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GROUNDWATER RESOURCES OF UNION COUNTY, NEW MEXICO: A PROGRESS REPORT

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Abstract — Beginning in 2007, the Northeastern Soil and Water Conservation District Board began a groundwater monitoring program for Union County in northeastern New Mexico. Repeated regular static water level measurements, sampling of wells and springs for major element chemistry, ^{14}C and tritium, as well as geologic mapping and examination of petroleum and water well data have led to a better understanding of the groundwater resources beneath Union County. Agricultural producers and communities rely on a partitioned system of smaller aquifers created by geologic complexities in the subsurface. Here we provide a progress report on development of data sets related to these groundwater resources and discuss changes in local agricultural management practices that have resulted from these efforts.

INTRODUCTION

Located in the far northeastern corner of New Mexico, Union County contains 3,817 mi^2 of semiarid open grasslands, multiple volcanic features and canyonlands (Fig. 1). In 2005, the Office of the State Engineer declared the Clayton groundwater basin an administered groundwater basin, the last such basin designated in New Mexico. Recognizing a lack of information about groundwater resources in the area, the Northeastern Soil and Water Conservation Board (NESWCD) decided to undertake a more rigorous study of their groundwater resources in 2007 and developed a multi-phase project that sought to develop data regarding groundwater quantity and quality throughout the county. The project is ongoing and now encompasses nearly 75 wells across the county that are routinely monitored for changes in static water level and general chemistry, as well as continued revisions to existing geologic maps of the area. Here we present a progress report on efforts to better understand the hydrogeology of Union County.

PREVIOUS GROUNDWATER-RELATED WORK

The first substantial study of groundwater resources in Union County was published in 1957 by Baldwin and Bushman. In their report, hydrologic data from a small number of wells around the Clayton area were published after several years of monitoring. In 1959, Baldwin and Muehlberger published the first complete study of the geology of Union County, wherein they described the stratigraphy and structure, and included a more detailed study of the volcanic rocks in the northern part of the county. This publication included detailed geologic maps of the county, cross-sections developed from well log data and a number of important observations about the stratigraphy and structural features of the county that strongly control the aquifer systems utilized by the population. In 1967, Cooper and Davis published a groundwater report for

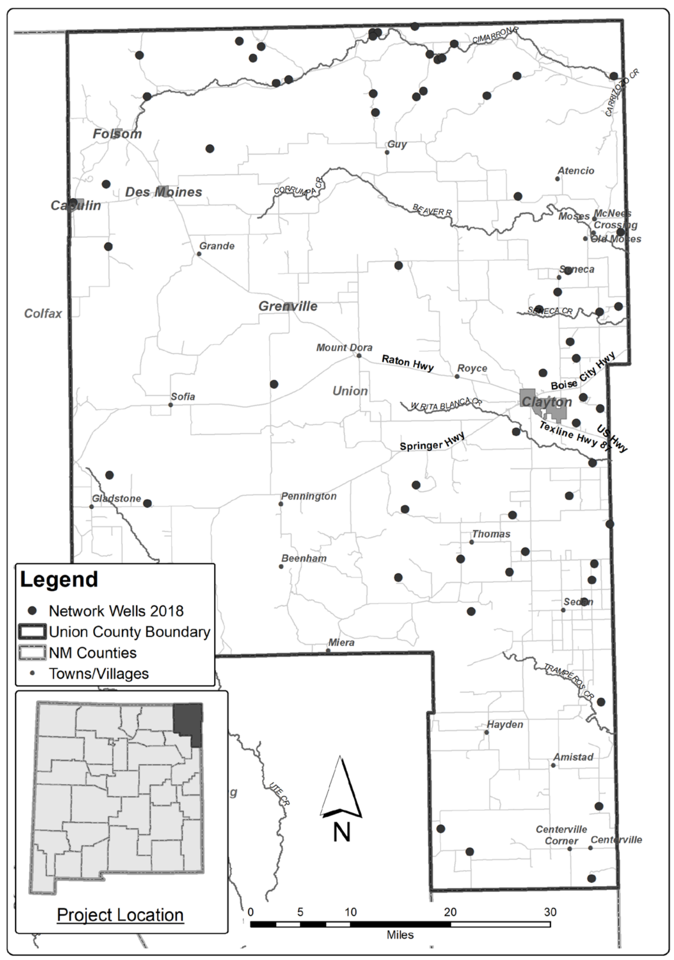

FIGURE 1. Map showing the location of Union County in New Mexico and the current NESWCD well network.

the county that built, in part, on Baldwin and Bushman's earlier work and added a significant amount of new data including well drilling data, static water levels and water chemistry for a number of wells around the county. After the 1960s, investigations of groundwater resources in Union County were reduced to occasional routine water level measurements conducted by the U.S. Geological Survey. In 2013, Rawling published a detailed study of groundwater characteristics in the east-central part of Union County, as well as an updated water table map of the county in 2015.

