo-channels incised into the underlying bedrock (Figure 5; Gustavson and Winkler, 1988).

The aquifer system is best described as complex and vertically layered, with multiple water-bearing zones formed by the permeable sandstone beds in which groundwater flow is subhorizontal and parallel to bedding. The finer-grained units, particularly the Graneros Shale and shaly beds in the Dakota Formation, can act as aquitards and will inhibit vertical groundwater flow. The degree of confinement of should increase with depth, and vertical connectivity amongst conductive sandstone beds will be limited to areas where fine-grained beds pinch out or have been eroded. As discussed above with regard to the Graneros Shale, mapping out these areas in detail is problematic.

Perched water may be present in the Ogallala Formation where it overlies the Graneros Shale. Where it is not present, the Ogallala is in good hydrologic connection with the underlying units, especially along paleochannels eroded into the Mesozoic rocks (Figure 5), as these are filled with coarser sediments than the intervening paleo-uplands.

Historic groundwater conditions

A map of hand-contoured historic water level elevations defining the potentiometric surface is shown in Figure 10 with the locations of wells from Cooper and Davis (1967) used to create the map. This map represents groundwater conditions in 1954. With few exceptions, smooth contours were easily drawn from the data.

Outlier wells are noted which had significantly different water levels from their neighbors. These may simply be poor quality measurements (for example, in a well recovering from pumping), but a few outlier wells had much greater total depths than their neighbors. These outlier water levels may represent a deeper aquifer that is poorly connected to the shallow aquifer tapped by most of the wells. This is to be expected in this vertically stratified aquifer.

Figure 11 highlights the outlier wells, along with probable perched zones of shallow groundwater in the Ogallala Formation (based on 1954 water levels contoured in this study) and inferred deeper groundwater contours beneath the perched zones. The perched zone east of Clayton that extends east to the state line was also noted by Baldwin and Bushman (1957, fig. 7; Figure 11). More broadly, areas where the Graneros Shale may exist under the Ogallala Formation (Figures 9 and 11) are potential sites for perched aquifer zones in the Ogallala Formation.

Hydraulic gradients range from 0.0018 (~10 feet per mile) south of Sedan to 0.026 (~137 feet per mile) in some areas north of Clayton. The gently sloping surface north and south of Sedan

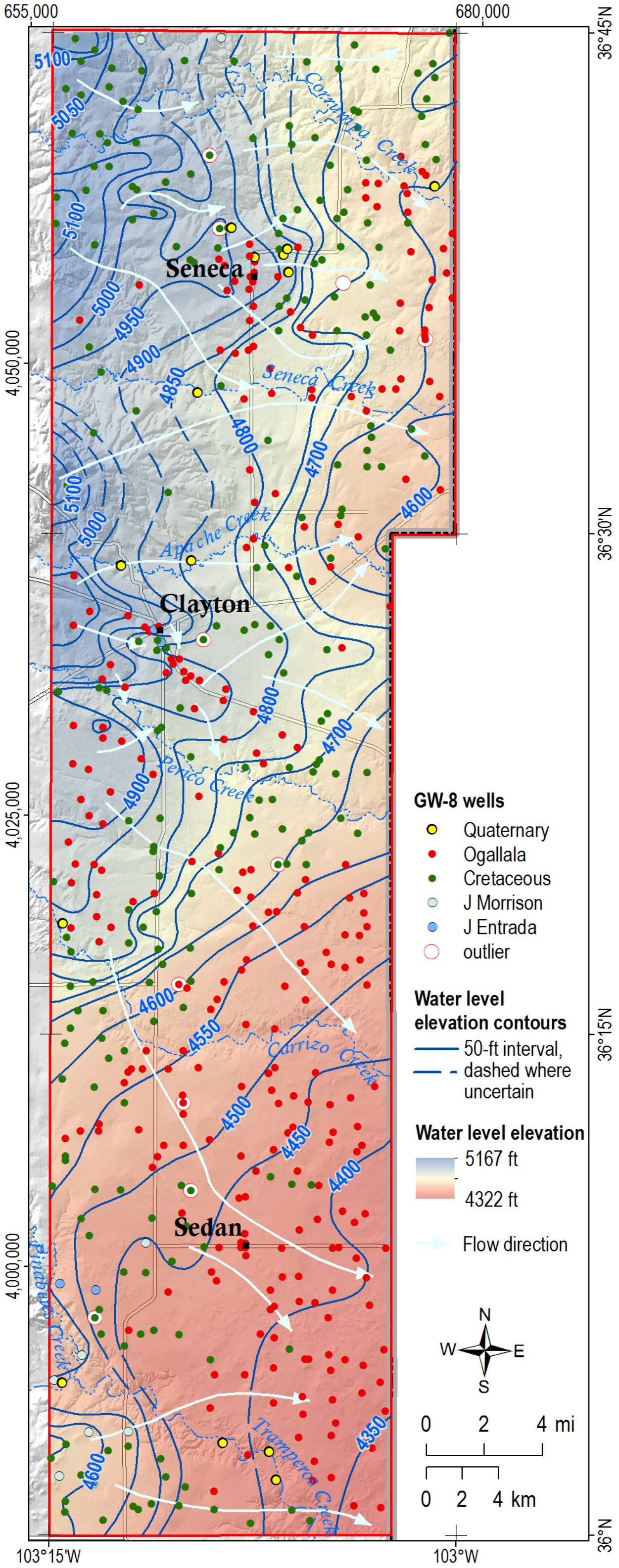


Figure 10–Map of water table elevations in 1954. Well data are from NMBGMR Groundwater Report 8 (Cooper and Davis, 1967) and are color coded for formation of completion. Outlier wells differ from the contoured intervals by more than 50 feet. Flow lines assume downgradient flow perpendicular to the contours and isotropic hydraulic conductivity.

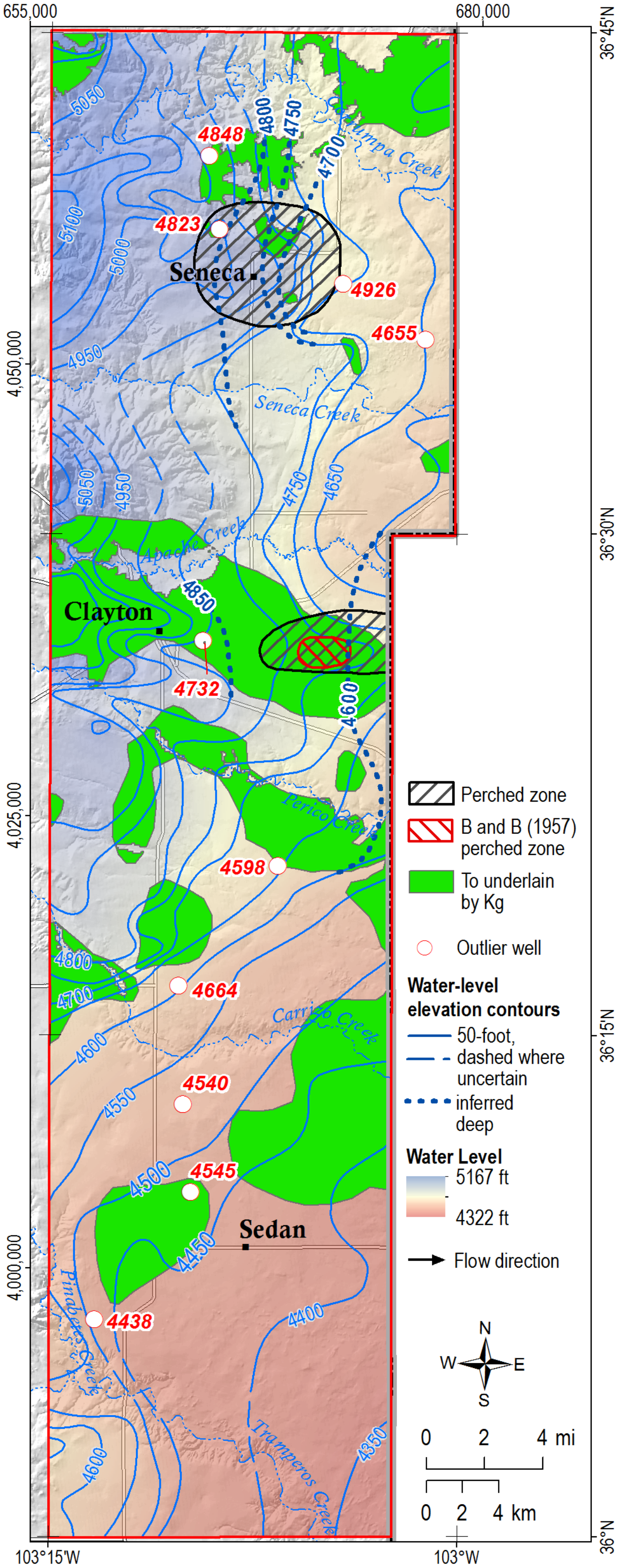


Figure 11–Map of water table conditions in 1954 showing interpreted zones of perched water, perched zone mapped by Baldwin and Bushman (1957), and areas where Ogallala Formation is probably underlain by Graneros Shale. Deep, inferred water level contours are shown under perched zones. Outlier wells differ from the contoured intervals by more than 50 feet.

(Figure 10) indicates that this is an area of high transmissivity, consistent with the generally thick and permeable Ogallala and Dakota Formations in this area. Gentle gradients in the potentiometric surface correspond better to areas of thick Ogallala Formation than with areas of thick or thin Dakota Formation (compare Figures 6 and 8 with Figure 10); for example, from Clayton to the south of Perico Creek. This implies that the potentiometric surface is most reflective of the thickness and conductivity of the Ogallala Formation. An exception is the ridge east of Clayton, which is along a zone of thick Dakota Formation where the Ogallala is quite thin and underlain by Graneros Shale. Overall, the map is reflective of hydrologic conditions in both the Dakota and Ogallala Formations, the exceptions being possible perched zones where the Ogallala overlies Graneros Shale.

Groundwater flow is mostly west to east in the northern half of the study area and northwest to southeast in the southern half with local complexities in areas of directionally variable gradients. These are likely due to juxtaposition of rock types along erosional contacts (e.g., Ogallala channel gravels against Dakota Formation or Morrison Formation shales) and lateral pinchouts of rock types within the Cretaceous and Jurassic units.

Figure 12 shows that the historic depth-to-water is mostly dependent on topography, as the surface relief is much greater then the relief on the water table. Depths are greatest beneath Rabbit Ears Mountain and in a large area northwest of Sedan where depths average over 200 feet. In several areas along Corrumpa Creek, Perico Creek, Carizo Creek and Tramperos Creek the depth-to-water is zero (or negative, up to -37 feet). In part, these areas are an artifact of the contouring process, as no attempt was made to identify perennial stream reaches in the 1950s and tie the contours to them. However, several of the areas are in proximity to mapped springs, and thus probably represent areas of historical groundwater discharge (Figure 12). The others, such as along Carrizo Creek and eastern Tramperos and Corrumpa Creeks, may have

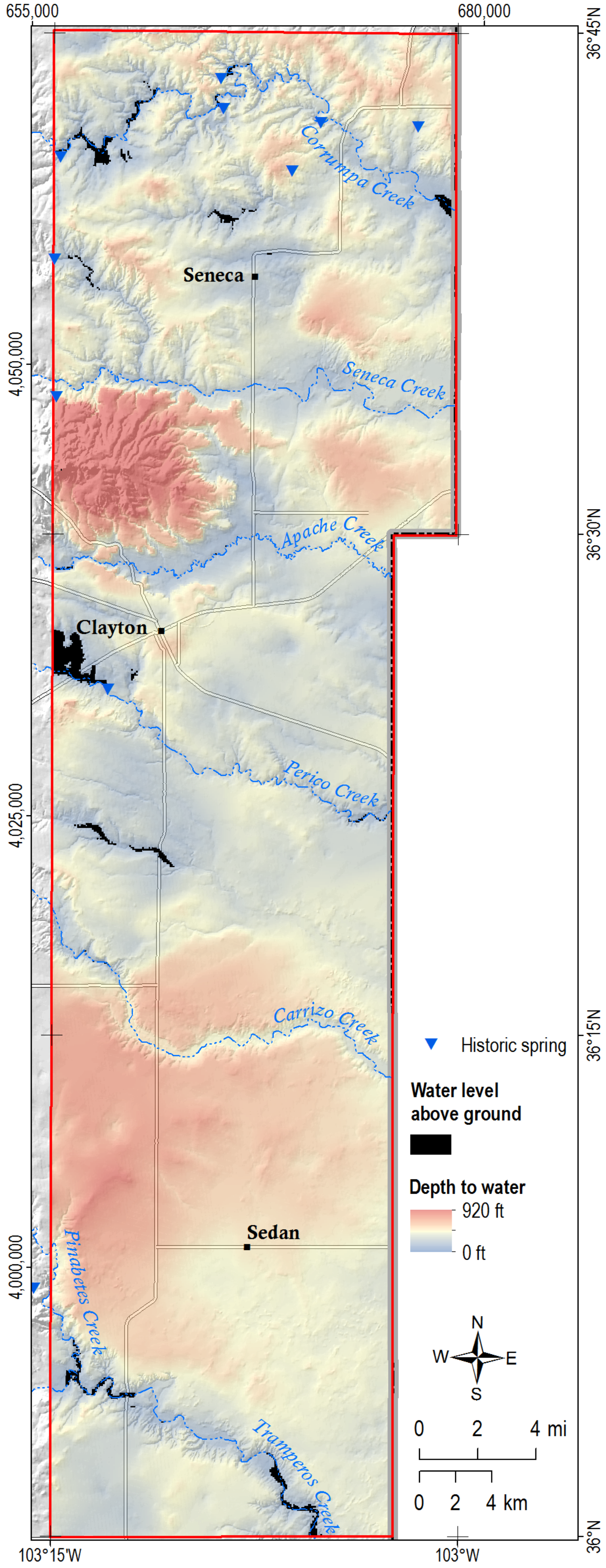


Figure 12–Map of depth to water in 1954. Areas where the potentiometric surface projects above ground are areas of very shallow groundwater or groundwater discharge to perennial streams.

been areas of distributed seepage into the creek bed. Throughout much of the study area the depth-to-water in 1954 was less than 120 feet, and much less in the major drainages.

Modern groundwater conditions

Figure 13 shows wells with long periods of annual or biannual water level measurements dating to the early 1960s. The data was collected by the USGS and the NESWCD. Figure 13 also shows wells from which I collected water samples and installed continuous water level recorders for this study.

A map of hand-contoured water level elevations defining the potentiometric surface in winter of 2011 is shown in Figure 14 with the locations of water level measurements used to define the surface. The winter 2011 water level contours are based on measurements in the long-record wells described above, and in additional wells that the NESWCD has measured biyearly for the past few years. Note that the 1954 water table map (Figure 10) is based on hundreds of measurements, whereas the 2011 map is based on only 32. The spatial resolution in the 2011 map is much less, and only the broad patterns in the water level changes are significant. There have been large water level declines over this time which have perturbed groundwater flow patterns. Present-day groundwater flow is still generally from west to east, but flowlines now converge into groundwater troughs induced by groundwater pumping northeast of Clayton and east of Sedan (Figure 14).

Water level changes 1954–2011

Figure 15 shows the change in water levels from 1954 to 2001. Comparing these two time periods is instructive as they are before and after major irrigated agriculture began in the study area in 1967 (Lappala, 1973). The map was constructed by subtracting the 2011 water table surface from the 1954 water table surface.

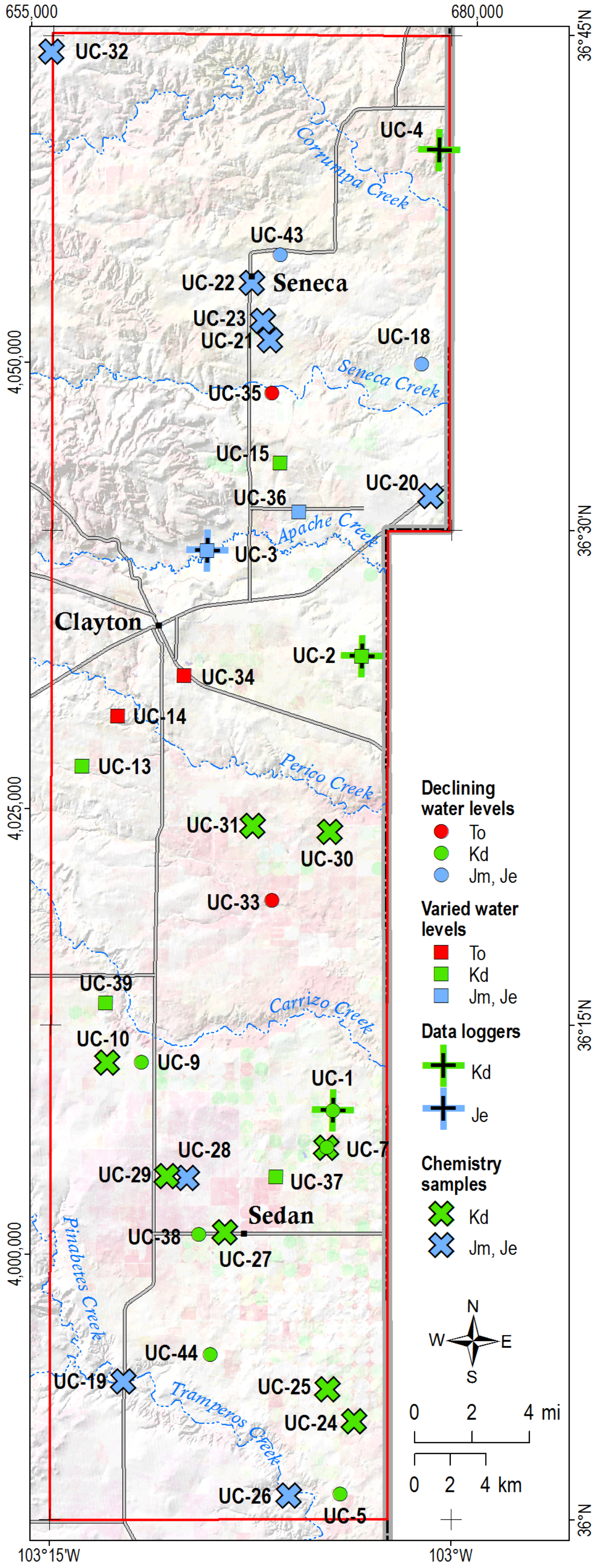


Figure 13–Locations of wells with long records of water level measurements and wells from which water chemistry samples were collected. Classified ("Declining" and "Varied") hydrographs are presented in Figures 18 and 19. Unit of completion for the wells is based on log interpretation or comparison with subsurface structure contours (To = Ogallala Fm, Kd = Dakota Fm, Jm, Je = Morrison and/or Entrada Fm).

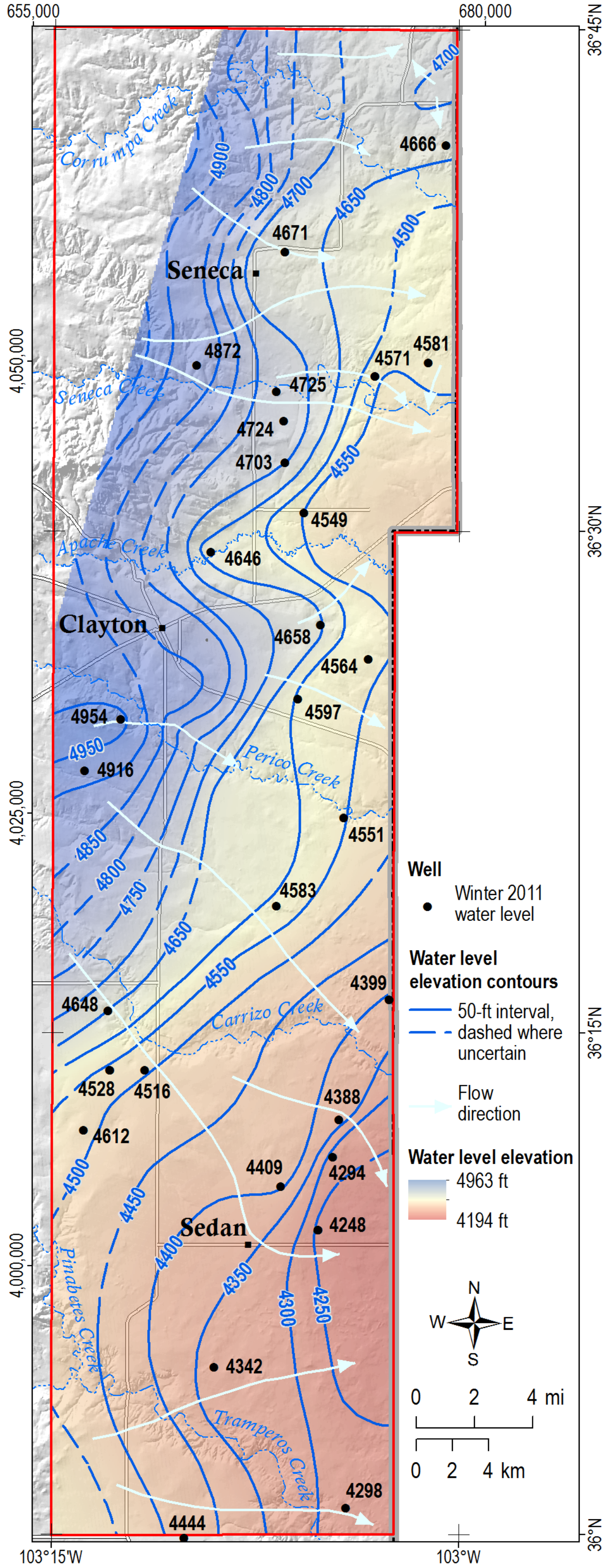


Figure 14–Map of water table elevations in winter of 2011. Data points used to construct the contours are shown. Flow lines assume down-gradient flow perpendicular to the contours and isotropic hydraulic conductivity.