Larger-scale studies of the geology and hydrology of northeastern New Mexico, as well as adjacent portions of Oklahoma and Texas, have tended to focus on the Ogallala Formation as a part of the High Plains aquifer system along with potentially hydrologically connected older Cretaceous and Jurassic strata (e.g., Luckey et al., 1981; Weeks and Gutentag, 1981; Gutentag et al., 1984; Weeks et al., 1988; Nativ and Smith, 1987; Nativ and Gutierrez, 1989). Recently Blumenberg (2018) initiated a more detailed study of stable isotopes in groundwater in northeastern New Mexico.

METHODS

Field work for this latest effort in Union County began in 2007 and is ongoing. Data collection includes 1:50,000 and 1:24,000 geologic mapping, examination of well logs and associated cuttings, repeated regular depth to water measurements, as well as one-time sampling of wells and springs for major element chemistry, stable isotopes, ^{14}C and tritium (sampling methods and analytical procedures adhere to those documented in Rawling, 2013 and Timmons et al., 2013).

GEOLOGY

The regional geology of northeastern New Mexico is reviewed in Zeigler et al. (*this volume*) and more detailed descriptions of rock units in Union County are found in Baldwin and Muehlberger (1959), Mankin (1972), Lucas et al. (1987), Kues and Lucas (1987), and Pazzaglia and Hawley (2004). We follow the stratigraphy as described in Zeigler et al. (*this volume*) and here briefly review the Upper Triassic Dockum Group, the Middle Jurassic Exeter Sandstone and Bell Ranch Formation, the Middle-Upper Jurassic Morrison Formation, the (?)Upper Jurassic Lytle Sandstone, the Upper Cretaceous Glencairn Formation, Dakota Group and Graneros Shale, the Miocene-Pliocene Ogallala Formation and Quaternary volcanic units (Fig. 2).

The Upper Triassic Dockum Group (the "redbeds" of local driller vernacular) crops out in the Dry Cimarron Valley in northern Union County, as well as in the southern end of the county along Monia Creek. The unit consists primarily of interbedded fine- to medium-grained sandstone, siltstone and mudstone with local intraformational conglomerate beds that range in color from reddish-brown to purplish-gray to greenish-gray. Deposition of these strata occurred in a complex landscape of aggradational fans shedding material off the remaining Ouachita Uplift to the east and Uncompaghre uplift to the north with drainages generally oriented to the west-northwest towards Nevada. The Dockum Group is gently folded with hingelines that generally trend north-south, creating a distinctive angular unconformity with the overlying Exeter Sandstone.

The Exeter Sandstone is an aeolianite that varies significantly in thickness due to underlying folded Triassic strata. It is probably laterally equivalent to the Entrada Sandstone, based on correlations by Heaton (1939) and represents an extension of the Four Corners dune fields. The Exeter Sandstone grades upwards into the Bell Ranch Formation, which also has variable thickness and primarily consists of brown mudstone to siltstone with local beds of nodular to tabular gypsum. The Bell Ranch Formation was likely deposited in a playa-dominated system. Overlying the Bell Ranch Formation is the Morrison Formation, which is subdivided into two informal facies. A lower member consists of mudstone, sandstone and limestone, and an upper member consists of variegated mudstone and sandstone. As with the Dockum Group, the Morrison represents deposition in a complex distal aggradational fan/fluvial/lacustrine system that results in lateral and vertical heterogeneity in the unit.

The top of the Morrison Formation is heavily incised, resulting in significant paleotopography infilled by the Lytle Sandstone, which may be Jurassic in age (Bartnik et al., *this volume*) although it was previously included in the Lower Cretaceous sequence (Fig. 2) by Baldwin and Muehlberger (1959) and Kues and Lucas (1987). The Lytle Sandstone consists of very pale pink coarse-grained sandstone and siltstone that grades upwards into the overlying Glencairn Formation, which consists of gray shales and tan sandstone and siltstone that are Cretaceous in age and represent shallow marine/estuarine deposition. The Glencairn Formation is overlain by the three subdivisions of the Dakota Group: lower Mesa Rica Sandstone, shales of the medial Pajarito Formation and upper Romeroville Sandstone, which reflect a transition from fluvial through shallow marine. Above the Dakota Group sequence is the Graneros Shale and overlying Greenhorn Limestone. The Graneros Shale and the shale units of the Greenhorn Limestone include thin beds of limestone or calcarenite that are locally fossiliferous, as well as zones containing selenite crystals. Younger Cretaceous units are not present in Union County.

Overlying and inset into these older Mesozoic units is the Miocene-Pliocene Ogallala Formation, a sequence of gravel, sandstone, mudstone and discontinuous calcrete horizons of variable thickness. In places, the Ogallala Formation is nothing more than a surficial lag of unconsolidated siliceous gravel, whereas in east-central Union County, it reaches thicknesses of up to 250 to 300 ft as paleovalley fill. In the western and northern portion of Union County, extensive lava flows and cinder cones of the Raton-Capulin-Clayton volcanic field cover the Ogallala Formation as well as older rock units. Overall, the geology of Union County is fairly complex with the presence of the Sierra Grande arch and Bravo Dome in the subsurface (see Zeigler et al., *this volume*), folding of Triassic strata and repeated episodes of regional erosion and infilling creating a highly partitioned subsurface (Fig. 3).

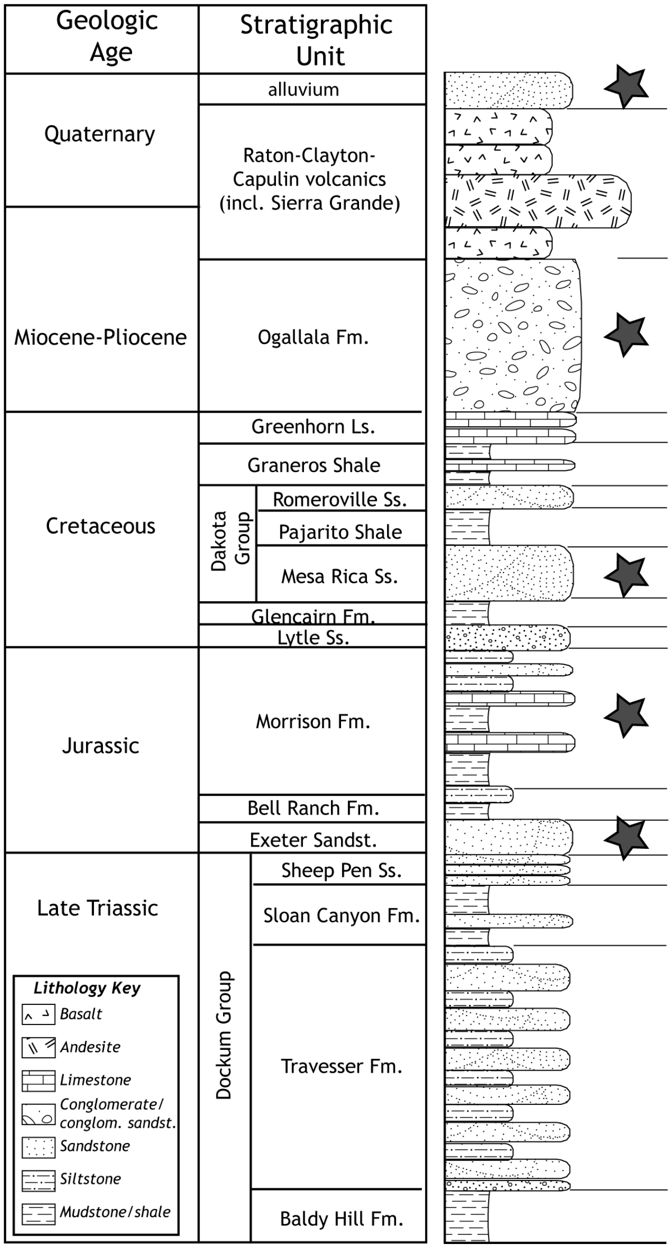

FIGURE 2. Schematic stratigraphic column showing Mesozoic and Cenozoic sedimentary units and Cenozoic volcanic units in Union County. Stars indicate principle hydrostratigraphic units.