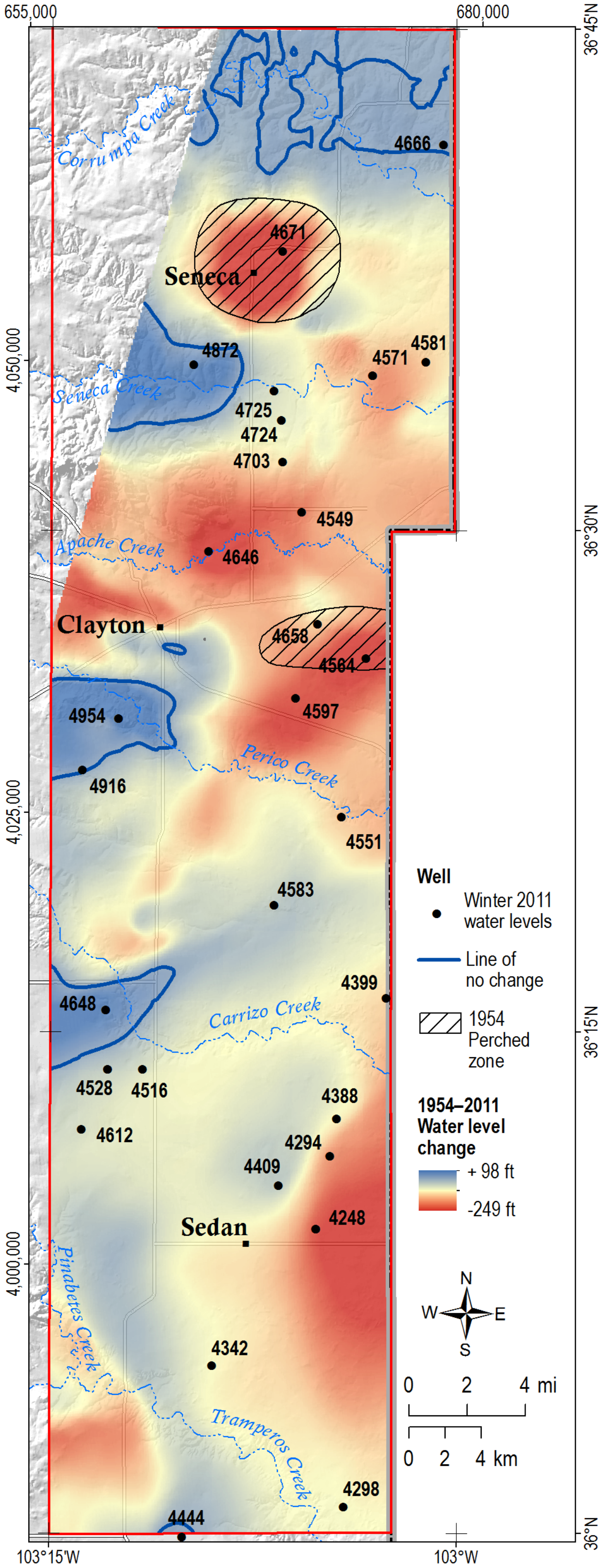


Figure 15–Change in water levels between 1954 and 2011. Declines are negative and shown in shades of yellow and red, and are separated from areas of water level rise (darker shades of blue) by the "line of no change". Declines in areas identified as perched zones on the 1954 map (hatched areas in Figure 11) are calculated from the perched zone water level. Declines in the regional aquifer beneath these perched zones are less.

The largest water level declines are east and north of Clayton, around Seneca, and east of Sedan (Figure 15). The maximum decline is 249 feet, whereas southwest of Clayton along the margin of the study area water levels have risen in some places many 10s of feet. The large declines around Seneca, and to a lesser degree directly east of Clayton, are due to the fact that the historic water level contours in these areas reflected perched zones above a continuous, deeper aquifer (Figures 10 and 11). Water level changes in the deeper aquifer beneath these perched zones are likely not as large as indicated in Figure 15; however, the perched zones have been essentially dewatered since 1954. For example, well UC-0002, in the perched aquifer east of Clayton (Figures 11 and 13), has been dry during the past several summers.

Ogallala Formation saturated thickness changes 1954–2011

The Ogallala and Dakota Formations are, in most areas, hydraulically connected to some degree, and thus comprise a single, though complex, aquifer system. However, it is instructive to look at saturated thickness changes in these units separately. Figures 16a, b, and c show the saturated thickness of the Ogallala Formation aquifer in 1954, 2011, and the calculated change between these two times. Saturated thicknesses for each time period were calculated by subtracting the base of the formation from the potentiometric surface.

The saturated thickness is obviously zero where the formation is absent. In 1954 much of the Ogallala Formation had no saturation at all, and it was rarely saturated throughout its full thickness. There was very good correlation between the areas of greatest saturated thickness of the Ogallala Formation, paleovalleys at the base of the formation, and occurrence of wells completed in the formation in 1954 (Figures 5 and 16a). By 2011 the spatial extent and thickness of the saturated zone in the Ogallala Formation has been greatly reduced.

Dakota Formation saturated thickness changes 1954–2011

Figure 17 shows the saturated thickness of the Dakota Formation aquifer in 1954, 2011, and the calculated change between these two times. Water level and well data show that the Dakota aquifer has multiple water bearing zones, the lower of which are partly confined (see below). In the Dakota aquifer, water level declines in some deep wells probably represent potentiometric surface declines in confined units, and in shallower wells represent true dewatering of shallow, unconfined aquifers. In 1954 areas along western Seneca Creek and Tramperos Creek where the Dakota Formation is thin and dissected had zero saturated thickness, but most of the unit was completely saturated. The increased extent of completely unsaturated Dakota Formation in 2011 is clear. Areas where there has been no change in saturation of the Dakota Formation (Figure 17c) correspond well to areas of great initial saturated thickness of the Ogallala Formation (Figure 16a).

Hydrographs

The water level declines since 1954 be understood in more detail by examining well hydrographs (Figures 18 and 19), which show water level changes over time. The wells shown were chosen from the USGS NWIS database and NESWCD monitoring networks because they have a significant number of repeat measurements extending back to the 1960s. It is difficult to determine which, if any, of the wells from these data sets are the same wells that were measured in the 1950s and reported in Baldwin and Bushman (1957) and Cooper and Davis (1967) because of different naming conventions and uncertainties in well locations. Nonetheless, the wells in Figures 18 and 19 give good spatial coverage of the study area and are completed in all the major geologic units to a variety of depths.

The hydrographs can be grouped simply into two types, those that show a continuous, fairly

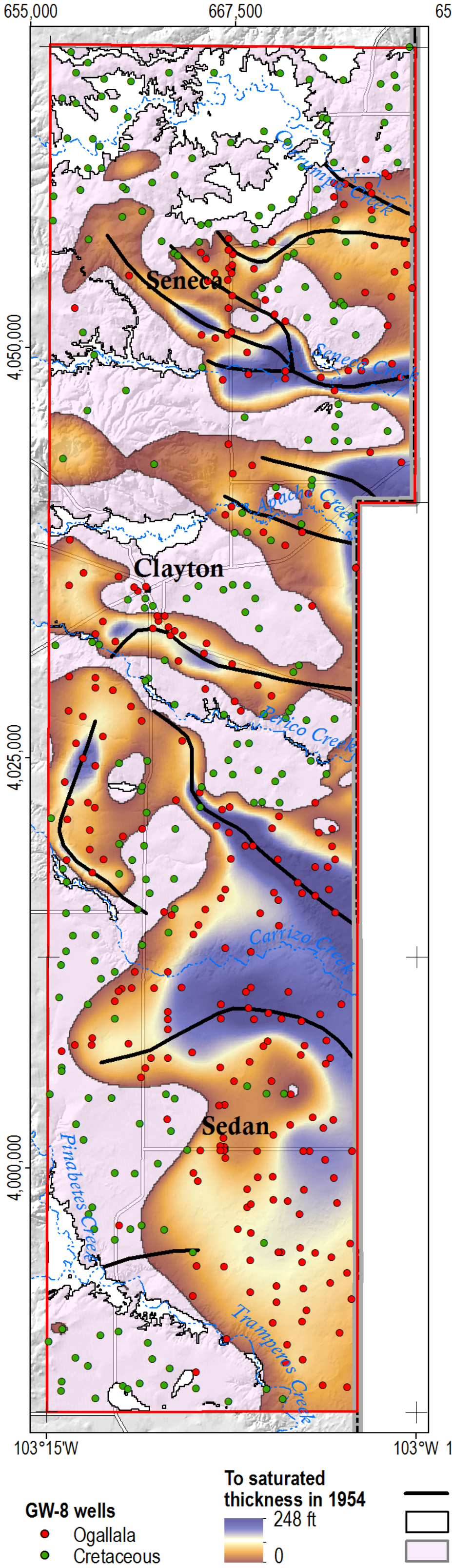


Figure 16a–Saturated thickness of the Ogallala Formation (To) in 1954 calculated from water level data in NMBGMR Groundwater Report 8 (GW-8; Cooper and Davis, 1967).

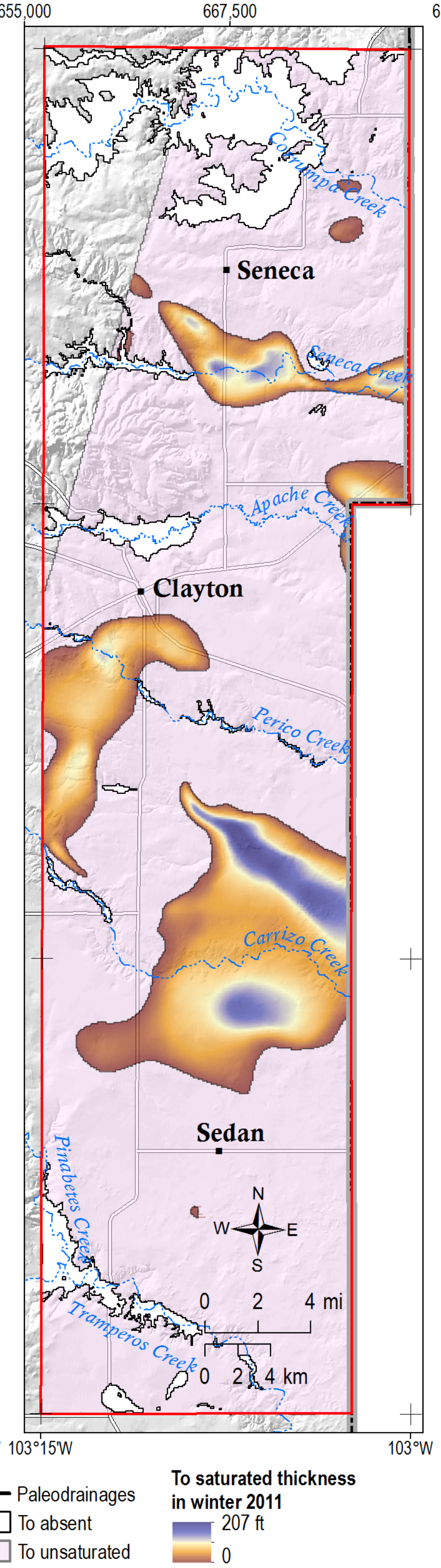


Figure 16b–Saturated thickness of the Ogallala Formation (To) in winter 2011.

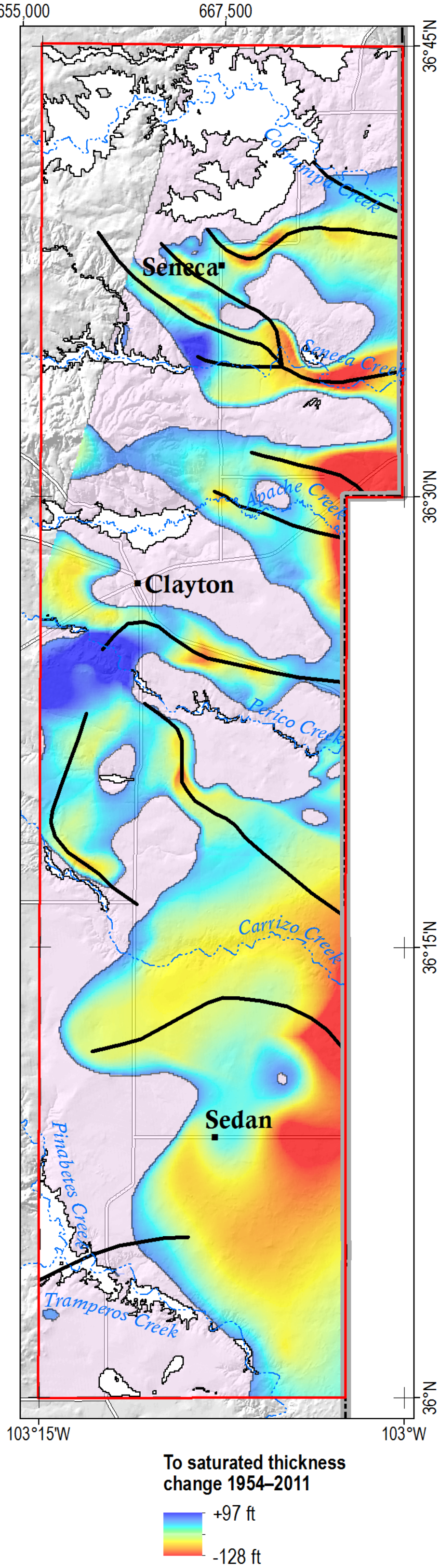


Figure 16c–Change in saturated thickness of the Ogallala Formation (To) from 1954 to winter 2011. Declines are negative, in shades of yellow and red.

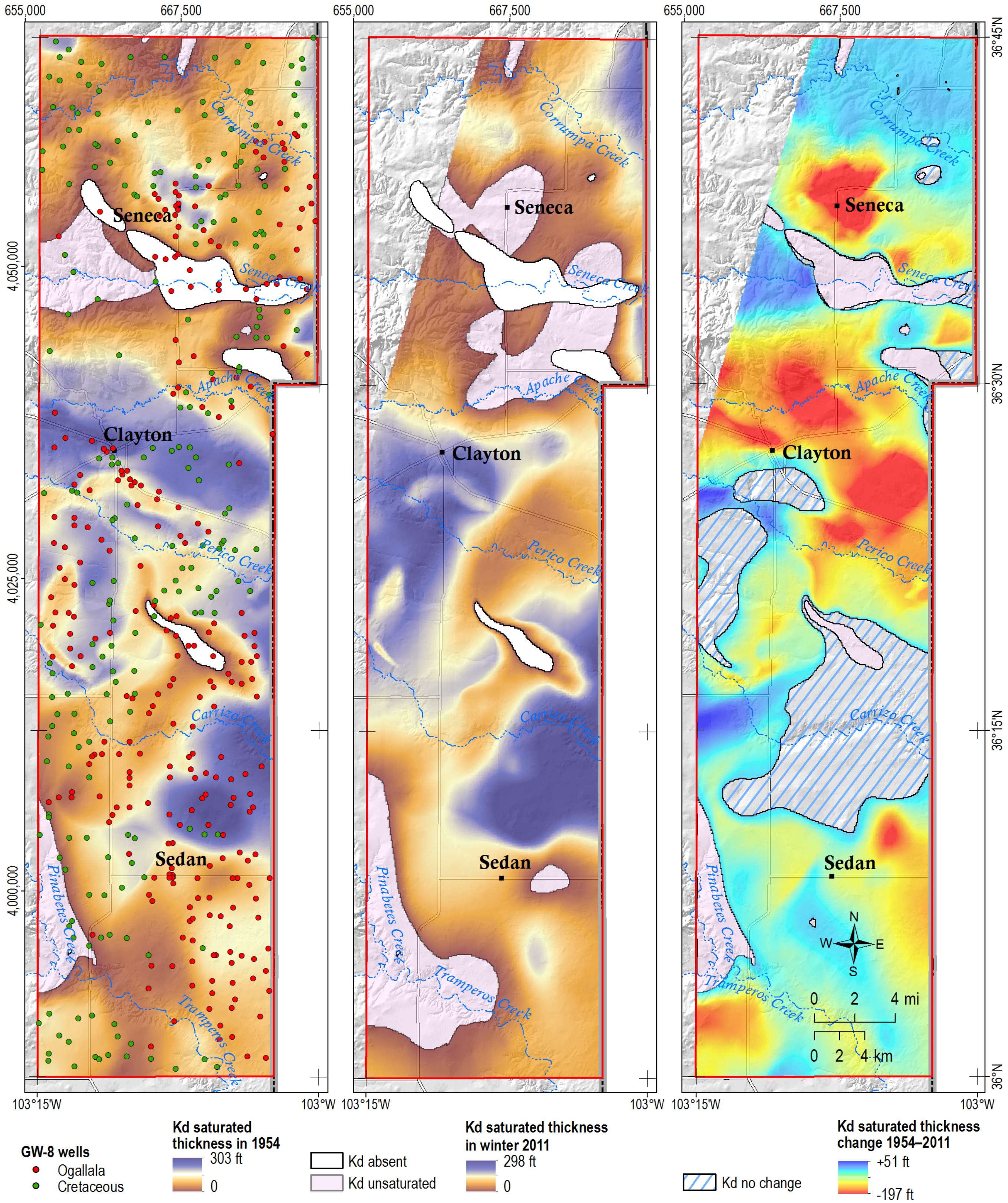


Figure 17a–Saturated thickness of the Dakota Formation (Kd) in 1954 calculated from water level data in NMBGMR Groundwater Report 8 (GW-8; Cooper and Davis, 1967).

Figure 17b–Saturated thickness of the Dakota Formation (Kd) in winter 2011.

Figure 17c–Change in saturated thickness of the Dakota Formation (Kd) from 1954 to winter 2011. Declines are negative, in shades of yellow and red. Hatched areas indicate no change in saturated thickness.

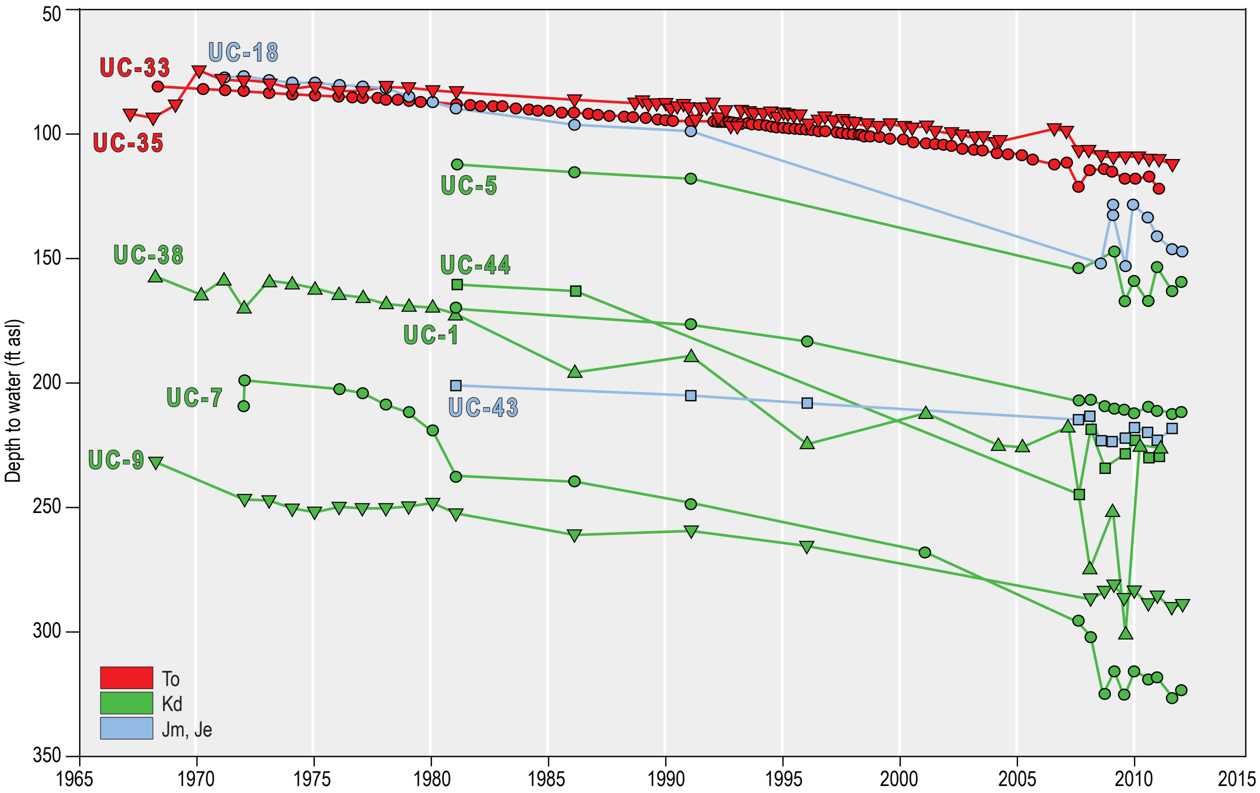


Figure 18–Hydrographs from wells that show an overall steady declining trend. Well locations shown in Figure 13. Data are tabulated in Appendices 4 and 5.

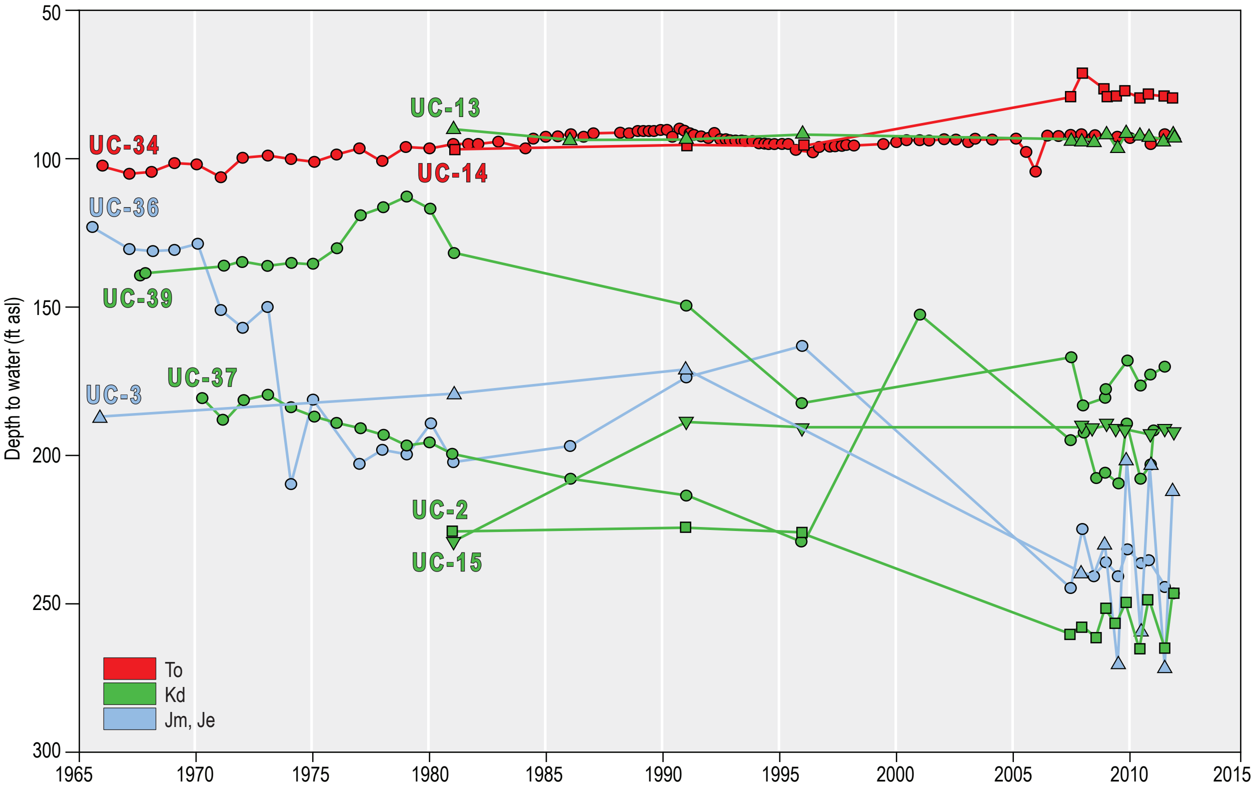


Figure 19–Hydrographs from wells showing a variety of water level trends with time. Well locations shown in Figure 13. Data are tabulated in Appendices 4 and 5.

steady decline in water levels over time (Figure 18), and those that do not (Figure 19). The continuously declining hydrographs have slopes that vary over a small range, from about 0.8 to 1.2 feet per year. The hydrographs that do not show continuous declines exhibit a variety of changes, with three wells showing no change (UC-13, -34) or a small rise (UC-14) over the period of observation. These three wells are all located less than five miles south of Clayton (Figure 13).

There is no consistent relationship between these different hydrograph types and formation of completion or well depth. These observations, together with the consistent slopes of the declining hydrographs, suggest that the main control on water level changes is the location, timing, and amount of groundwater pumping. The biannual measurements made in many of the wells since 2007 show declines and recoveries of water levels during and between irrigation seasons, respectively. Figures 18 and 19 show that most of these recoveries are superimposed on a long-term water level declines; that is, the recovering water levels are lower with each succeeding irrigation season. The variety of water level trends in space, with depth, and with formation imply that there are multiple water bearing zones tapped by the wells and that hydrologic connections between them are variable.

Relationships amongst well depth, formation, and water levels

Comparison of water levels to well depth can reveal information about subsurface flow patterns and the degree of confinement of aquifers. This approach was taken as few wells in this study have detailed logs or construction information with which to identify potential confining beds and their relation to screened intervals. Lappala (1973) and Kilmer (1987) noted that many irrigation wells in southeastern Union County have multiple completions tapping several Formations. Water levels in such wells reflect an integration of the hydraulic head distribution of all of the water-bearing zones accessed by the well.

Wells completed in the Jurassic Entrada Formation are the deepest overall; otherwise there are no significant trends of well depth with formation of completion. This is consistent with the large variation in elevation of the base of the Ogallala Formation and Dakota Formation (Figures 5 and 7)—a wide variety of depths completion are to be expected in these units.

Trends of depth-to-water with time and formation are shown in Figure 20. The well points fall below the line along which depth to water is equal to the well depth. Wells plotting far below this line have shallow depths to water relative to their total depth, and thus a long water column. This suggests they may be tapping confined aquifers.

Wells in the Ogallala Formation appear to be of two types. One group of wells shows a trend along the line of equivalence, with water levels decreasing with depth, small water columns, and probable unconfined conditions. A second group of wells plots below this line, around the 100 foot depth-to water mark.

In Dakota Formation wells the depth-to-water increases with well depth until about 250 feet total depth. Here the data points begin to curve away from the line of equivalence, especially the older data. Put another way, as the Dakota wells get deeper, the water column in the wells gets longer. The wells deeper than 250 feet may be tapping confined zones in the lower Dakota, wherein the water is under artesian pressure and thus rises significantly within the well bore. As noted above, this interpretation can not be confirmed without knowing the depth intervals over which the wells are screened.

No wells in the Jurassic Morrison and Entrada Formations are less than 200 feet deep. Water columns tend to become larger as in these wells as well depth increases, suggesting increasing confinement with depth.

These trends indicate that many Ogallala and Dakota wells are completed in unconfined portions of the aquifer, whereas deeper wells

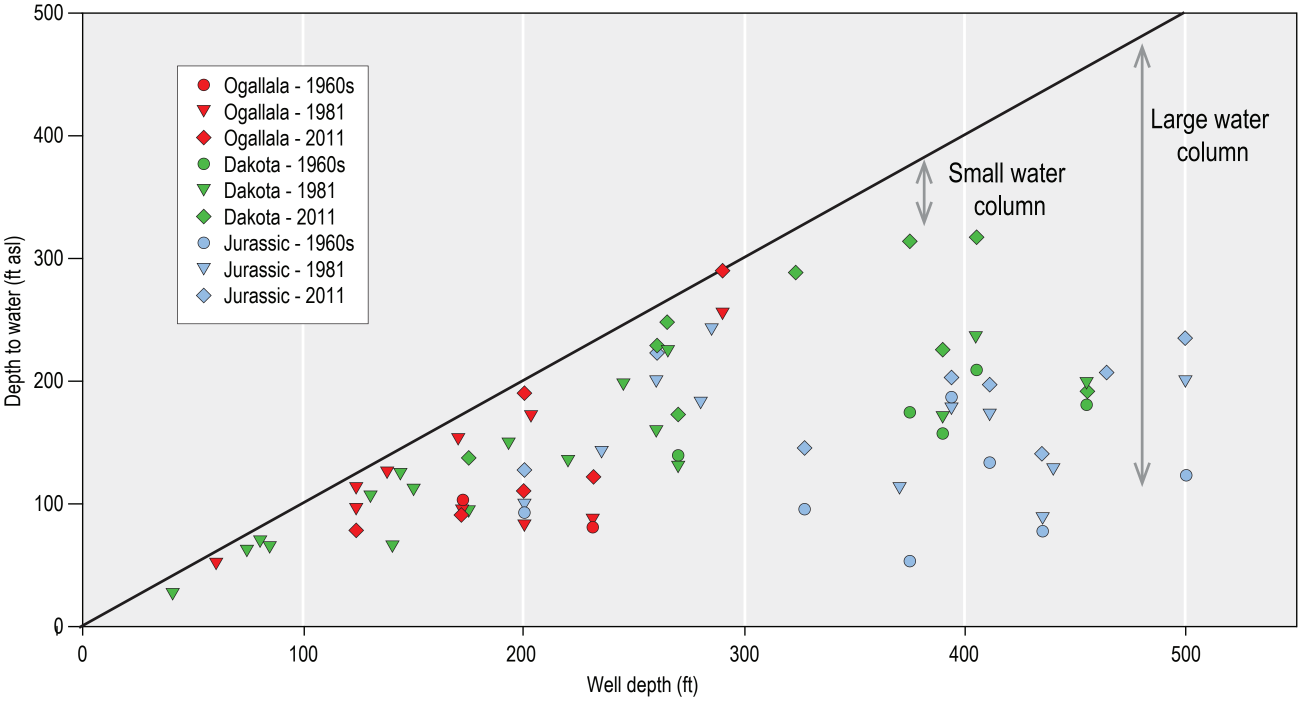


Figure 20–Depth-to-water plotted against well depth for wells with long records of measurement. Symbol shape denotes the year of measurement, and color denotes the formation of completion. The further below the diagonal "line of equivalence" a well plots, the longer the water column in the well. The overall trend is increasing depths-to-water and shorter water columns over time.

exist under confined or semi-confined conditions. What is most striking in Figure 20 is the drop in water levels (shown as increase in depth to water) from the 1960s, to 1981, and 2011. It is clear, regardless of well depth, formation, or degree of confinement, that there has been a decline in water levels across the study area. This implies that groundwater recharge is much less than discharge through pumping.

Continuous hydrographs from water level recorders

Figure 21 shows hydrographs from the four wells with continuous data recorders. They are completed to depths of 175 to 394 feet in the Dakota Formation (UC-1, -2, -4) and Entrada Sandstone (UC-3). The water level in well UC-3 dropped 66 feet during the 2011 irrigation season but recovered between August 2011 and February 2012. Water levels and saturated thickness of the Dakota in this area have declined more than 150 feet since 1954 (Figures 15 and 17c). The steep water-level decline and ensuing recovery in well UC-3 are probably due to onset and cessation of irrigation pumping in nearby wells.

Water levels in the other three wells shown in Figure 21 all changed less than three feet over the year of monitoring. Well UC-1 is northeast of Sedan in an area with abundant irrigation. Water levels and saturated thicknesses have dropped considerably around UC-2 since 1954 and this well has a one-foot water column at present. It is in an area that was probably a perched aquifer in 1954 (Figures 13 and 15).

Hydrogeologic conditions – confinement and compartmentalization

The vertical geologic stratification of the study area (Figures 3 and 4) should cause compartmentalization of the aquifers, with much better lateral than vertical connectivity of water-bearing zones. To a lesser degree, lateral connectivity will be limited by pinchouts and erosional truncation of both permeable water-bearing zones (sandstones) and shale/mudstone confining beds.

There is evidence for these geologic controls in the hydrologic data.

Wells in close proximity to each other, but completed at different depths can provide information on variations of hydraulic head with depth. Wells UC-29, UC-27, and UC-28 west of Sedan (Figure 13) increase in depth from 335 to 495 feet, and depths to water increase from 199 to 250 feet. The drop in water levels (decreasing head) with increasing well depth implies that effective confining beds stratify the aquifer and allow vertical head variations to persist. Downward groundwater flow is not likely even with the downward decreasing head gradient because of geologic stratification. In contrast, wells UC-22 and UC-23 south of Seneca (Figure 13) are 364 and 510 feet deep respectively, with water levels of 289 and 260 feet. Here the deeper well has the shallower water level (higher head).

The large and rapid recoveries in water levels in well UC-3 (Figure 21), together with observations of increasing head with well depth near Seneca described above, indicate that the Entrada Sandstone is a confined aquifer in this area. Cooper and Davis (1967) reported several wells completed to less than 300 feet in the Entrada Sandstone that had artesian flow, and were thus discharging from a confined aquifer, during the 1950s. They are located along Tramperos Creek about 13 miles west of the present study area, where the surface bedrock is the Morrison Formation.

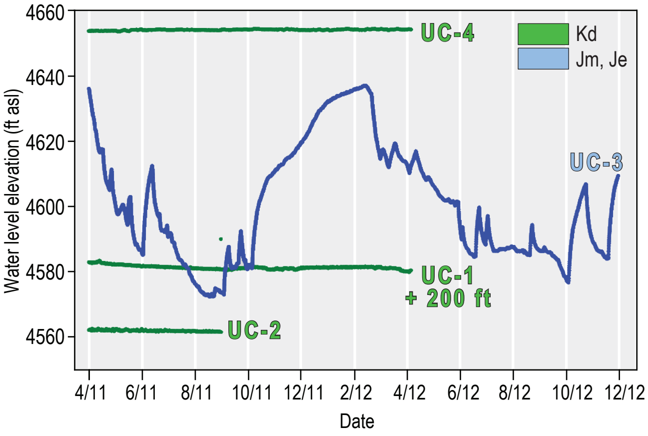


Figure 21–Continuous hydrographs from data loggers. 200 feet was added to the water levels in well UC-1 for ease of display on the figure. Kd = Dakota Formation. Jm, Je = Morrison and/or Entrada Formations. See Figure 13 for well locations.

The hydrograph of well UC-1 (Figure 21) shows little change over one irrigation season. This well is in an area with abundant irrigation (note the abundant circular, irrigated fields around the well in Figure 13) and is completed in a water-bearing zone in the Dakota Formation that is not tapped by adjacent wells and/or is hydrologically isolated from other productive parts of the aquifer.

The declining hydrographs in Figure 18 show similar slopes, 0.8 to 1.2 feet per year. It is interesting that these wells, completed to a variety of depths and in different formations, show similar behavior. It may reflect similarities in the hydraulic properties of the tapped water-bearing zones, similar time-averaged pumping rates, or more likely, some combination of both. The hydrographs also suggest connectivity amongst the tapped formations. Conversely, the variety of water level changes in Figure 19 imply the opposite scenario: some combination of disconnected, compartmentalized water-bearing zones, hydraulic properties outside the "average" range, and variable pumping rates over time.

The limited number of detailed well logs available show numerous shale/mudstone intervals that can act as confining beds. Four of the seven well logs in Figure 4 have shale/mudstone intervals that could act as confining layers in the Dakota Formation, as well as shale/mudstone intervals in the underlying Purgatorie Formation. Two wells in areas where the Graneros Shale is present (Figures 9 and 13), UC-28 and -29, had static water levels above shale/mudstone intervals as shown in the well logs.

Integration of new and historic hydrologic data with subsurface geology thus creates a picture of a vertically stratified aquifer system, with multiple water-bearing zones separated by low-permeability confining beds. Lateral connectivity is on average much higher than vertical, and confinement increases with depth. These hydrogeologic characteristics have important implications for groundwater flow paths, mixing, and recharge.

VII. GROUNDWATER CHEMISTRY

I collected water samples from sixteen wells (Figures 13 and 22) and attempted to obtain good spatial coverage across the study area as well as good depth and Formation coverage, but unfortunately no wells completed in the Ogallala Formation could be sampled. All water samples were analyzed for general chemistry; four were analyzed for tritium, and seven for ^{14}C. I recalculated hardness data presented in Cooper and Davis (1967) to Ca and Mg concentrations for comparison with the new data to investigate changes in groundwater chemistry over time.

General chemistry

Field parameters measured during sampling included temperature, pH, and specific conductance, and are summarized in Table 1. Water temperatures were 16 to 17 ºC, apart from two samples that were about 22 ºC, most likely due to having to flush the water through a long, sun-warmed hose. pH values are neutral to slightly basic, with no significant spatial variability. Specific conductance ranges from 380 to 800 µS/cm, again with no significant spatial trends.

Table 1 also summarizes the general chemistry and trace metal data. All samples have total dissolved solids (TDS) below 500 mg/l, and by this criteria are high-quality drinking water (http://ga.water.usgs.gov/edu/dictionary.html#F). Most wells have nitrate concentrations well below the drinking water standard of 44 mg/L (http://water.epa.gov/drink/contaminants/basicinformation/nitrate.cfm), but two wells (UC-26, -27; Figures 13 and 22) have relatively elevated values of 26 and 35 mg/L. These values may be a natural occurrence from nitrate in shale beds (S. Timmons, personal commun., 2013) or possibly due to drainage from septic systems, concentrated animal waste, or heavily fertilized fields, thus indicating some mixing of shallow groundwater with deeper water tapped by the wells, perhaps due to leakage thru well bores. Concentrations of other measured constituents are below established drinking water limits.

The sampled well waters consist of several water types based on the dominant cations and anions present (Figure 22), and when plotted on a Piper diagram the waters can be separated into three groups (Figure 23). Sample UC-19 (Group 1) near the lower apex of the diamond has nearly 500 mg/l total dissolved solids (TDS) and a unique sodium – bicarbonate water type. This well is completed in Jurassic Morrison Formation sandstone. Samples UC-10, 27, and 31, all in the

Table 1–Statistical summary of chemical parameters for sampled wells. “STD” is standard deviation, “SC” is specific conductance, and “TDS” is total dissolved solids.

Parameter	Unit	Mean	Min	Max	STD
Temperature	ºC	17.3	14.7	22.4	2.1
pH	pH units	7.5	7	8.2	0.3
SC	µS/cm	536	380	800	131
TDS	mg/L	330	233	496	83
Calcium	mg/L	48	7	65	15
Magnesium	mg/L	21	8	44	8
Sodium	mg/L	33	13	165	37
Potassium	mg/L	3.58	2.1	5.8	0.96
Bicarbonate	mg/L	229	185	370	43
Sulfate	mg/L	47	17	110	27
Chloride	mg/L	24	6	77	20
Nitrate	mg/L	13	4	35	8
Bromide	mg/L	0.21	0.075	0.76	0.18
Silicon	mg/L	11.9	5.6	16	2.7
Fluoride	mg/L	0.99	0.57	1.6	0.25
Iron	mg/L	0.3	0.033	0.57	0.38
Boron	mg/L	0.11	0.055	0.37	0.078
Barium	mg/L	0.084	0.016	0.14	0.031
Nickel	mg/L	0.0008	0.0006	0.0013	0.0002
Strontium	mg/L	0.81	0.24	1.8	0.33
Zinc	mg/L	0.025	0.0013	0.14	0.04

Dakota Formation, form Group 2. These three are distinguished in the anion triangle by their higher chloride (20–30 %) compared to the samples from the other wells (5–15 %). Group 3 (wells UC-7, 20–26, 28–30, and 32) forms a group in the diamond and a slightly linear pattern in the anion triangle of the piper diagram (Figure 23). These wells are in the Entrada, Morrison, and Dakota Formations. The waters are dominantly Ca-Mg-HCO_3 type with secondary Na, Cl, and SO_4.

There is no difference in TDS between waters from different formations, and there are no trends of the major chemical constituents with depth. Waters from the Jurassic rocks show a decrease of TDS with depth, but the trend is weak. Stiff diagrams (Figure 22) graphically display the variations in major ion chemistry across the study area. The distinctiveness of sample UC-19 in the southwest corner is clear.