HYDROLOGY AND HYDROGEOLOGY

Surface Water and Groundwater Hydrology

Union County is classified as semiarid with precipitation averaging between 12 and 16 inches a year. Two pulses of moisture affect Union County that arrive in the winter as snowfall and as mid- to late-summer monsoon rains. Drainages generally trend to the southeast and include Ute Creek, a primary tributary to the Canadian River. The Dry Cimarron is unique in the area in that it drains to the east and eventually joins the Arkansas River. Overall, there is very little surface water in the county with local drainages having flow only after significant rainfall or snowmelt events. Springs are not common and generally occur at the base of Quaternary basalt flows and Dakota Group outcrops. Spring flow is perennial only over short distances and many drainages exhibit small seeps or sub-irrigated zones, although these rarely contribute significant discharge.

Groundwater use in Union County includes domestic, livestock and center-pivot irrigation. Wells in the county range from less than 10 ft in depth to over 800 ft deep, and include several older, hand-dug wells that have persisted from homesteader days. Water levels generally range from at ground surface to greater than 600 ft below land surface. As described in Cooper and Davis (1967), wells completed in basalt flows, alluvial deposits and the shallower areas of the Ogallala Formation are not considered to be under artesian pressure. Wells completed in the deeper Ogallala Formation and other older groundwater-bearing units are under artesian pressure, although this very rarely results in flow above the surface from a well. Generally, highest yields are confined to the Ogallala Formation – filled paleovalleys and local points of higher yield, such as some wells along Tramperos Creek in the southern part of the county. Observations by local agricultural producers indicate that yields from nearly all wells have declined over the last 50 years. For example, wells in the Sedan area (southeast of Clayton) were described as producing at 800 gpm (gallons per minute) to over 1000 gpm. Currently, many of these wells yield less than 500 gpm and yield is steadily declining. In general, livestock wells are located in areas where groundwater sources yield less than 35 gpm, and in most cases, the yield on livestock wells ranges from less than one gpm to 10 gpm. A well that produces more than 10 gpm is considered a very good well in most rangeland areas.

Hydrogeologic Framework

We identify five primary hydrostratigraphic units in Union County (from oldest rock unit to youngest): Dockum+alluvium, Morrison, Dakota, Ogallala, and basalt. Each of these is

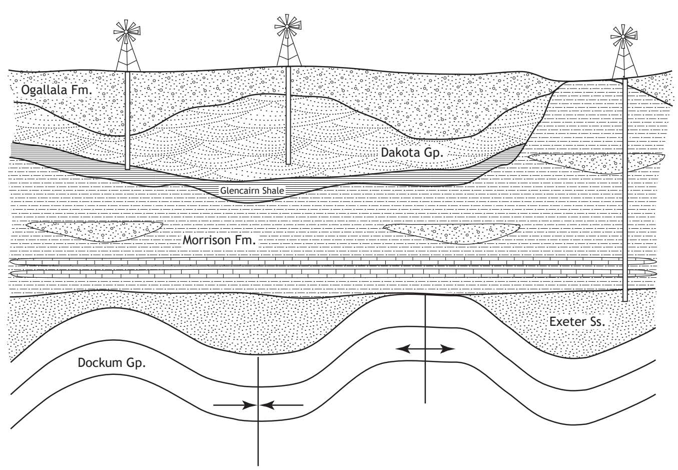

FIGURE 3. Schematic cross-section showing the interpreted subsurface north to south along the Texas state line, south of Clayton. Developed from petroleum well geophysical logs and water well log information, it demonstrates the complications in the geologic framework that lead to variations in well behavior and water chemistry. Vertical scale is approximately 900 feet from land surface and horizontal scale is approximately 50 miles.

defined by a combination of yield rate and chemical characteristics (discussed below). Due to most wells in the county being perforated along their entire cased lengths, many wells are frequently drawing from more than one of these hydrostratigraphic units simultaneously. In some cases, more than one rock unit may be hydrologically connected due to stratigraphic relationships such that groundwater sources may be mixed. For example, the Ogallala Formation and Dakota Group are not stratigraphically isolated from one another in much of the area, with Ogallala Formation strata resting directly on underlying sandstone of the Dakota Group, resulting in a combined hydrostratigraphic unit where both units are present. The Exeter Sandstone is here considered a secondary groundwater source, given that is not commonly penetrated and seems to only be relied on where it has unexpectedly provided reasonable groundwater yields.