Cooper and Davis (1967) reported numerous chemical analyses of well water samples collected in the 1950s and 1960s, but these data are not as complete as the analyses performed for this study. The data they presented are from a subset of the wells shown in Figure 10. Calcium and magnesium were reported together as “hardness as $CaCO_3$” and sodium and potassium were in most cases reported as the sum. To compare the historical data of Cooper and Davis (1967) with the newly collected data, I performed an inverse-distance-weighted spatial interpolation of Ca/Mg and Na/K ratios of the current data. I then extracted the interpolated values of these chemical ratios at each of the well locations for the Cooper and Davis (1967) data, and back-calculated Ca, Mg, Na, and K values from their reported hardness and sum data. Implicit in this method is that the Ca/Mg and Na/K ratios have not changed over time, so changes in Ca vs. Mg and Na vs. K cannot be detected. However, any radical changes in the spatial patterns of groundwater chemistry should be evident.

The recalculated historical data are plotted in Figure 24. The majority of the historical water analyses plot similarly to the main cluster of data (Group 3) collected for this study (Figure 23).

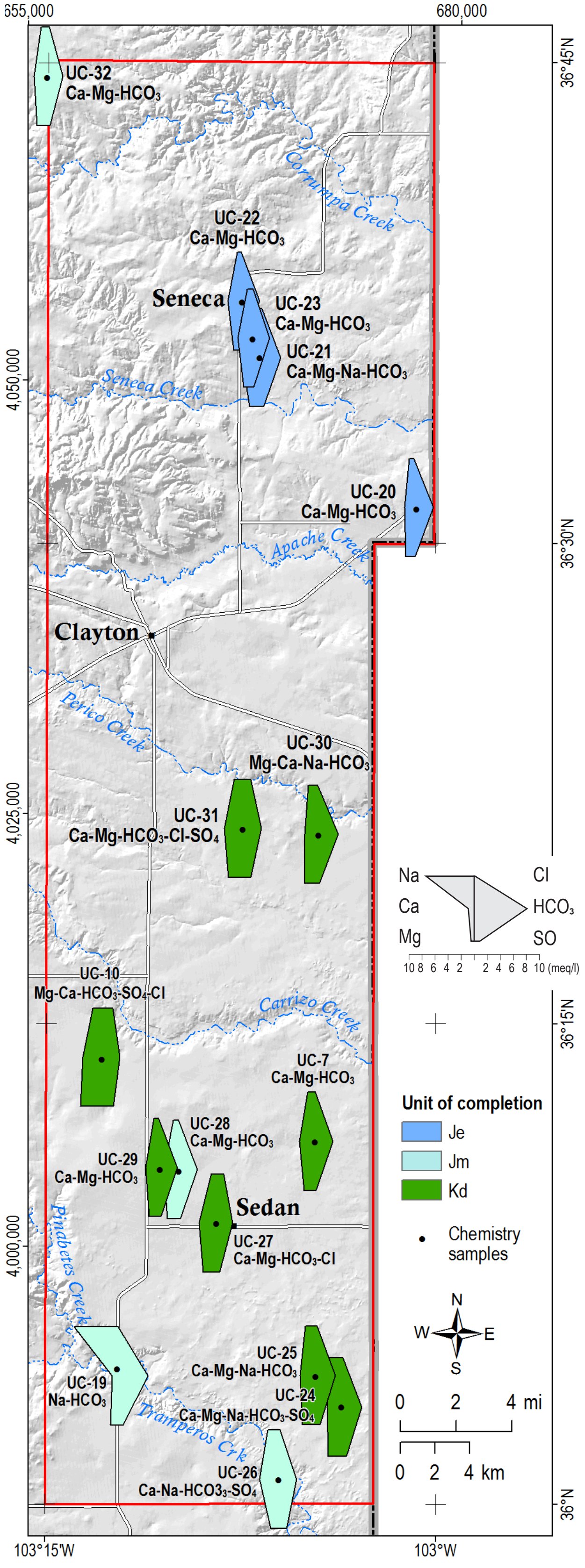
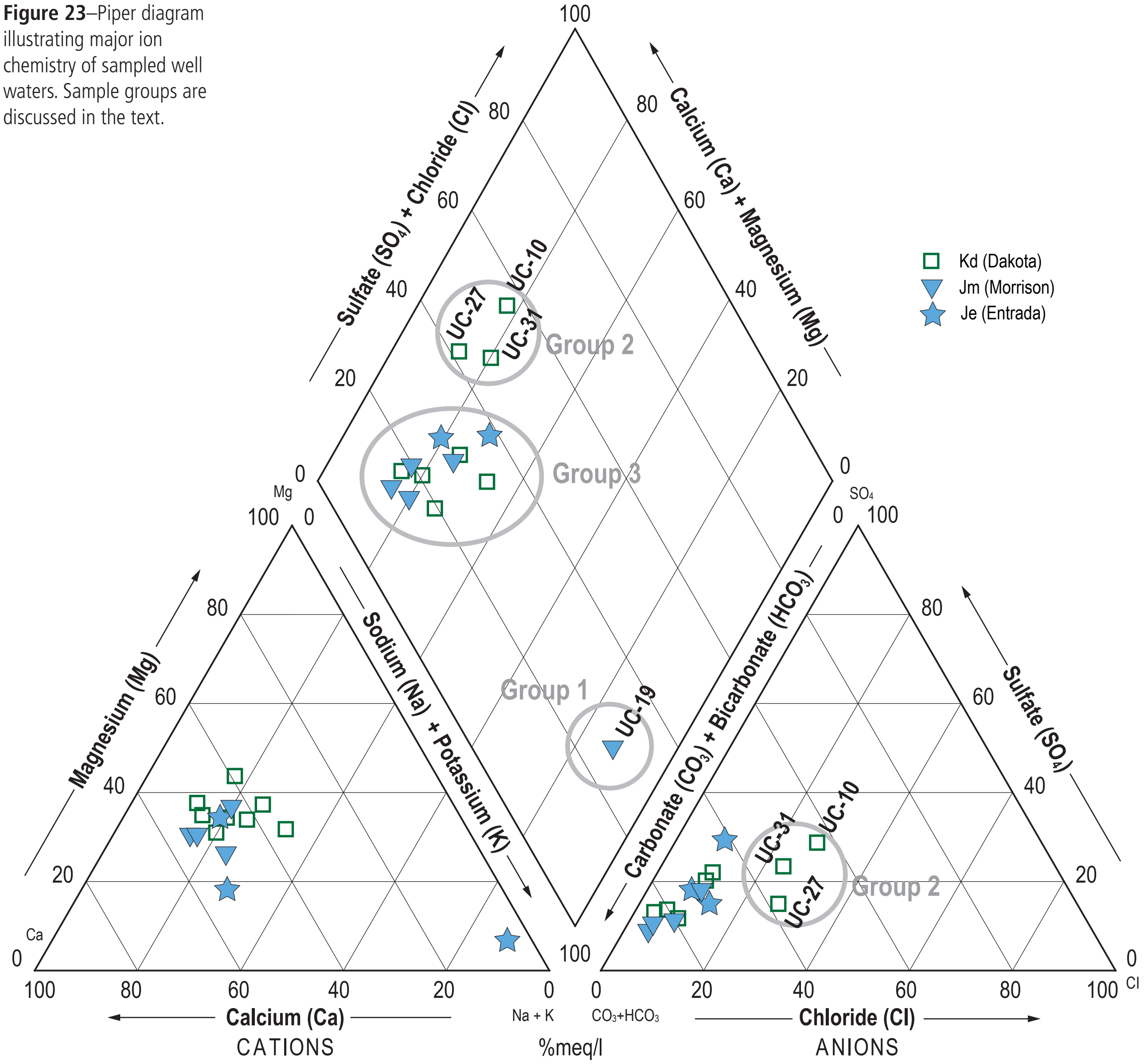


Figure 22–Water types of sampled well waters based on major ion chemistry (noted by text below well ID) and Stiff diagrams illustrating water chemistry.

Figure 23–Piper diagram illustrating major ion chemistry of sampled well waters. Sample groups are discussed in the text.

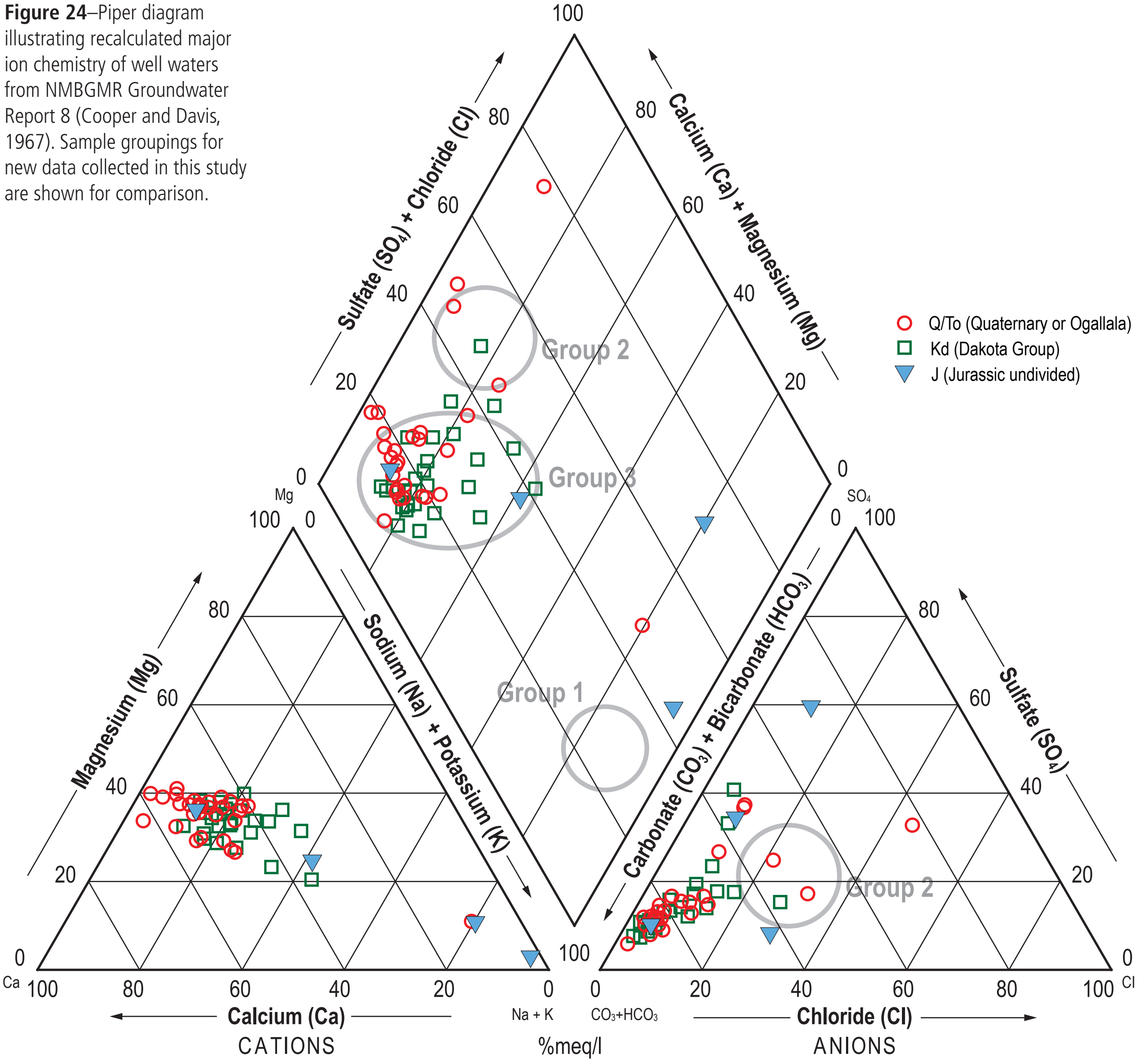


Waters from the Ogallala Formation tended to have less Na + K than waters from the Dakota, but there is much overlap, and both groups are bicarbonate waters.

There are four outliers in the historical data; three are similar to well UC-19 (Figure 23) in that they have high sodium concentrations and low Ca and Mg. They plot along the lower right side of the diamond in Figure 24. Like UC-19, these three wells are located in the southwest corner of the present study area along Tramperos Creek. Two of these wells are completed in the Jurassic Morrison Formation and one in shallow Quaternary alluvium above the Morrison Formation. The other outlier analysis is from a shallow well northeast of Clayton completed in the Ogallala Formation with anomalously high sulfate and chloride. It plots near the top apex of the diamond in Figure 24.

There have not been any drastic changes in groundwater chemistry over the nearly 60 years since the Cooper and Davis (1967) data was collected, despite the large changes in water levels due to groundwater withdrawals. The waters in the southwestern portion of the study area from the Morrison Formation have a distinct

Figure 24–Piper diagram illustrating recalculated major ion chemistry of well waters from NMBGMR Groundwater Report 8 (Cooper and Davis, 1967). Sample groupings for new data collected in this study are shown for comparison.



Na–HCO$_3$ chemistry that is evident in the historical samples and modern sample UC-19. This chemistry can be explained by cation-exchange which occurs as groundwater moves through shales and claystones in the Morrison Formation, and perhaps the underlying Triassic rocks. Nativ (1992) reported that Triassic rocks underlying the southern High Plains are characterized by Na–HCO$_3$ waters. In the cation exchange process, Ca and Mg in the water are adsorbed on the clay mineral surfaces and Na and K are released (Hem, 1985). This process has been documented in the Dakota Sandstone aquifer of South Dakota (Swenson, 1968). Other Morrison Formation waters (UC-26, -28, and -32, Group 3 in Figure 23) are similar to waters from the Dakota Formation and Entrada Sandstone.

Stable isotopes

The hydrogen and oxygen stable isotopic compositions of well waters collected in this study are shown in Figure 25 (see also Appendix 2). Mean δ^{18}O and δD of the Union County well waters are -7.30 ‰ and -51.54 ‰, respectively. Waters from Dakota Formation wells tend to be more enriched compared to waters from Jurassic wells, but there is overlap of the two groups. The overall range of isotopic values is small and there is no trend with depth.

No precipitation samples were collected in this study: the stable isotopic analyses plot below the meteoric water line (MWL) based on precipitation collected by Nativ and Riggio (1989) in Clovis NM, and Amarillo, Lubbock, Midland, and Paducah, TX (Figure 25). Isotopic compositions of well waters collected by Nativ and Smith (1987) from wells in the Ogallala and Cretaceous Formations in the southern High Plains of west Texas are also plotted in Figure 25. The Union County well waters are lighter (more isotopically depleted) than the $\delta^{18}O$ and δD values from either the Ogallala or Cretaceous well water samples of Nativ and Smith (1987). This is consistent with the spatial trends of both precipitation and groundwater isotopic compositions noted by Nativ and Smith (1987) in the southern High Plains—both $\delta^{18}O$ and δD become more depleted to the north and west. These areas (and eastern Union County) have higher altitudes, lower average temperatures, and are at a greater distance from the Gulf of Mexico than areas to the southeast. The Gulf of Mexico is the largest moisture source for precipitation in northwest Texas and eastern New Mexico (Nativ and Smith, 1987; Nativ and Riggio, 1989, 1990).

Age-dating

Natural waters, whether from a well or spring, are usually a mix of waters recharged at different times and in different places. Complexities of flow within aquifers, such as leakage across aquitards and dispersion, for example, conspire to mix waters of different ages. The end result

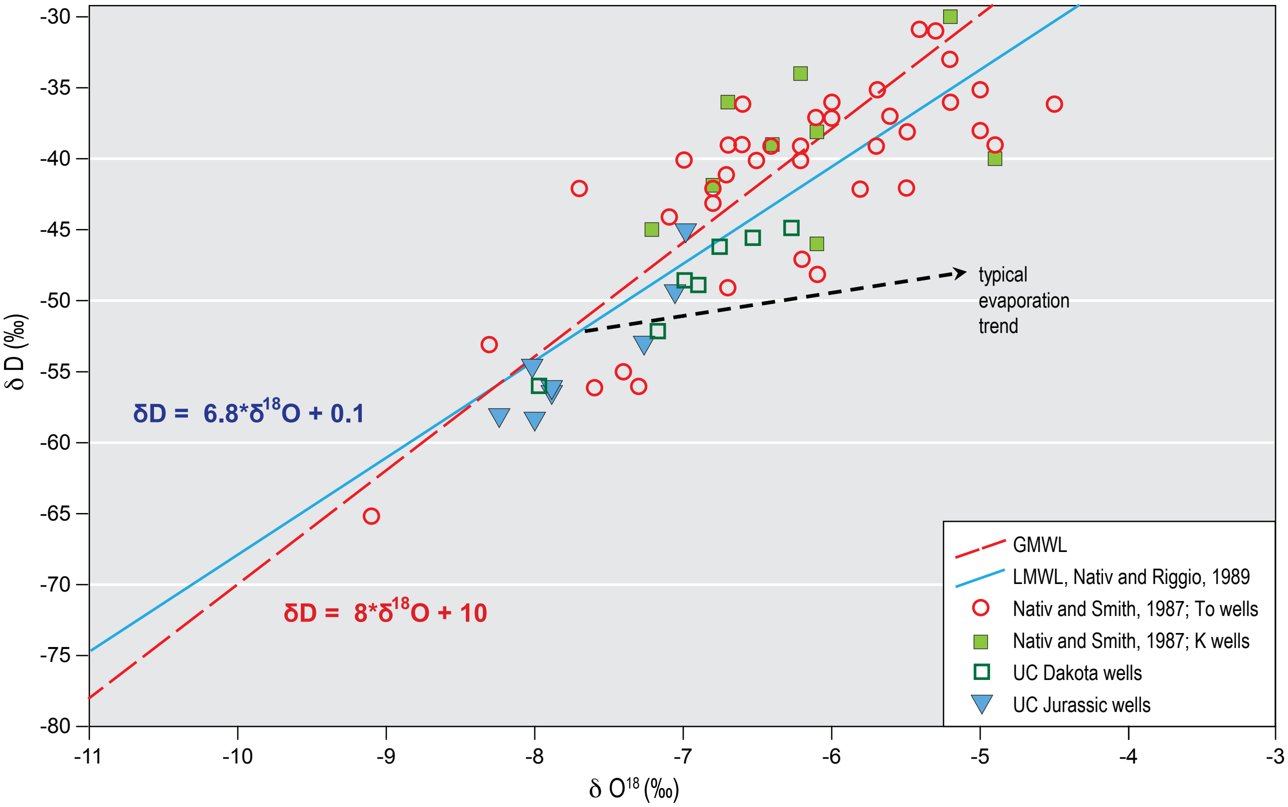


Figure 25–Stable isotope data for well water samples. Also plotted is the global meteoric water line (GMWL; Craig, 1961) and a local meteoric water line (LMWL) determined by Nativ and Riggio (1989), and waters from wells in the Ogallala (To) and Cretaceous (K) formations in the Southern High Plains analyzed by Nativ and Smith (1987). "UC" data are samples from this study.

is that the measured age is a weighted average of the ages of the different water fractions in the sample. In an extreme case, a sample composed of a large component of very young water and a small component of very old water would yield an average old age, which would be very misleading in the interpretation of recharge. Analyzing for basic chemistry, using multiple age-dating tracers, and having a good understanding of the geology and physical hydrology of the sampled area is essential for proper interpretations. The locations of wells sampled for age dating by the tritium and carbon-14 (^{14}C) methods (Appendix 3) are shown in Figure 26.

Tritium

Tritium was analyzed from four wells, UC-10, -19, -22, and -24. The values are very low, from 0.02 to 0.62 TU (Figure 26). All but the highest value (UC-10) are smaller than the measurement errors and thus the tritium content is essentially zero. These data are consistent with the ^{14}C results presented below. UC-10 receives a small component of modern (<50 years old) recharge; the other well waters were recharged prior to 1952, and probably long before then.

Carbon-14

Seven groundwater samples were analyzed for ^{14}C and yielded uncorrected ages ranging from 1180 to 11620 years (Figure 26). In addition to having distinct chemistry, well UC-19 has the oldest water, although it is only 100 feet deep. Adjacent wells UC-29 (240 feet deep, Dakota Formation; 3950 years) and UC-28 (495 feet deep, Morrison Formation; 5610 years) show an increase in age with depth, but together all of the data show a poor trend of increasing age with depth. The ^{14}C ages are consistent with the tritium results. The waters were recharged thousands of years ago, and mixing with any recent recharge appears to be minor and local (e.g., around well UC-10).

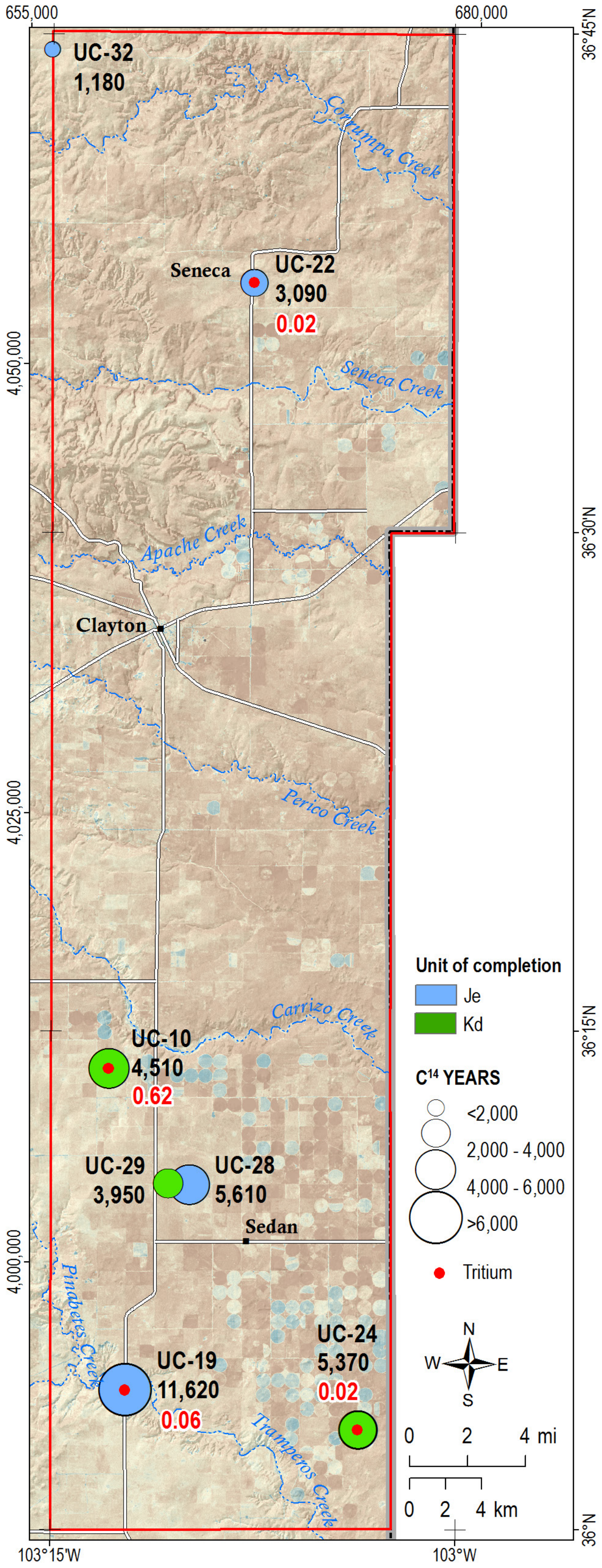


Figure 26–Age dating results. Tritium data reported as tritium units (Appendix 3). ^{14}C data reported as uncorrected years before present (1950). ^{14}C data circles are color -coded for formation of completion of the well: green is Dakota Formation and blue is Morrison or Entrada Formation.

VIII. DISCUSSION

Groundwater flowpaths

Based on the historic and recent water level contours in Figures 10, 11, and 14, regional groundwater flow is from west to east, tending towards the southeast in the southern third of the study area. We thus may expect groundwater ages to increase in this direction, however the ^{14}C age data do not follow this pattern (Figure 26).

There is some suggestion in the ^{14}C age data of multiple flowpaths at different depths in the vicinity of Sedan (Figure 26). Well UC-24 (300 feet deep, Dakota Formation) has a younger age than well UC-28 (495 feet deep, Morrison Formation) ten miles to the northwest, but it may be on a shallower flowpath. This possibility is also suggested by well pairs UC-29 and UC-24, and UC-10 and UC-28. These pairs of wells show ages and depths increasing to the southeast. However, waters from these four wells are of three different chemical types (Figure 22) so this flowpath explanation is probably too simplistic.

Wells UC-32 and UC-22 north of Clayton show an increase in age from west to east (1,180 and 3,090 years respectively, Figure 26) and have similar chemistry, but based on the groundwater contours it is not likely that they are on a direct flowpath. The chemistry and old age of water from well UC-19 in the Morrison Formation argue for both a distinct history and source as well as a lack of mixing of this water type with other sampled waters in the southern portion of the study area. Well UC-19 is shallow (100 feet) and the unique water in this area may discharge to the surface downstream along Tramperos Creek.

Hydrogeologic conceptual model

The water chemistry, age-dating results, and water level data are consistent with the geologic framework of the study area, and lead to the following hydrogeologic conceptual model (Figure 27). The aquifer system is vertically stratified, with multiple water-bearing zones separated by low-permeability confining beds. Lateral connectivity is on average much higher than vertical, and confinement increases with depth. The Ogallala Formation and the upper portion of Dakota Formation comprise one unconfined, locally discontinuous, aquifer. There are no significant distinctions in the chemistry of waters from these two units. The Graneros Shale is discontinuous and is not a regional aquitard, but it does act a local perching unit, causing hydrologic discontinuity between the Ogallala and Dakota Formations. The water level data indicate that several large perched zones that were present in the Ogallala Formation in the 1950s have been largely dewatered

Trends of water levels with depth and response to pumping indicate that the Entrada Formation is a confined aquifer. It is overlain by shales of the Morrison Formation and Purgatorie Formation (lowest Dakota Group; Figures 3 and 4), which act as nearly continuous confining layers. Water bearing zones in the lower Dakota Formation and Morrison Formation sandstones are semi-confined (Figure 27). Generally similar water chemistry and ages (~3,000 to ~5,600 years) imply some degree of hydraulic connectivity across leaky confining layers (shale beds) between all of these units that decreases with depth, resulting in the development of confined conditions.

Relating the chemistry and age-dating results of well waters to flow directions based on the

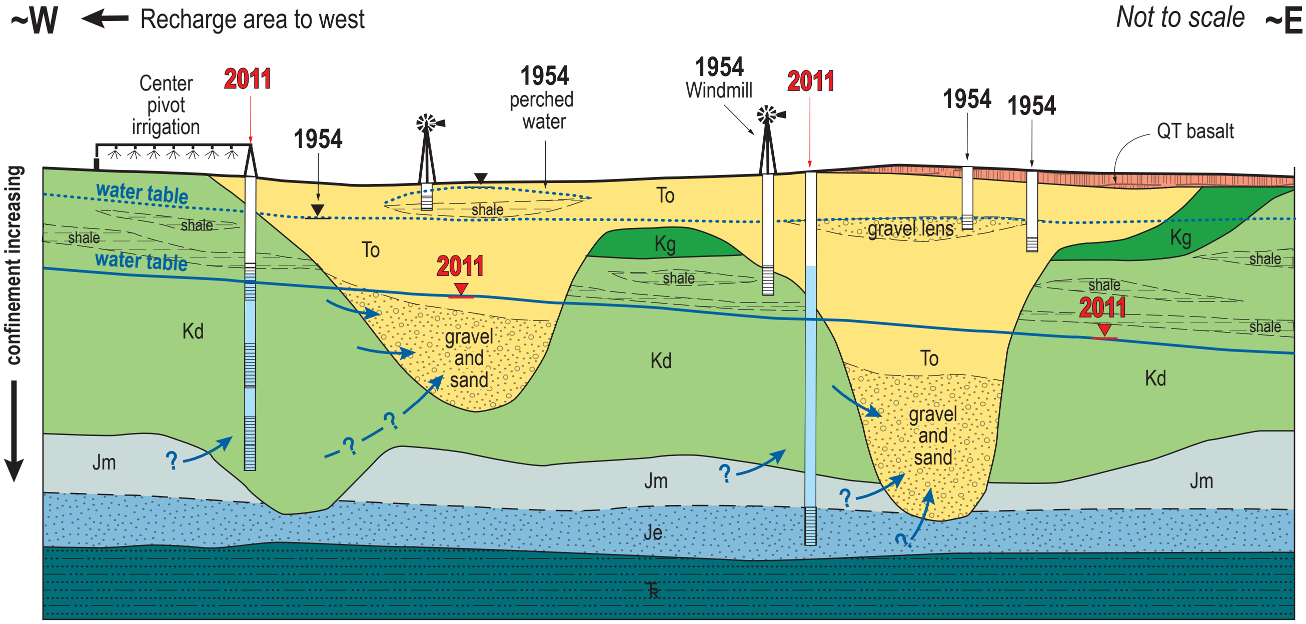


Figure 27–Conceptual model of the aquifer system in east-central Union County. Water level elevations have dropped considerably since 1954 and much of the shallow Ogallala and Dakota Formations have been dewatered. Irrigation and domestic wells are now on average much deeper than in 1954 and tap lower, at least partially confined, portions of the aquifer system. Locally, shallow groundwater probably still exists in the Ogallala Formation and continues to supply low-yield stock wells. Groundwater flows readily between underlying units and the Ogallala Formation where permeable sands and conglomerates are juxtaposed. QTb - Clayton Basalt; To - Ogallala Formation; Kg – Graneros Shale; Kd - Dakota Formation and Purgatoire Formation, undivided; Jm - Morrison Formation; Je - Entrada Formation; ₮ - Triassic rocks, undivided.

water table surface suggests multiple flowpaths that correspond to water-bearing zones tapped by individual wells. The long period hydrographs suggest both connectivity amongst some water-bearing zones (Figure 18) and compartmentalization of others (Figure 19). Changes in horizontal and vertical gradients due to pumping have altered subsurface flow patterns over the past 50–60 years, inducing variable amounts of leakage across confining beds. This will result in groundwater mixing across the boundaries of water-bearing zones that were formerly isolated and can explain some of the variation in water chemistry and the poor correlation of age with depth. A more refined picture of the subsurface flow conditions will require many more detailed well logs, more spatially dense water level measurements, and more sampling for water chemistry and age dating over a larger area than the present study.

It is notable that there is no evidence of mixing of the unique, older, Na-HCO$_3$ waters from the Morrison Formation in the southwest corner of the study area (well UC-19) with waters in the overlying Dakota Formation to the north and east. Waters from the Morrison Formation and Entrada Sandstone sampled to the north of well UC-19 are much more like the Dakota group in chemistry and age. In this southwestern area, shales in the Morrison Formation and/or lower Dakota Group may form more continuous and impermeable confining beds.

Recharge

The large water level declines and dewatering of the shallow aquifers indicate that recharge in the study area has been far less than groundwater withdrawals over the past 50–60 years. No measurable tritium and ^{14}C ages of thousands of years show that no significant amount recharge is presently occurring to replenish the aquifers tapped by the sampled wells. The sampled groundwater is thousands of years old and has likely moved a great distance from the recharge area. Regional flow directions based on the water table maps are from west to east and the youngest groundwater age is in the northwest corner of the study area. Groundwater flows into the study area at depth from recharge areas to the west.

Stable isotopic compositions of sampled groundwater in this study plot below the meteoric water line of Nativ and Riggio (1989; Figure 25), suggestive of evaporation prior to recharge. However, it is not valid to directly compare the sampled well waters to this meteoric water line because of the distance of the sampled wells from the precipitation stations (several hundred miles), and the great ages of the sampled well waters. Even so, the isotopic data are not inconsistent with recharge models that have been proposed for the southern High Plains.

Nativ and Riggio (1989) noted that their sampled groundwaters always had slightly more enriched compositions when compared to local precipitation samples by 1–2 ‰ δ^{18}O. They concluded that much of the present recharge to the Ogallala Formation is by focused (presumably rapid) infiltration of slightly evaporated playa water. This conclusion was also reached by Wood and Sanford (1995). Wood and Sanford (1995) and other studies summarized by Gurdak and Roe (2010) also showed that groundwaters collected below and downgradient from playa lake basins on the Southern High Plains have abundant tritium compared to interplaya areas.

Many lines of geologic, hydrologic, and chemical evidence have led to focused recharge through playa bottoms becoming the accepted model for the vast majority of the present recharge to the Ogallala Formation and the High Plains aquifer (Gurdak and Roe, 2010). Estimates of recharge rates beneath playas on the southern High Plains range from ~0.25 to >500 mm/yr, whereas recharge in interplaya areas is estimated at ~0.25 to 25 mm/yr. In general it can be assumed that recharge beneath playas is 1–2 orders of magnitude higher than in interplaya areas (Gurdak and Roe, 2010).

The sampled waters in the present study were recharged by runoff water not only in playas, which are abundant in and west of the study area. but also in flowing drainages floored by porous and/or fractured sandstones, or precipitation infiltrating highly porous basalt flows and/or volcanic edifices. Neither of these two additional potential recharge environments are present in the southern High Plains where most of the relevant recharge studies have been conducted.

Most important when considering recharge however, is the fact that the sampled well waters have no measurable tritium and ^{14}C ages of thousands of years. Thus, while the processes that recharged the sampled groundwaters appear to be similar to those proposed for the southern High Plains (Gurdak and Roe, 2010), the sampled waters were recharged thousands of years ago. The recharge processes in playas, drainages, and on volcanic terranes are probably ongoing in the present study area, yet apparently contribute no water to the depths of the aquifer tapped by the sampled wells due to volumetrically small recharge amounts, large vertical travel distances, and increasing aquifer confinement with depth. The greater the degree of confinement of a particular water bearing zone, the less likely that that local recharge at the surface will have any affect on the quantity of water at depth.

The likely geographic area where the sampled waters were recharged extends about 80 km west from the study area to eastern Colfax and western Union Counties. Here the drainage divide occurs between the south flowing Canadian River and the east flowing drainages of the Dry Cimmaron, Seneca Creek, Perico Creek, Carrizo Creek, and Tramperos Creek

(Figure 1). Eastern Colfax and Western Union counties have numerous volcanic edifices composed of porous lava and cinders, surficial basalt flows, surface exposures on uplands and in drainages of the all of aquifer units in the present study area, and playa lakes. Recharge by the processes described above is probably ongoing in these areas, but the rates are unknown and likely small, on the order of recharge rates estimated for the southern High Plains aquifer; certainly less than rates of groundwater withdrawal in the study area.

Assuming that that sampled groundwaters are receiving no local recharge, the measured groundwater ages should be indicative of travel times from the recharge area. Using ranges of transmissivity from Kilmer (1987), average hydraulic gradients and ranges of saturated thickness from this study, and typical ranges of sandstone porosity (5–30 %), groundwater flow velocity in the Dakota Formation can be determined by the following equation:

$$v_x = -\frac{T}{bn_e}\frac{dh}{dl},$$

where v_x is horizontal seepage velocity (i.e., true groundwater flow velocity), T is transmissivity, b is saturated thickness, n_e is the effective porosity through which water can flow, and dh/dl is the average hydraulic gradient. The negative sign indicates that flow is down the gradient, to the east in this case.

When divided into the ~80 km distance given above, the seepage velocity yields travel times on the order of several thousand years, consistent with the measured groundwater ages. All of the variables in this simple calculation vary over factors of two to ten, but many reasonable combinations yield travel times of the same magnitude as the ages.

IX. CONCLUSIONS AND SUGGESTED FUTURE WORK

This study has incorporated new and historical geologic and hydrologic data to improve understanding of the aquifer system in east-central Union County. The Ogallala Formation and Dakota Formation together vary from zero to several hundred feet in thickness and form a complex unconfined aquifer. Deeper levels of the Dakota Formation, the Morrison Formation, and the Entrada Sandstone are confined to varying degrees. Shale layers form leaky confining beds amongst these units.

Water level declines and saturated thickness changes from the mid-1950s to the present have been large and widespread. Large portions of the Ogallala-Dakota aquifer have been dewatered. Although there is much variability in well hydrographs spatially and with formation and depth, it clear that ground water extraction from all aquifers in the study area exceeds recharge. Water levels in deep wells generally recover after irrigation season ends, but the recoveries are superimposed on a long-term declining water-level trend.

With one exception, sampled groundwaters are largely Ca-Mg-HCO_3-SO_4 waters, and based on recalculation of historical analyses, the water chemistry has not changed since the 1950s. Waters from the Morrison Formation in the southwest corner of the study area have distinct Na-HCO_3 chemistry that can be explained by cation-exchange processes occurring on clay mineral surfaces. These waters appear to be isolated from the other aquifers by effective confining layers and probably discharge to surface drainages.

Although recharge processes similar to those operative on the southern High Plains are probably operative in the study area, tritium and ^{14}C analyses indicate that there is no significant recharge occurring to the sampled water bearing zones of the aquifer. This is consistent with the large and ongoing water level declines. Simple seepage velocity calculations are consistent with a recharge model in which these waters have traveled tens of miles from recharge areas west of the present study area. Stable isotopic compositions of sampled groundwaters have a weak evaporative signature. The sampled groundwaters were recharged thousands of years ago by rapid infiltration of playa lake waters and of precipitation on porous volcanic features, lava flows, and exposed bedrock of the aquifer units. Both the physical mechanism and proposed geographic region of recharge are hypotheses worthy of future study.

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APPENDICES

APPENDIX 1–Derivation of the extent and thickness of the Graneros Shale

The Graneros Shale is of hydrologic interest as it may act an aquitard separating the overlying and underlying aquifers. I inferred its subsurface extent in the following manner (Baldwin and Muehlberger, 1959; D. Romero, personal commun., 2013). The total thickness of the Dakota Formation and Graneros Shale, undivided, was calculated as the difference between the base of the Dakota Formation (Figure 7) and the base of the Ogallala Formation (Figure 5), and ranges from 0 to 303 feet (Figure 8). Baldwin and Muehlberger (1959) estimated the maximum uneroded thickness of the Dakota Formation in Union County as about 180 feet, and the maximum uneroded thickness of the Graneros Shale as about 125 feet. Subtracting 180 from the thickness of the Dakota Formation and Graneros Shale, undivided, gives the extent and potential thickness of the Graneros Shale. Areas where this resulting thickness is greater than 125 feet may be areas where the Purgatorie Formation and perhaps even sandstones of the Jurassic Morrison Formation have been included with the Dakota Formation in well log descriptions.

Unfortunately, this calculation is subject to several errors, which are cumulative – the elevations of the two contoured surfaces, themselves interpolated from sparse data of variable quality, and the assumption of essentially constant uneroded thicknesses of the Dakota Formation and Graneros Shale. This assumption is almost certainly incorrect. As a check on the calculation, I compared the resulting extent and thickness of the Graneros Shale with mapped outcrops and well logs in which the Graneros Shale can be identified with some confidence. In both cases the agreement is marginal. The extent of the Graneros Shale so determined is presented in Figure 9 with mapped exposures for comparison.

APPENDIX 2–Analysis of stable isotopes of hydrogen and oxygen

Most oxygen atoms contain 8 protons and 8 neutrons in their nucleus for an atomic weight of 16; a small fraction (~ 0.2%) contains 10 neutrons for an atomic weight of 18. Similarly, the nucleus of most hydrogen atoms consists of a single proton, but a small fraction also contain a neutron, for an atomic weight of 2. These heavier hydrogen atoms are referred to as deuterium and abbreviated "D".

The isotopic composition of a water sample is the ratio of heavy to light oxygen or hydrogen isotopes in the water molecules that comprise the sample. The compositions are reported as the per mil (‰, parts per thousand) deviation of the sample concentration from a standard:

$$\delta = \left(\frac{R_{sample} - R_{standard}}{R_{standard}} \right) * 1000‰$$

A negative value for $\delta^{18}O$ or δD indicates that the water sample is lighter (has less of the heavier isotope, or is "depleted") than the standard. The standard is called Standard Mean Ocean Water (SMOW). The data are usually plotted together as in Figure 25. Precipitation samples collected throughout the world define a line called the Global Meteoric Water Line (GMWL; Craig, 1961). Along this line precipitation samples collected during summer and/or in warmer regions will generally plot along the heavier (more enriched, less negative, to the right) end of the line and samples collected during winter and/or in colder regions will tend to plot along the lighter (more depleted, more negative, to the left) end of the line. This fundamental behavior is due to the effect of temperature on efficiency of condensation and evaporation of water molecules containing the different isotopes.

Evaporation has a strong effect on the isotopic composition of water and tends to change it along a trend shown in Figure 25. As evaporation proceeds, the isotopic composition of the remaining water will evolve away from the meteoric water line along an evaporation line, with the slope of the evaporation line depending on the humidity under which the evaporation occurs.

In a groundwater study such as this it is ideal to collect local precipitation throughout the year at multiple sites within the study area to develop a Local Meteoric Water Line (LMWL). Its slope and y-intercept (δD-intercept) will usually vary from the GMWL due to local climate effects. I did not collect such data in this study, so I compared the stable isotopic analyses to both the GMWL and LMWL data collected at Clovis, New Mexico, and Amarillo, Lubbock, Midland, and Paducah, Texas (Figure 25). These were the nearest available data to the present study area. Nativ and Riggio (1989) determined the equation of the LMWL for these sampling sites on the southern High Plains to be $\delta D = 6.8 * \delta^{18}O + 0.1$ (Figure 25). The slope is slightly less than that of the GMWL (6.8 vs. 8) and is due to the semi-arid climate of west Texas and eastern New Mexico (Nativ and Riggio, 1989).

APPENDIX 3–Age-dating with tritium and carbon-14

Tritium is a naturally occurring radioactive isotope of hydrogen. Whereas deuterium has one neutron in the nucleus, tritium has two, for an atomic weight of three. It has a short half-life of 12.32 years and is commonly used for relative age determinations of groundwaters that are less than 50 years old. Tritium is continuously produced in small amounts in the atmosphere by cosmic radiation, and large amounts were produced by atmospheric nuclear weapons testing between 1951 and 1962. Most of the "bomb-pulse" tritium has since decayed and modern tritium levels in the atmosphere have returned to natural levels. Tritium atoms are incorporated into water molecules, enter the hydrologic cycle as precipitation and thus enter the groundwater system with recharge. It is difficult to get absolute age measurements from tritium data, yet it remains useful for qualitative and relative estimates of groundwater age. Tritium concentrations are expressed in tritium units (TU), in which one TU indicates a tritium - hydrogen abundance ratio of 10–18 (Kazemi et al., 2006). Waters with tritium contents less than 0.8 TU are assumed to be pre-modern waters that were recharged prior to 1952 (Clark and Fritz, 1997). Analyses for this study were conducted at the University of Miami Tritium Laboratory. The data have one standard deviation of 0.09 TU; sample values less than this indicate essentially zero tritium content.

Carbon-14 (^{14}C) is a naturally occurring radioactive isotope of carbon that, like tritium, is continuously produced in the atmosphere by cosmic radiation and was produced in abundance by atmospheric nuclear weapons testing. It decays at a rate governed by its half-life of 5730 years, and can thus be used to date waters much older than the tritium method, up to about 50,000 years (Kazemi et al., 2006). ^{14}C results are presented in terms of percent modern carbon (pMC) relative to the abundance of ^{14}C in the atmosphere. The pMC values are converted to ages in calendar years before present, where "present" is 1950, using calibration curves (Beta Analytic, 2012). In carbonate aquifers where dissolution and precipitation processes affect the groundwater chemistry it is necessary to correct the ^{14}C results to account for these chemical processes (e.g., Newton et al., 2012; Morse, 2010). Carbonate rocks are a minor component of the aquifer system examined here and the $\delta^{13}C$ does not change linearly with pMC (and thus age) or systematically with depth, thus no corrections were applied to the data.

APPENDIX 4–Wells with water level measurements

UTM coordinates are NAD83 datum.
Formation determined by examination of well log and/or comparison with subsurface structure contours.
Hydrograph column indicates whether hydrograph is presented in Figure 18, 19, or not presented ("-").

NMBGMR ID	USGS ID	NMOSE ID	UTM Easting	UTM Northing	Total Depth (ft)	Formation	Hydrograph
UC-0001	361226103042401	none	673096	4008598	unknown	Dakota	18
UC-0002	362554103034201	none	674186	4034094	269	Dakota	19
UC-0003	362921103092101	CT-00325	665379	4039835	394	Entrada	19
UC-0004	364135103003001	none	677910	4062577	175	Dakota	-
UC-0005	360039103040001	none	673928	3987119	unknown	Dakota	18
UC-0006	360910103051301	CT-00317	672083	4002475	375	Dakota	-
UC-0007	361121103044001	none	672788	4006530	405	Dakota	18
UC-0008	361207103135101	CT-00384	659005	4007732	200	Ogallala	-
UC-0009	361350103112401	none	662305	4011101	unknown	Dakota	18
UC-0010	361351103125401	CT-00018?	660393	4011056	323	Dakota	-
UC-0012	362132103043001	none	673019	4025294	108	Dakota	-
UC-0013	362250103135101	none	658639	4027612	96	Dakota	19
UC-0014	362422103123101	none	660580	4030483	100	Ogallala	19
UC-0015	363213103061101	none	669376	4044857	unknown	Dakota	19
UC-0016	363344103030401	CT-01098	674235	4049754	464	Entrada	-
UC-0017	363500103094201	none	664361	4050139	unknown	Dakota	-
UC-0018	363502103021101	none	677165	4050554	435	Entrada	18
UC-0033	361847103064701	none	669400	4020324	254	Ogallala	18
UC-0034	362540103095001	CT-00870?	664253	4032824	172	Ogallala	19
UC-0035	363410103064801	none	668819	4048768	200	Ogallala	18
UC-0036	363041103054601	CT-00832	670483	4042107	500	Entrada	19
UC-0037	371021103060701	none	669960	4004829	455	Dakota	19
UC-0038	360837103090701	none	665711	4001519	390	Dakota	18
UC-0039	361659103125501	none	660207	4014360	270	Dakota	19
UC-0040	363320103062601	CT-01087	669249	4047148	200	Morrison	-
UC-0043	363820103062601	none	669121	4056512	260	Morrison	18
UC-0044	360445103090601	none	666479	3994786	260	Dakota	18
UC-0102	355934103100901	none	665019	3985292	178	Entrada	-
UC-0106	361556103024501	none	675722	4015304	unknown	Dakota	-
UC-0112	362501103055901	none	670355	4031808	unknown	Dakota	-
UC-0113	362713103051501	none	671501	4035922	unknown	Dakota	-

APPENDIX 5–Water level measurements

Status codes: D = dry; P = site was being pumped; R = site was pumped recently; S = nearby site in same aquifer was being pumped; T = nearby site in same aquifer was pumped recently; Z = other conditions existed that may have affected the measurement.
Method codes: R = reported, method not known; S = steel tape measurement

NMBGMR ID	Date Measured	Depth to Water (ft)	Status	Method	Measured by
UC-0001	2/2/1981	170.30		R	USGS
UC-0001	1/31/1991	176.80		R	USGS
UC-0001	1/25/1996	183.54		R	USGS
UC-0001	8/16/2007	207.30		S	NESWCD
UC-0001	2/19/2008	206.90		S	NESWCD
UC-0001	9/16/2008	209.15		S	NESWCD
UC-0001	2/9/2009	210.56		S	NESWCD
UC-0001	8/1/2009	211.04		S	NESWCD
UC-0001	1/1/2010	212.52		S	NESWCD
UC-0001	8/1/2010	209.96		S	NESWCD
UC-0001	1/1/2011	211.40		S	NESWCD
UC-0001	8/13/2011	212.20		S	NESWCD
UC-0001	1/2/2012	211.91		S	NESWCD
UC-0001	8/1/2012	216.01		S	NESWCD
UC-0001	1/6/2013	215.74		S	NESWCD
UC-0002	2/17/1981	226.00		R	USGS
UC-0002	2/1/1991	224.13		R	USGS
UC-0002	1/6/1996	225.88		R	USGS
UC-0002	8/17/2007	260.15		S	NESWCD
UC-0002	2/27/2008	257.70		S	NESWCD
UC-0002	9/17/2008	261.08		S	NESWCD
UC-0002	2/11/2009	251.29		S	NESWCD
UC-0002	8/1/2009	256.10		S	NESWCD
UC-0002	1/1/2010	249.58		S	NESWCD
UC-0002	8/1/2010	265.00	D	S	NESWCD
UC-0002	1/1/2011	248.68		S	NESWCD
UC-0002	8/10/2011	265.00	D	S	NESWCD
UC-0002	1/6/2012	246.31		S	NESWCD
UC-0002	8/1/2012	244.43		S	NMBGMR
UC-0002	1/6/2013	244.80		S	NMBGMR
UC-0003	11/16/1965	187.00		R	driller
UC-0003	1/31/1981	179.80		R	USGS
UC-0003	1/24/1991	171.44		R	USGS
UC-0003	2/2/2008	239.40		S	NESWCD
UC-0003	8/6/2008	240.11		S	NESWCD
UC-0003	2/4/2009	230.38		S	NESWCD
UC-0003	8/1/2009	269.60		S	NESWCD
UC-0003	1/1/2010	202.10		S	NESWCD
UC-0003	8/1/2010	259.82		S	NESWCD
UC-0003	1/1/2011	203.34		S	NESWCD
UC-0003	8/21/2011	271.26		S	NESWCD
UC-0003	1/6/2012	212.38		S	NESWCD
UC-0003	8/1/2012	256.95		S	NESWCD
UC-0003	1/6/2013	215.20		S	NESWCD
UC-0004	1/28/1981	96.70		R	USGS
UC-0004	2/4/1986	127.88		R	USGS
UC-0004	1/24/1996	126.86		R	USGS
UC-0004	8/15/2007	134.56		S	NESWCD
UC-0004	2/2/2008	137.00		S	NESWCD
UC-0004	8/6/2008	145.38		S	NESWCD
UC-0004	1/30/2009	135.16		S	NESWCD
UC-0004	8/1/2009	143.78		S	NESWCD
UC-0004	1/1/2010	137.80		S	NESWCD
UC-0004	8/1/2010	136.26		S	NESWCD
UC-0004	8/6/2011	137.80		S	NESWCD
UC-0004	1/5/2012	137.98		S	NESWCD
UC-0004	8/1/2012	135.74		S	NESWCD
UC-0004	1/6/2013	135.90		S	NESWCD
UC-0005	2/13/1981	112.50		R	USGS
UC-0005	2/6/1986	115.38		R	USGS
UC-0005	1/30/1991	118.30		R	USGS
UC-0005	8/15/2007	154.00		S	NESWCD
UC-0005	2/24/2009	146.82		S	NESWCD
UC-0005	8/1/2009	167.39		S	NESWCD
UC-0005	1/1/2010	159.24		S	NESWCD
UC-0005	8/1/2010	167.14		S	NESWCD
UC-0005	1/1/2011	153.29		S	NESWCD
UC-0005	8/5/2011	162.84		S	NESWCD
UC-0005	1/7/2012	159.74		S	NESWCD
UC-0005	8/1/2012	157.30		S	NESWCD
UC-0005	1/6/2013	158.20		S	NESWCD
UC-0006	11/2/1967	174.75		R	USGS
UC-0006	3/21/1968	168.37		R	USGS
UC-0006	4/8/1970	171.85		R	USGS
UC-0006	1/9/1972	176.00		R	USGS
UC-0006	2/1/1973	178.04		R	USGS
UC-0006	2/6/1974	180.26		R	USGS
UC-0006	1/22/1975	178.80		R	USGS
UC-0006	1/27/1976	182.14		R	USGS
UC-0006	1/25/1977	183.01		R	USGS
UC-0006	1/23/1979	194.49		R	USGS
UC-0006	1/29/1980	201.51		R	USGS
UC-0006	2/6/1986	230.00		R	USGS
UC-0006	1/28/1991	243.14		R	USGS
UC-0006	1/24/1996	289.18		R	USGS
UC-0006	8/16/2007	306.30		S	NESWCD
UC-0006	2/19/2008	308.20		S	NESWCD
UC-0006	9/16/2008	311.40		S	NESWCD
UC-0006	2/9/2009	310.51		S	NESWCD
UC-0006	8/1/2009	312.22		S	NESWCD
UC-0006	1/1/2010	311.35		S	NESWCD
UC-0006	8/1/2010	341.79		S	NESWCD
UC-0006	1/1/2011	314.23		S	NESWCD
UC-0006	8/13/2011	332.93		S	NESWCD
UC-0006	1/2/2012	316.08		S	NESWCD
UC-0006	8/1/2012	321.29		S	NESWCD
UC-0006	1/6/2013	317.00		S	NESWCD
UC-0007	1/9/1972	209.05		R	USGS
UC-0007	1/22/1972	199.05		R	USGS
UC-0007	1/27/1976	202.32		R	USGS
UC-0007	1/25/1977	203.93		R	USGS
UC-0007	1/25/1978	208.81		R	USGS
UC-0007	1/23/1979	211.66		R	USGS
UC-0007	1/30/1980	219.43		R	USGS
UC-0007	2/3/1981	237.57		R	USGS
UC-0007	2/5/1986	239.80		R	USGS
UC-0007	1/28/1991	249.01		R	USGS
UC-0007	2/14/2001	267.45		R	USGS
UC-0007	8/16/2007	295.20		S	NESWCD
UC-0007	2/19/2008	301.80		S	NESWCD
UC-0007	9/16/2008	325.08		S	NESWCD
UC-0007	2/9/2009	315.44		S	NESWCD
UC-0007	8/1/2009	325.22		S	NESWCD
UC-0007	1/1/2010	316.10		S	NESWCD
UC-0007	8/1/2010	318.83		S	NESWCD

NMBGMR ID	Date Measured	Depth to Water (ft)	Status	Method	Measured by
UC-0007	1/1/2011	318.10		S	NESWCD
UC-0007	8/12/2011	326.22		S	NESWCD
UC-0007	1/2/2012	323.42		S	NESWCD
UC-0007	8/1/2012	326.57		S	NESWCD
UC-0007	1/6/2013	318.20		S	NESWCD
UC-0008	2/26/2008	184.50		S	NESWCD
UC-0008	9/17/2008	191.94		S	NESWCD
UC-0008	2/24/2009	192.24		S	NESWCD
UC-0008	8/1/2009	190.08		S	NESWCD
UC-0008	1/1/2010	189.32		S	NESWCD
UC-0008	8/1/2010	196.94		S	NESWCD
UC-0008	1/1/2011	189.79		S	NESWCD
UC-0008	8/15/2011	191.46		S	NESWCD
UC-0008	1/3/2012	188.10		S	NESWCD
UC-0008	8/1/2012	193.79		S	NESWCD
UC-0008	1/6/2013	183.80		S	NESWCD
UC-0009	3/28/1968	231.69		R	USGS
UC-0009	1/8/1972	246.78		R	USGS
UC-0009	2/1/1973	247.38		R	USGS
UC-0009	2/7/1974	250.39		R	USGS
UC-0009	1/22/1975	251.58		R	USGS
UC-0009	1/27/1976	249.58		R	USGS
UC-0009	1/25/1977	250.16		R	USGS
UC-0009	1/26/1978	250.35		R	USGS
UC-0009	1/23/1979	249.69		R	USGS
UC-0009	1/30/1980	248.02		R	USGS
UC-0009	2/5/1981	252.27		R	USGS
UC-0009	2/5/1986	260.90		R	USGS
UC-0009	1/30/1991	259.34		R	USGS
UC-0009	1/25/1996	265.22		R	USGS
UC-0009	2/26/2008	286.30		S	NESWCD
UC-0009	9/17/2008	283.84		S	NESWCD
UC-0009	2/24/2009	281.13		S	NESWCD
UC-0009	8/1/2009	285.58		S	NESWCD
UC-0009	1/1/2010	283.29		S	NESWCD
UC-0009	8/1/2010	288.79		S	NESWCD
UC-0009	1/1/2011	285.58		S	NESWCD
UC-0009	8/11/2011	290.43		S	NESWCD
UC-0009	1/3/2012	288.47		S	NESWCD
UC-0010	2/26/2008	295.70		S	NESWCD
UC-0010	8/1/2008	0.00		S	NESWCD
UC-0010	2/3/2009	314.90		S	NESWCD
UC-0010	8/1/2009	316.82		S	NESWCD
UC-0010	1/1/2010	295.62		S	NESWCD
UC-0010	8/1/2010	322.16		S	NESWCD
UC-0010	1/1/2011	289.52		S	NESWCD
UC-0010	8/11/2011	317.49		S	NESWCD
UC-0010	1/3/2012	292.83		S	NESWCD
UC-0010	1/6/2013	297.60		S	NESWCD
UC-0012	2/17/1981	94.68		R	USGS
UC-0012	2/6/1986	95.48		R	USGS
UC-0012	1/26/1991	102.00	R	R	USGS
UC-0012	8/17/2007	99.00		S	NESWCD
UC-0012	3/4/2008	138.90		S	NESWCD
UC-0012	9/16/2008	136.57	R	S	NESWCD
UC-0012	2/13/2009	140.01		S	NESWCD
UC-0012	8/1/2009	142.53		S	NESWCD
UC-0012	1/1/2010	144.04		S	NESWCD
UC-0012	8/1/2010	142.54		S	NESWCD
UC-0012	1/1/2011	142.68		S	NESWCD
UC-0012	8/11/2011	144.06		S	NESWCD
UC-0012	1/6/2012	144.21		S	NESWCD
UC-0012	8/1/2012	145.98		S	NESWCD
UC-0012	1/6/2013	146.20		S	NESWCD
UC-0013	2/2/1981	90.70		R	USGS
UC-0013	1/30/1986	94.11		R	USGS
UC-0013	1/30/1991	94.36		R	USGS
UC-0013	1/25/1996	92.54		R	USGS
UC-0013	8/25/2007	93.74		S	NESWCD
UC-0013	2/27/2008	93.70	R	S	NESWCD
UC-0013	9/16/2008	94.46		S	NESWCD
UC-0013	2/13/2009	93.04		S	NESWCD
UC-0013	8/1/2009	97.01		S	NESWCD
UC-0013	1/1/2010	91.98		S	NESWCD
UC-0013	8/1/2010	92.67		S	NESWCD
UC-0013	1/1/2011	93.00		S	NESWCD
UC-0013	8/12/2011	93.88		S	NESWCD
UC-0013	1/6/2012	93.10		S	NESWCD
UC-0013	8/1/2012	93.84		S	NESWCD
UC-0013	1/6/2013	96.20	D	S	NESWCD
UC-0014	2/17/1981	97.55		R	USGS
UC-0014	1/26/1991	95.17		R	USGS
UC-0014	1/29/1996	95.24		R	USGS
UC-0014	8/25/2007	79.98		S	NESWCD
UC-0014	2/27/2008	72.00		S	NESWCD
UC-0014	8/1/2008	0.00	Z	S	NESWCD
UC-0014	2/5/2009	77.81		R	USGS
UC-0014	2/13/2009	79.90		R	USGS
UC-0014	2/26/2009	79.90		S	NESWCD
UC-0014	8/1/2009	79.04		S	NESWCD
UC-0014	1/1/2010	78.04		S	NESWCD
UC-0014	8/1/2010	80.09		S	NESWCD
UC-0014	1/1/2011	79.19		S	NESWCD
UC-0014	8/13/2011	79.35		S	NESWCD
UC-0014	1/6/2012	80.05		S	NESWCD
UC-0014	8/1/2012	78.41		S	NESWCD
UC-0014	1/6/2013	78.90		S	NESWCD
UC-0015	2/1/1981	228.80		R	USGS
UC-0015	1/24/1991	189.19		R	USGS
UC-0015	1/23/1996	190.76		R	USGS
UC-0015	2/28/2008	191.10		S	NESWCD
UC-0015	8/7/2008	190.97		S	NESWCD
UC-0015	2/11/2009	189.68		S	NESWCD
UC-0015	8/1/2009	191.31		S	NESWCD
UC-0015	1/1/2010	191.32		S	NESWCD
UC-0015	8/1/2010	0.00	Z	S	NESWCD
UC-0015	1/1/2011	192.38		S	NESWCD
UC-0015	8/11/2011	191.53		S	NESWCD
UC-0015	1/6/2012	191.50		S	NESWCD
UC-0015	8/1/2012	190.98		S	NESWCD
UC-0015	1/6/2013	190.60		S	NESWCD
UC-0016	2/29/2008	193.60		S	NESWCD
UC-0016	8/1/2008	0.00	Z	S	NESWCD
UC-0016	2/11/2009	187.47		S	NESWCD
UC-0016	8/1/2009	153.11		S	NESWCD
UC-0016	1/1/2010	200.29		S	NESWCD
UC-0016	8/1/2010	206.72		S	NESWCD
UC-0016	1/1/2011	207.30		S	NESWCD
UC-0016	8/13/2011	197.09		S	NESWCD
UC-0016	1/6/2012	207.66		S	NESWCD
UC-0016	8/1/2012	225.60		S	NESWCD
UC-0016	1/6/2013	205.90		S	NESWCD
UC-0017	2/1/1981	87.90		R	USGS
UC-0017	2/4/1986	83.19		R	USGS
UC-0017	1/25/1991	83.51		R	USGS
UC-0017	8/16/2007	86.54	R	S	NESWCD

NMBGMR ID	Date Measured	Depth to Water (ft)	Status	Method	Measured by
UC-0017	2/2/2008	103.60	R	S	NESWCD
UC-0017	8/6/2008	108.61	P	S	NESWCD
UC-0017	2/28/2009	121.66		S	NESWCD
UC-0017	8/1/2009	86.57		S	NESWCD
UC-0017	1/1/2010	119.54		S	NESWCD
UC-0017	8/1/2010	122.46		S	NESWCD
UC-0017	1/1/2011	94.80		S	NESWCD
UC-0017	8/10/2011	124.79		S	NESWCD
UC-0017	1/5/2012	95.02		S	NESWCD
UC-0017	8/1/2012	91.15		S	NESWCD
UC-0017	1/6/2013	86.90		S	NESWCD
UC-0018	4/8/1971	77.91		R	USGS
UC-0018	1/7/1972	77.73		R	USGS
UC-0018	1/31/1973	78.50		R	USGS
UC-0018	2/6/1974	80.37		R	USGS
UC-0018	1/21/1975	80.15		R	USGS
UC-0018	1/27/1976	81.03		R	USGS
UC-0018	1/26/1977	81.93		R	USGS
UC-0018	1/24/1978	82.07		R	USGS
UC-0018	1/23/1979	85.03		R	USGS
UC-0018	1/30/1980	87.20		R	USGS
UC-0018	2/1/1981	89.71		R	USGS
UC-0018	2/4/1986	96.48		R	USGS
UC-0018	1/23/1991	99.07		R	USGS
UC-0018	8/7/2008	152.07	R	R	USGS
UC-0018	2/9/2009	128.50		S	NESWCD
UC-0018	2/11/2009	133.10		R	USGS
UC-0018	8/1/2009	153.11		S	NESWCD
UC-0018	1/1/2010	129.08		S	NESWCD
UC-0018	8/1/2010	133.79		S	NESWCD
UC-0018	1/1/2011	141.00		S	NESWCD
UC-0018	8/14/2011	146.32		S	NESWCD
UC-0018	1/6/2012	147.52		S	NESWCD
UC-0018	1/6/2013	140.70		S	NESWCD
UC-0033	5/8/1968	81.38		R	USGS
UC-0033	4/10/1970	82.53		R	USGS
UC-0033	3/18/1971	82.90		R	USGS
UC-0033	1/8/1972	82.99		R	USGS
UC-0033	2/1/1973	83.67		R	USGS
UC-0033	2/7/1974	84.28		R	USGS
UC-0033	1/22/1975	84.84		R	USGS
UC-0033	1/27/1976	85.34		R	USGS
UC-0033	8/24/1976	85.75		R	USGS
UC-0033	1/26/1977	85.86		R	USGS
UC-0033	9/20/1977	86.10		R	USGS
UC-0033	1/26/1978	86.50		R	USGS
UC-0033	8/9/1978	86.91		R	USGS
UC-0033	1/24/1979	87.10		R	USGS
UC-0033	7/25/1979	87.47		R	USGS
UC-0033	1/31/1980	87.88		R	USGS
UC-0033	2/2/1981	88.50		R	USGS
UC-0033	9/4/1981	88.82		R	USGS
UC-0033	2/11/1982	89.10		R	USGS
UC-0033	9/1/1982	89.47		R	USGS
UC-0033	1/19/1983	89.63		R	USGS
UC-0033	8/24/1983	90.19		R	USGS
UC-0033	3/14/1984	90.47		R	USGS
UC-0033	7/18/1984	90.83		R	USGS
UC-0033	1/21/1985	91.13		R	USGS
UC-0033	8/7/1985	91.61		R	USGS
UC-0033	2/5/1986	91.92		R	USGS
UC-0033	9/9/1986	92.28		R	USGS
UC-0033	2/11/1987	92.67		R	USGS
UC-0033	8/19/1987	92.92		R	USGS
UC-0033	4/14/1988	93.49		R	USGS
UC-0033	8/16/1988	93.73		R	USGS
UC-0033	3/2/1989	93.87		R	USGS
UC-0033	9/19/1989	94.36		R	USGS
UC-0033	1/11/1990	94.59	Z	R	USGS
UC-0033	4/25/1990	94.75		R	USGS
UC-0033	1/26/1991	95.35		R	USGS
UC-0033	2/5/1992	95.35		R	USGS
UC-0033	4/16/1992	95.51		R	USGS
UC-0033	5/29/1992	95.69		R	USGS
UC-0033	7/30/1992	95.83		R	USGS
UC-0033	8/13/1992	95.79		R	USGS
UC-0033	9/24/1992	95.95		R	USGS
UC-0033	10/29/1992	95.97		R	USGS
UC-0033	1/26/1993	96.19		R	USGS
UC-0033	4/13/1993	96.24		R	USGS
UC-0033	7/22/1993	96.49		R	USGS
UC-0033	9/21/1993	96.68		R	USGS
UC-0033	10/13/1993	96.49		R	USGS
UC-0033	1/20/1994	96.97		R	USGS
UC-0033	4/28/1994	97.07		R	USGS
UC-0033	7/23/1994	97.35		R	USGS
UC-0033	10/26/1994	97.62		R	USGS
UC-0033	1/18/1995	97.67		R	USGS
UC-0033	4/18/1995	97.91		R	USGS
UC-0033	7/25/1995	98.23		R	USGS
UC-0033	10/24/1995	98.43		R	USGS
UC-0033	1/26/1996	98.60		R	USGS
UC-0033	4/22/1996	98.88		R	USGS
UC-0033	7/24/1996	99.18		R	USGS
UC-0033	10/15/1996	99.38		R	USGS
UC-0033	5/14/1997	99.84		R	USGS
UC-0033	7/23/1997	100.24		R	USGS
UC-0033	10/14/1997	100.34		R	USGS
UC-0033	1/22/1998	100.40		R	USGS
UC-0033	1/23/1998	100.49		R	USGS
UC-0033	4/16/1998	100.80		R	USGS
UC-0033	5/27/1998	100.95		R	USGS
UC-0033	6/26/1998	102.08		R	USGS
UC-0033	8/13/1998	101.21		R	USGS
UC-0033	10/20/1998	101.46		R	USGS
UC-0033	11/23/1998	101.47		R	USGS
UC-0033	11/24/1998	101.45		R	USGS
UC-0033	2/23/1999	101.75		R	USGS
UC-0033	8/17/1999	102.54		R	USGS
UC-0033	2/25/2000	102.90		R	USGS
UC-0033	7/21/2000	103.51		R	USGS
UC-0033	2/14/2001	104.02		R	USGS
UC-0033	7/6/2001	104.44		R	USGS
UC-0033	10/30/2001	104.84		R	USGS
UC-0033	3/22/2002	105.46		R	USGS
UC-0033	9/10/2002	106.30		R	USGS
UC-0033	2/28/2003	106.64		R	USGS
UC-0033	7/10/2003	107.00		R	USGS
UC-0033	3/9/2004	107.79		R	USGS
UC-0033	8/24/2004	108.42		R	USGS
UC-0033	3/29/2005	109.13		R	USGS
UC-0033	9/13/2005	110.60		R	USGS
UC-0033	8/9/2006	112.53		R	USGS
UC-0033	2/15/2007	112.03		R	USGS
UC-0033	8/17/2007	121.60		R	USGS
UC-0033	2/5/2008	114.76		R	USGS

NMBGMR ID	Date Measured	Depth to Water (ft)	Status	Method	Measured by
UC-0033	9/17/2008	114.38		R	USGS
UC-0033	2/5/2009	115.57	R	R	USGS
UC-0033	8/26/2009	118.22	R	R	USGS
UC-0033	1/15/2010	118.60		R	USGS
UC-0033	8/25/2010	117.69		R	USGS
UC-0033	1/13/2011	122.41		R	USGS
UC-0033	8/13/2011	121.00		S	NESWCD
UC-0033	1/6/2012	122.50		S	NESWCD
UC-0033	8/1/2012	122.98		S	NESWCD
UC-0033	1/6/2013	123.30		S	NESWCD
UC-0034	12/8/1965	102.90		R	USGS
UC-0034	2/23/1967	105.60		R	USGS
UC-0034	2/19/1968	104.90		R	USGS
UC-0034	2/6/1969	102.40		R	USGS
UC-0034	2/2/1970	102.80		R	USGS
UC-0034	2/2/1971	106.85		R	USGS
UC-0034	1/8/1972	100.07		R	USGS
UC-0034	2/1/1973	99.44		R	USGS
UC-0034	2/7/1974	100.49		R	USGS
UC-0034	1/21/1975	101.44		R	USGS
UC-0034	1/27/1976	99.55		R	USGS
UC-0034	1/26/1977	97.20		R	USGS
UC-0034	1/25/1978	101.40		R	USGS
UC-0034	1/23/1979	96.82		R	USGS
UC-0034	1/30/1980	97.12		R	USGS
UC-0034	1/31/1981	96.22		R	USGS
UC-0034	9/4/1981	95.99		R	USGS
UC-0034	2/11/1982	95.82		R	USGS
UC-0034	1/19/1983	95.21		R	USGS
UC-0034	3/14/1984	97.14		R	USGS
UC-0034	7/18/1984	93.85		R	USGS
UC-0034	1/21/1985	93.38		R	USGS
UC-0034	8/7/1985	93.26		R	USGS
UC-0034	2/20/1986	92.86		R	USGS
UC-0034	9/9/1986	93.08		R	USGS
UC-0034	2/11/1987	92.17		R	USGS
UC-0034	4/14/1988	92.01		R	USGS
UC-0034	9/13/1988	91.99		R	USGS
UC-0034	1/9/1989	91.14		R	USGS
UC-0034	4/18/1989	91.52		R	USGS
UC-0034	7/11/1989	91.32		R	USGS
UC-0034	9/18/1989	91.46		R	USGS
UC-0034	1/10/1990	91.17	Z	R	USGS
UC-0034	4/25/1990	91.17		R	USGS
UC-0034	7/18/1990	92.89	Z	R	USGS
UC-0034	10/11/1990	91.04	Z	R	USGS
UC-0034	1/10/1991	91.97	Z	R	USGS
UC-0034	2/1/1991	91.76		R	USGS
UC-0034	4/11/1991	92.56	Z	R	USGS
UC-0034	7/2/1991	93.20		R	USGS
UC-0034	10/15/1991	93.51		R	USGS
UC-0034	1/27/1992	93.76		R	USGS
UC-0034	4/16/1992	92.28		R	USGS
UC-0034	7/29/1992	94.36		R	USGS
UC-0034	10/29/1992	94.60		R	USGS
UC-0034	1/26/1993	94.87		R	USGS
UC-0034	4/13/1993	94.85		R	USGS
UC-0034	7/22/1993	95.04		R	USGS
UC-0034	10/13/1993	95.17		R	USGS
UC-0034	1/20/1994	95.50		R	USGS
UC-0034	4/28/1994	95.51		R	USGS
UC-0034	7/23/1994	95.67		R	USGS
UC-0034	10/26/1994	95.72		R	USGS
UC-0034	1/18/1995	95.83		R	USGS
UC-0034	4/18/1995	95.90		R	USGS
UC-0034	7/25/1995	96.05		R	USGS
UC-0034	10/24/1995	96.80		R	USGS
UC-0034	1/24/1996	95.82		R	USGS
UC-0034	7/24/1996	98.45		R	USGS
UC-0034	10/15/1996	96.86		R	USGS
UC-0034	4/22/1997	96.51		R	USGS
UC-0034	7/23/1997	96.33		R	USGS
UC-0034	10/14/1997	96.47		R	USGS
UC-0034	1/22/1998	95.99		R	USGS
UC-0034	4/16/1998	95.97		R	USGS
UC-0034	8/17/1999	95.22		R	USGS
UC-0034	2/25/2000	94.78		R	USGS
UC-0034	7/21/2000	94.62		R	USGS
UC-0034	2/15/2001	94.34		R	USGS
UC-0034	7/6/2001	94.34		R	USGS
UC-0034	3/22/2002	94.05		R	USGS
UC-0034	9/10/2002	94.15		R	USGS
UC-0034	3/28/2003	94.95		R	USGS
UC-0034	7/10/2003	94.18		R	USGS
UC-0034	2/24/2004	94.09		R	USGS
UC-0034	3/10/2004	93.95		R	USGS
UC-0034	3/29/2005	93.98		R	USGS
UC-0034	9/13/2005	98.00		R	USGS
UC-0034	2/17/2006	105.00	Z	R	USGS
UC-0034	8/10/2006	92.96		R	USGS
UC-0034	2/15/2007	92.87		R	USGS
UC-0034	8/16/2007	92.85		R	USGS
UC-0034	2/5/2008	92.74		R	USGS
UC-0034	8/6/2008	92.80		R	USGS
UC-0034	8/7/2008	93.86		R	USGS
UC-0034	2/24/2009	93.00	S	R	USGS
UC-0034	8/25/2009	92.96		R	USGS
UC-0034	3/16/2010	93.32		R	USGS
UC-0034	8/25/2010	92.85		R	USGS
UC-0034	2/8/2011	95.50		R	USGS
UC-0034	8/31/2011	92.92		R	USGS
UC-0035	2/24/1967	92.32		R	USGS
UC-0035	2/20/1968	93.92		R	USGS
UC-0035	2/5/1969	88.75		R	USGS
UC-0035	2/3/1970	75.00		R	USGS
UC-0035	2/2/1971	78.40		R	USGS
UC-0035	1/7/1972	78.78		R	USGS
UC-0035	2/1/1973	79.71		R	USGS
UC-0035	2/6/1974	82.40		R	USGS
UC-0035	1/21/1975	81.16		R	USGS
UC-0035	1/27/1976	83.16		R	USGS
UC-0035	1/26/1977	83.04		R	USGS
UC-0035	1/24/1978	81.65		R	USGS
UC-0035	1/23/1979	81.93		R	USGS
UC-0035	1/30/1980	82.96		R	USGS
UC-0035	1/31/1981	84.05		R	USGS
UC-0035	2/4/1986	86.63		R	USGS
UC-0035	9/13/1988	87.89		R	USGS
UC-0035	1/9/1989	87.44		R	USGS
UC-0035	4/18/1989	88.39		R	USGS
UC-0035	9/18/1989	88.86		R	USGS
UC-0035	1/10/1990	88.88	Z	R	USGS
UC-0035	4/25/1990	90.20		R	USGS
UC-0035	7/30/1990	89.57	Z	R	USGS
UC-0035	10/11/1990	89.32	Z	R	USGS
UC-0035	1/10/1991	89.60	Z	R	USGS

NMBGMR ID	Date Measured	Depth to Water (ft)	Status	Method	Measured by
UC-0035	1/23/1991	89.80		R	USGS
UC-0035	4/11/1991	94.88	Z	R	USGS
UC-0035	7/2/1991	90.13		R	USGS
UC-0035	10/15/1991	90.05		R	USGS
UC-0035	1/27/1992	88.77		R	USGS
UC-0035	4/16/1992	93.91		R	USGS
UC-0035	7/29/1992	91.71		R	USGS
UC-0035	10/29/1992	97.31		R	USGS
UC-0035	1/26/1993	97.44		R	USGS
UC-0035	4/13/1993	91.24		R	USGS
UC-0035	7/22/1993	91.59		R	USGS
UC-0035	10/13/1993	91.80		R	USGS
UC-0035	1/20/1994	92.16		R	USGS
UC-0035	4/28/1994	92.43		R	USGS
UC-0035	7/23/1994	92.70		R	USGS
UC-0035	10/26/1994	93.62		R	USGS
UC-0035	1/18/1995	92.54		R	USGS
UC-0035	4/18/1995	92.79		R	USGS
UC-0035	7/25/1995	93.25		R	USGS
UC-0035	10/23/1995	93.78		R	USGS
UC-0035	1/23/1996	96.26		R	USGS
UC-0035	7/24/1996	94.89		R	USGS
UC-0035	10/15/1996	94.24		R	USGS
UC-0035	4/22/1997	94.96		R	USGS
UC-0035	7/23/1997	95.34		R	USGS
UC-0035	10/14/1997	95.89		R	USGS
UC-0035	1/22/1998	96.29		R	USGS
UC-0035	8/13/1998	97.08		R	USGS
UC-0035	2/22/1999	97.58		R	USGS
UC-0035	8/17/1999	97.00		R	USGS
UC-0035	2/25/2000	97.22		R	USGS
UC-0035	7/21/2000	97.94		R	USGS
UC-0035	2/22/2001	97.74		R	USGS
UC-0035	7/6/2001	99.20		R	USGS
UC-0035	3/22/2002	100.22		R	USGS
UC-0035	9/11/2002	101.20		R	USGS
UC-0035	3/28/2003	101.90		R	USGS
UC-0035	7/9/2003	102.09		R	USGS
UC-0035	2/24/2004	103.80	P	R	USGS
UC-0035	3/10/2004	103.25		R	USGS
UC-0035	8/10/2006	98.19	P	R	USGS
UC-0035	2/15/2007	99.42		R	USGS
UC-0035	8/16/2007	106.74		R	USGS
UC-0035	2/5/2008	106.89		R	USGS
UC-0035	8/6/2008	108.99		R	USGS
UC-0035	2/24/2009	109.45	R	R	USGS
UC-0035	8/26/2009	109.33		R	USGS
UC-0035	3/16/2010	109.95		R	USGS
UC-0035	8/26/2010	110.33	R	R	USGS
UC-0035	1/25/2011	110.87		R	USGS
UC-0035	8/31/2011	112.15		R	USGS
UC-0036	7/30/1965	123.46		R	driller
UC-0036	2/24/1967	130.86		R	USGS
UC-0036	2/20/1968	131.60		R	USGS
UC-0036	2/5/1969	131.40		R	USGS
UC-0036	2/3/1970	129.10		R	USGS
UC-0036	2/2/1971	151.40		R	USGS
UC-0036	1/7/1972	157.34		R	USGS
UC-0036	2/1/1973	150.43		R	USGS
UC-0036	2/6/1974	209.58		R	USGS
UC-0036	1/21/1975	181.55		R	USGS
UC-0036	1/26/1977	203.06		R	USGS
UC-0036	1/24/1978	198.00		R	USGS
UC-0036	1/23/1979	199.25		R	USGS
UC-0036	1/30/1980	189.33		R	USGS
UC-0036	1/31/1981	201.84		R	USGS
UC-0036	2/5/1986	196.99		R	USGS
UC-0036	1/24/1991	173.59		R	USGS
UC-0036	1/23/1996	163.36		R	USGS
UC-0036	8/16/2007	244.57		R	USGS
UC-0036	2/2/2008	224.80		R	USGS
UC-0036	8/6/2008	240.65		R	USGS
UC-0036	2/11/2009	235.90		R	USGS
UC-0036	8/26/2009	240.59		R	USGS
UC-0036	1/13/2010	231.76		R	USGS
UC-0036	8/12/2010	236.49		S	NESWCD
UC-0036	8/26/2010	236.09		R	USGS
UC-0036	1/3/2011	235.20		R	USGS
UC-0036	8/10/2011	244.46		S	NESWCD
UC-0036	8/31/2011	244.36		R	USGS
UC-0036	1/6/2012	240.16		S	NESWCD
UC-0036	8/1/2012	243.80		S	NESWCD
UC-0036	1/6/2013	242.50		S	NESWCD
UC-0037	4/8/1970	181.09		R	USGS
UC-0037	3/7/1971	188.40		R	USGS
UC-0037	1/9/1972	181.51		R	USGS
UC-0037	2/1/1973	179.91		R	USGS
UC-0037	2/7/1974	183.93		R	USGS
UC-0037	1/22/1975	187.15		R	USGS
UC-0037	1/27/1976	189.52		R	USGS
UC-0037	1/26/1977	191.04		R	USGS
UC-0037	1/25/1978	193.22		R	USGS
UC-0037	1/23/1979	196.96		R	USGS
UC-0037	1/30/1980	196.04		R	USGS
UC-0037	2/3/1981	199.80		R	USGS
UC-0037	2/6/1986	207.91		R	USGS
UC-0037	1/28/1991	213.61		R	USGS
UC-0037	1/25/1996	228.84		R	USGS
UC-0037	2/14/2001	152.73		R	USGS
UC-0037	8/16/2007	194.90		R	USGS
UC-0037	3/4/2008	192.00		R	USGS
UC-0037	9/16/2008	207.43		R	USGS
UC-0037	2/9/2009	205.50		R	USGS
UC-0037	8/26/2009	209.33	T	R	USGS
UC-0037	1/15/2010	189.40		R	USGS
UC-0037	8/24/2010	208.05		R	USGS
UC-0037	1/14/2011	203.16		R	USGS
UC-0037	2/9/2011	191.88		R	USGS
UC-0037	8/15/2011	204.06		S	NESWCD
UC-0037	1/2/2012	208.68		S	NESWCD
UC-0038	3/21/1968	157.76		R	USGS
UC-0038	3/26/1970	164.76	S	R	USGS
UC-0038	3/16/1971	158.59		R	USGS
UC-0038	1/9/1972	171.25		R	USGS
UC-0038	2/1/1973	159.20		R	USGS
UC-0038	2/6/1974	160.23		R	USGS
UC-0038	1/22/1975	162.31		R	USGS
UC-0038	1/27/1976	165.03		R	USGS
UC-0038	1/26/1977	165.84		R	USGS
UC-0038	1/25/1978	167.83		R	USGS
UC-0038	1/23/1979	169.28		R	USGS
UC-0038	1/30/1980	169.75		R	USGS
UC-0038	2/3/1981	172.24		R	USGS
UC-0038	2/6/1986	195.82		R	USGS
UC-0038	1/26/1991	189.58		R	USGS
UC-0038	1/25/1996	224.40		R	USGS

NMBGMR ID	Date Measured	Depth to Water (ft)	Status	Method	Measured by
UC-0038	2/14/2001	211.75		R	USGS
UC-0038	3/9/2004	225.28		R	USGS
UC-0038	3/29/2005	225.19		R	USGS
UC-0038	3/5/2007	217.33		R	USGS
UC-0038	2/6/2008	274.64		R	USGS
UC-0038	2/4/2009	251.43	R	R	USGS
UC-0038	8/27/2009	300.58	P	R	USGS
UC-0038	3/17/2010	224.54		R	USGS
UC-0038	2/10/2011	226.40		R	USGS
UC-0038	2/15/2012	233.00	P	R	USGS
UC-0039	8/16/1967	139.83		R	USGS
UC-0039	11/7/1967	139.15		R	USGS
UC-0039	3/16/1971	136.65		R	USGS
UC-0039	1/8/1972	135.29		R	USGS
UC-0039	2/2/1973	136.73		R	USGS
UC-0039	2/7/1974	135.67		R	USGS
UC-0039	1/22/1975	135.76		R	USGS
UC-0039	1/27/1976	130.54		R	USGS
UC-0039	1/25/1977	119.57		R	USGS
UC-0039	1/26/1978	117.00		R	USGS
UC-0039	1/23/1979	113.42		R	USGS
UC-0039	1/30/1980	117.55		R	USGS
UC-0039	2/5/1981	132.34		R	USGS
UC-0039	1/25/1991	149.83		R	USGS
UC-0039	1/25/1996	182.64		R	USGS
UC-0039	8/25/2007	167.34		R	USGS
UC-0039	2/27/2008	183.50		R	USGS
UC-0039	2/5/2009	180.48		R	USGS
UC-0039	2/16/2009	178.17		R	USGS
UC-0039	2/16/2009	178.17		S	NESWCD
UC-0039	8/16/2009	173.68		S	NESWCD
UC-0039	1/15/2010	168.25		R	USGS
UC-0039	8/24/2010	176.64		R	USGS
UC-0039	1/10/2011	172.79		R	USGS
UC-0039	8/12/2011	177.17		S	NESWCD
UC-0039	9/1/2011	170.17		R	USGS
UC-0039	1/3/2012	154.19		S	NESWCD
UC-0039	8/1/2012	178.01		S	NESWCD
UC-0039	1/6/2013	159.50		S	NESWCD
UC-0040	3/6/1968	92.62		R	USGS
UC-0040	3/24/1970	94.15		R	USGS
UC-0040	3/16/1971	96.59		R	USGS
UC-0040	1/7/1972	96.87		R	USGS
UC-0040	1/31/1973	96.70		R	USGS
UC-0040	2/6/1974	97.34		R	USGS
UC-0040	1/21/1975	99.21		R	USGS
UC-0040	1/27/1976	101.26		R	USGS
UC-0040	1/26/1977	101.51		R	USGS
UC-0040	1/24/1978	98.10		R	USGS
UC-0040	1/23/1979	97.93		R	USGS
UC-0040	1/30/1980	100.12		R	USGS
UC-0040	2/1/1981	100.16		R	USGS
UC-0040	2/4/1986	103.62		R	USGS
UC-0040	1/24/1991	104.48		R	USGS
UC-0040	1/23/1996	123.50		R	USGS
UC-0040	2/22/2001	114.12		R	USGS
UC-0040	2/14/2006	120.00	R	R	USGS
UC-0040	2/6/2008	122.54		R	USGS
UC-0040	2/6/2009	127.33	R	R	USGS
UC-0040	3/16/2010	125.02		R	USGS
UC-0040	1/25/2011	127.89		R	USGS
UC-0043	1/27/1981	201.29		R	USGS
UC-0043	1/22/1991	204.80		R	USGS
UC-0043	1/24/1996	208.50		R	USGS
UC-0043	8/15/2007	214.73		R	USGS
UC-0043	2/2/2008	213.10	R	R	USGS
UC-0043	8/6/2008	223.35	R	R	USGS
UC-0043	1/31/2009	222.83		R	USGS
UC-0043	8/26/2009	222.01		R	USGS
UC-0043	1/19/2010	217.49	R	R	USGS
UC-0043	8/26/2010	219.88	R	R	USGS
UC-0043	1/5/2011	223.20		R	USGS
UC-0043	8/14/2011	226.54		S	NESWCD
UC-0043	8/31/2011	218.09	R	R	USGS
UC-0043	1/5/2012	224.23		S	NESWCD
UC-0043	8/1/2012	222.91		S	NESWCD
UC-0043	1/6/2013	218.60		S	NESWCD
UC-0044	2/14/1981	160.79		R	USGS
UC-0044	2/6/1986	163.27		R	USGS
UC-0044	8/15/2007	243.90		R	USGS
UC-0044	2/18/2008	219.00		R	USGS
UC-0044	9/16/2008	233.89	S	R	USGS
UC-0044	8/26/2009	228.25	T	R	USGS
UC-0044	1/8/2010	222.38		R	USGS
UC-0044	8/24/2010	229.78		R	USGS
UC-0044	1/14/2011	229.04		R	USGS
UC-0044	8/6/2011	237.98		S	NESWCD
UC-0044	1/2/2012	232.04		S	NESWCD
UC-0044	8/1/2012	237.23		S	NESWCD
UC-0044	1/6/2013	228.50		S	NESWCD
UC-0102	8/13/2007	94.30		S	USGS/NESWCD
UC-0102	2/18/2008	92.40		S	USGS/NESWCD
UC-0102	9/16/2008	90.95		S	USGS/NESWCD
UC-0102	1/30/2009	90.30		S	USGS/NESWCD
UC-0102	8/15/2009	93.69		S	USGS/NESWCD
UC-0102	1/20/2010	91.10		S	USGS/NESWCD
UC-0102	8/14/2010	93.22		S	USGS/NESWCD
UC-0102	1/13/2011	94.55		S	USGS/NESWCD
UC-0102	8/12/2011	91.02		S	USGS/NESWCD
UC-0102	1/3/2012	90.79		S	USGS/NESWCD
UC-0106	2/19/2008	174.20		S	USGS/NESWCD
UC-0106	9/16/2008	214.33		S	USGS/NESWCD
UC-0106	2/13/2009	205.10		S	USGS/NESWCD
UC-0106	8/25/2009	214.44		S	USGS/NESWCD
UC-0106	1/15/2010	205.48		S	USGS/NESWCD
UC-0106	1/13/2011	196.99		S	USGS/NESWCD
UC-0106	8/13/2011	214.38		S	USGS/NESWCD
UC-0106	1/6/2012	200.42		S	USGS/NESWCD
UC-0106	1/6/2013	197.90		S	USGS/NESWCD
UC-0112	8/17/2007	248.77		S	USGS/NESWCD
UC-0112	2/27/2008	255.80		S	USGS/NESWCD
UC-0112	8/7/2008	258.26		S	USGS/NESWCD
UC-0112	2/11/2009	252.86		S	USGS/NESWCD
UC-0112	8/24/2009	269.00		S	USGS/NESWCD
UC-0112	1/14/2010	247.50		S	USGS/NESWCD
UC-0112	8/12/2010	264.90		S	USGS/NESWCD
UC-0112	1/13/2011	256.40		S	USGS/NESWCD
UC-0112	8/10/2011	265.83		S	USGS/NESWCD
UC-0112	1/6/2012	252.05		S	USGS/NESWCD
UC-0112	8/1/2012	268.18		S	USGS/NESWCD
UC-0112	1/6/2013	253.70		S	USGS/NESWCD
UC-0113	8/17/2007	180.59		S	USGS/NESWCD
UC-0113	2/27/2008	177.90		S	USGS/NESWCD
UC-0113	8/6/2008	171.59		S	USGS/NESWCD
UC-0113	2/11/2009	178.51		S	USGS/NESWCD
UC-0113	8/22/2009	182.04		S	USGS/NESWCD
UC-0113	1/15/2010	169.60		S	USGS/NESWCD
UC-0113	8/23/2010	174.74		S	USGS/NESWCD
UC-0113	1/13/2011	174.17		S	USGS/NESWCD
UC-0113	8/11/2011	175.19		S	USGS/NESWCD
UC-0113	1/6/2012	167.75		S	USGS/NESWCD
UC-0113	8/1/2012	175.08		S	USGS/NESWCD
UC-0113	1/6/2013	173.20		S	USGS/NESWCD

APPENDIX 6–Water chemistry data

All units are mg/L, except where noted.
Locations are UTM NAD83.

					Field parameters				Environmental Tracers								Major ions and trace metals																			
NMBGMR ID	UTM Easting	UTM Northing	Date Collected	Formation	Temperature (°C)	Field Specific Conductivity (µS/cm)	Dissolved Oxygen	Field pH (pH units)	Tritium (TU)	δC13	C14 % modern carbon	C14 %MC error	C14 years	C14 years error	δD	$\delta^{18}O$	Ag	Al	As	B	Ba	Be	Br	Ca	Cd	Cl	Co	Lab Conductivity (µS/cm)	Cr	Cu	F	Fe	HCO$_3$	Hardness	K	Li
UC-0007	672788	4006530	9/8/2011	Dakota	17.43	390	8.4	7.57							-48.95	-6.89	<0.0005	0.0035	0.0009	0.078	0.096	<0.0005	0.14	47	<0.0005	15	<0.0005	450	0.0007	0.0013	0.82	<0.02	225	191	3	0.027
UC-0010	660393	4011056	9/9/2011	Dakota	16.8	706	8.17	7.6	0.62	-7.4	57.04	± 0.21	4510	± 30	-45.08	-6.26	<0.0005	0.0008	0.003	0.19	0.059	<0.0005	0.76	65	<0.0005	77	<0.0005	800	0.0009	0.0009	1.6	<0.02	210	344	5.8	0.077
UC-0019	661671	3993197	9/16/2011	Morrison	16.96	695	7.03	8.23	0.06	-9.1	23.54	± 0.14	11620	± 50	-56.39	-7.89	<0.0005	0.0034	0.0028	0.37	0.016	<0.0005	0.23	7.2	<0.0005	23	<0.0005	800	0.0011	0.0005	1.4	<0.02	370	51	3.7	0.086
UC-0020	677888	4043207	9/7/2011	Entrada	16.16	366	7.13	7.52							-54.92	-8.01	<0.0005	0.002	0.001	0.055	0.069	<0.0005	0.093	31	<0.0005	7.9	<0.0005	420	0.0006	0.0006	0.88	<0.02	225	143	2.1	0.018
UC-0021	668686	4051745	9/7/2011	Entrada	16.66	484	7.93	7.4							-53.29	-7.26	<0.0005	0.0019	0.0018	0.083	0.14	<0.0005	0.21	60	<0.0005	22	<0.0005	555	0.0007	0.0011	0.76	<0.02	250	227	2.8	0.032
UC-0022	667599	4054947	9/8/2011	Entrada	17.76	331	8.5	7.36	0.02	-7.1	68.07	± 0.25	3090	± 30	-58.31	-8.23	<0.0005	0.0024	0.0016	0.059	0.085	<0.0005	0.075	45	<0.0005	7.1	<0.0005	380	0.0007	0.0008	0.85	<0.02	210	173	2.7	0.03
UC-0023	668245	4052820	9/8/2011	Entrada	17.02	363	10.9	7.4							-56.61	-7.89	<0.0005	0.0009	0.0016	0.063	0.11	<0.0005	0.11	47	<0.0005	12	<0.0005	410	0.0006	0.0049	0.82	<0.02	205	184	2.7	0.029
UC-0024	674646	3991249	9/8/2011	Dakota	17.22	515	7.27	7.44	0.02	-7.4	51.25	± 0.18	5370	± 30	-48.89	-6.98	<0.0005	0.0007	0.0012	0.18	0.055	<0.0005	0.2	44	<0.0005	23	<0.0005	580	0.0007	0.0011	1.1	<0.02	250	208	4.3	0.045
UC-0025	673129	3992999	9/8/2011	Dakota	21.93	489	8.38	7.48							-48.62	-6.98	<0.0005	0.0033	0.0016	0.12	0.058	<0.0005	0.18	49	<0.0005	21	<0.0005	550	0.0008	0.0012	1.1	<0.02	240	220	4	0.04
UC-0026	671094	3986999	9/14/2011	Morrison	16.13	509	9.71	7.42							-45.26	-6.98	<0.0005	<0.0005	0.002	0.083	0.077	<0.0005	0.11	65	<0.0005	18	<0.0005	580	0.0007	0.0006	0.57	<0.02	210	220	3.9	0.021
UC-0027	667201	4001695	9/14/2011	Dakota	16.95	518	8.82	7.49							-46.31	-6.74	<0.0005	0.0029	0.0017	0.11	0.081	<0.0005	0.35	59	<0.0005	50	<0.0005	590	0.0011	0.0006	1.1	<0.02	185	259	5	0.041
UC-0028	664988	4004687	9/14/2011	Morrison	17.6	393	3.5	7.4		-7.5	49.74	± 0.24	5610	± 40	-49.57	-7.04	<0.0005	<0.0005	0.0009	0.087	0.095	<0.0005	0.11	48	<0.0005	9	<0.0005	450	0.0009	<0.0005	0.92	<0.02	220	206	3.7	0.029
UC-0029	663886	4004767	9/14/2011	Dakota	22.4	373	3	7.2		-7.9	61.16	± 0.22	3950	± 30	-45.67	-6.52	<0.0005	<0.0005	0.0007	0.08	0.11	<0.0005	0.08	45	<0.0005	5.6	<0.0005	420	0.0007	0.0011	0.84	<0.02	215	192	3.3	0.033
UC-0030	672625	4024245	9/15/2011	Dakota	15.67	423	2.2	6.96							-55.99	-7.96	<0.0005	<0.0005	0.0006	0.098	0.072	<0.0005	0.12	39	<0.0005	11	<0.0005	480	0.0007	<0.0005	0.92	0.57	250	196	4	0.033
UC-0031	668263	4024510	9/15/2011	Dakota	15.5	587	9.6	7.29							-52.28	-7.16	<0.0005	0.0005	0.0011	0.095	0.087	<0.0005	0.43	65	<0.0005	55	<0.0005	670	0.0006	<0.0005	1.1	0.033	210	285	3.8	0.045
UC-0032	656091	4067661	9/15/2011	Morrison	14.7	390	9.18	7.58		-3	86.34	± 0.31	1180	± 30	-58.48	-8.01	<0.0005	<0.0005	0.0024	0.081	0.13	<0.0005	0.15	44	<0.0005	20	<0.0005	445	0.0002	0.002	1	<0.02	185	191	2.5	0.038

					Major ions and trace metals																												
NMBGMR ID	UTM Easting	UTM Northing	Date Collected	Formation	Mg	Mn	Mo	Na	Ni	NO$_2$	NO$_3$	Pb	Lab pH (pH units)	PO$_4$	Sb	Se	Si	SiO$_2$	Sn	SO$_4$	Sr	TDS	Th	Ti	Tl	U	V	Zn	Ti	Tl	U	V	Zn
UC-0007	672788	4006530	9/8/2011	Dakota	18	<0.001	0.003	20	0.0007	<0.1	10	<0.0005	7.5	<0.5	<0.0005	0.003	12	27	<0.0005	27	0.65	280	<0.0005	0.0014	<0.0005	0.0036	0.0061	0.0064	0.0014	<0.0005	0.0036	0.0061	0.0064
UC-0010	660393	4011056	9/9/2011	Dakota	44	<0.001	0.002	30	0.0012	<0.1	19	<0.0005	7.6	<0.5	<0.0005	0.016	16	35	<0.0005	110	1.8	496	<0.0005	0.0018	<0.0005	0.0049	0.017	0.004	0.0018	<0.0005	0.0049	0.017	0.004
UC-0019	661671	3993197	9/16/2011	Morrison	8.1	0.001	0.006	165	<0.0005	<0.1	3.5	<0.0005	8.2	<0.5	<0.0005	0.004	8	17	<0.0005	77	0.24	491	<0.0005	<0.001	<0.0005	0.0065	0.017	0.0019	<0.001	<0.0005	0.0065	0.017	0.0019
UC-0020	677888	4043207	9/7/2011	Entrada	16	<0.001	0.004	15	<0.0005	<0.1	5.7	<0.0005	7.6	<0.5	<0.0005	0.002	8.9	19	<0.0005	22	0.5	233	<0.0005	0.001	<0.0005	0.0032	0.007	0.0019	0.001	<0.0005	0.0032	0.007	0.0019
UC-0021	668686	4051745	9/7/2011	Entrada	19	<0.001	0.002	32	0.0009	<0.1	10	<0.0005	7.5	<0.5	<0.0005	0.004	14	30	<0.0005	49	0.73	351	<0.0005	0.0016	<0.0005	0.0055	0.014	0.0013	0.0016	<0.0005	0.0055	0.014	0.0013
UC-0022	667599	4054947	9/8/2011	Entrada	15	<0.001	0.002	13	0.0008	<0.1	5.6	0.0007	7.5	<0.5	<0.0005	0.002	14	30	<0.0005	17	0.68	242	<0.0005	0.0015	<0.0005	0.0063	0.013	0.0617	0.0015	<0.0005	0.0063	0.013	0.0617
UC-0023	668245	4052820	9/8/2011	Entrada	16	0.0026	0.002	15	0.0008	<0.1	7.3	<0.0005	7.5	<0.5	<0.0005	0.003	14	30	<0.0005	23	0.7	257	<0.0005	0.0015	<0.0005	0.0046	0.011	0.004	0.0015	<0.0005	0.0046	0.011	0.004
UC-0024	674646	3991249	9/8/2011	Dakota	24	<0.001	0.008	45	0.0006	<0.1	6.6	<0.0005	7.6	<0.5	<0.0005	0.003	12	26	<0.0005	65	0.87	364	<0.0005	0.0013	<0.0005	0.007	0.0067	0.0025	0.0013	<0.0005	0.007	0.0067	0.0025
UC-0025	673129	3992999	9/8/2011	Dakota	24	0.0012	0.005	31	0.0011	<0.1	9.1	<0.0005	7.6	<0.5	<0.0005	0.004	12	27	<0.0005	55	0.9	341	<0.0005	0.0014	<0.0005	0.0078	0.0077	0.014	0.0014	<0.0005	0.0078	0.0077	0.014
UC-0026	671094	3986999	9/14/2011	Morrison	14	<0.001	0.003	37	0.0009	<0.1	26	<0.0005	7.5	<0.5	<0.0005	0.002	9.5	20	<0.0005	80	0.66	371	<0.0005	<0.001	<0.0005	0.0034	0.0075	0.0062	<0.001	<0.0005	0.0034	0.0075	0.0062
UC-0027	667201	4001695	9/14/2011	Dakota	27	<0.001	0.004	15	0.0008	<0.1	35	<0.0005	7.6	<0.5	<0.0005	0.005	13	27	<0.0005	38	0.91	352	<0.0005	0.001	<0.0005	0.0044	0.0095	0.0063	0.001	<0.0005	0.0044	0.0095	0.0063
UC-0028	664988	4004687	9/14/2011	Morrison	21	<0.001	0.003	15	0.0007	<0.1	12	<0.0005	7.5	<0.5	<0.0005	0.002	11	23	<0.0005	27	0.7	270	<0.0005	<0.001	<0.0005	0.0037	0.0056	0.017	<0.001	<0.0005	0.0037	0.0056	0.017
UC-0029	663886	4004767	9/14/2011	Dakota	19	<0.001	0.002	14	0.0007	<0.1	10	<0.0005	7.3	<0.5	<0.0005	0.002	13	28	<0.0005	27	0.81	261	<0.0005	0.001	<0.0005	0.0036	0.0055	0.044	0.001	<0.0005	0.0036	0.0055	0.044
UC-0030	672625	4024245	9/15/2011	Dakota	24	0.081	0.003	29	0.0006	<0.1	<0.1	<0.0005	6.9	<0.5	<0.0005	<0.001	5.6	12	<0.0005	34	0.71	280	<0.0005	<0.001	<0.0005	<0.0005	<0.0005	0.0013	<0.001	<0.0005	<0.0005	<0.0005	0.0013
UC-0031	668263	4024510	9/15/2011	Dakota	30	0.012	<0.001	31	0.0013	<0.1	15	<0.0005	7.3	<0.5	<0.0005	0.007	14	30	<0.0005	74	1	411	<0.0005	0.001	<0.0005	0.0026	0.0062	0.14	0.001	<0.0005	0.0026	0.0062	0.14
UC-0032	656091	4067661	9/15/2011	Morrison	20	0.002	0.002	19	0.0006	<0.1	14	<0.0005	7.6	<0.5	<0.0005	0.004	14	31	<0.0005	33	1.1	278	<0.0005	0.001	<0.0005	0.0043	0.019	0.086	0.001	<0.0005	0.0043	0.019	0.086

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