The Dockum Group plus overlying alluvium serve as a source of groundwater primarily in the northern portion of Union County, along the floor of the Dry Cimarron valley, as well as in localized areas in the southernmost and southwestern corner of the county where local structural features such as the Clapham anticline have raised older units into the shallow subsurface. This lithologically heterogeneous unit can provide moderate yields of water, ranging from a few gpm to upwards of 20 gpm. The Exeter Sandstone can be a potential source of groundwater throughout the county, but little is known about this unit other than where well drilling efforts have penetrated it. It is not generally considered a target for drilling due to the variability of both thickness and depth to the unit. For example, south of Clayton, the Exeter Sandstone can be 700 ft or more below land surface.

Due to lateral and vertical heterogeneity within the Morrison Formation, it is not generally a reliable source of groundwater. Reasonable resources occur where multiple beds of limestone are present and/or relatively extensive channel sandstone beds can create small-scale groundwater resources that can yield up to 30 to 40 gpm. Wells drawing water from the Morrison Formation occur in a northwest-southeast trending zone along the northeastern limb of the Clapham anticline, which brings the Morrison to the surface at Tramperos Creek, as well as individual wells scattered across the county that intersect the Morrison Formation where it occurs as paleoridgelines below the surface. The Lytle Sandstone is laterally extensive, but is not easily discerned from the overlying Dakota Group where wells may penetrate both units.

The Dakota Group is probably the most utilized source of groundwater in the area. Ranging from 50 to 250 ft in thickness, it consists of quartzose sandstone with local lenses and partings of shale that yields anywhere from less than one gpm to 15 gpm. The Ogallala Formation (frequently in association with the Dakota Group) is the primary source of groundwater for areas of center pivot irrigation with significant thicknesses of the unit occurring in two discrete paleovalleys – one northeast of Clayton near the village of Seneca and one to the southeast around the village of Sedan – as well as a small isolated pocket of Ogallala just west of Gladstone in the west-central portion of the county. Quaternary basalt flows act as local aquifers and are highly fractured. Where basalt flows sit above Ogallala Formation deposits, or subcrop of the Dakota Group or Morrison Formation, they are generally hydrologically connected. Basalt flows sitting on shale-dominated units such as the Graneros Shale are a strong control on the presence of the few springs in the county, which primarily occur around the Folsom area.

Primary aquitards include the Dockum Group, where it is more mudstone dominated, the Bell Ranch and Morrison Formations where the Morrison is mudstone dominated, the Glencairn Formation and the Graneros Shale.

Hydrographs

As described in Rawling (2013), historic and current water level measurements used to develop contoured water elevation maps show a general trend of groundwater flow to the east-southeast. Rawling (2013) also compared a water table map developed for data from 1954 to one developed in 2011 to understand pre-center-pivot irrigation water tables to the water table after the onset of intensive irrigated production in the Sedan area. Water level declines of up to 150 ft are common in the Sedan area over the last six decades. He documented significant water level declines around Seneca and Sedan in east-central Union County and indicated that shallower, perched zones within the Ogallala aquifer are effectively dewatered. Overall estimated maximum saturated thickness of the Ogallala Formation in the Sedan area is approximately 300 ft and with overall declines of upwards of 150 ft, the trend is towards a loss of usable saturated thickness within the next few decades. Our observations, continued beyond the extent of his work, continue to document this trend.

At the start of this project, the NESWCD chose 50 wells that were already included in the U.S. Geological Survey National Water Information System (NWIS) database and began recording static water levels biannually beginning in August of 2007. From 2014 onwards, these original 50 wells were measured annually in January to document the behavior of the water table(s) during minimum use. Of the original 50 wells, only 35 are still monitored annually and the 15 wells removed either were dry for several successive years or had infrastructure issues that resulted in measurement problems. The majority of the remaining 35 wells continue to show the two behaviors documented by Rawling (2013): a steady decline in water level and others with variable behavior (Fig. 4).

Wells in the Ogallala Formation have depths to water ranging from approximately 170 ft below ground surface (bgs) to over 320 ft bgs. Dakota Group and Morrison Formation wells range from 70 to 170 ft bgs. Water levels in wells in the Dry Cimarron valley, which are generally completed in shallow alluvium ± Dockum Group, range from 20 to 70 ft bgs.

Wells in the Sedan and Seneca area, which draw from the Ogallala Formation ± Dakota Group, have traditionally shown the greatest declines from year to year and up until 2015, most of these showed water levels dropping between five and ten feet a year. Beginning in January of 2015, many of these wells continued to show declines, but on the order of two feet or less

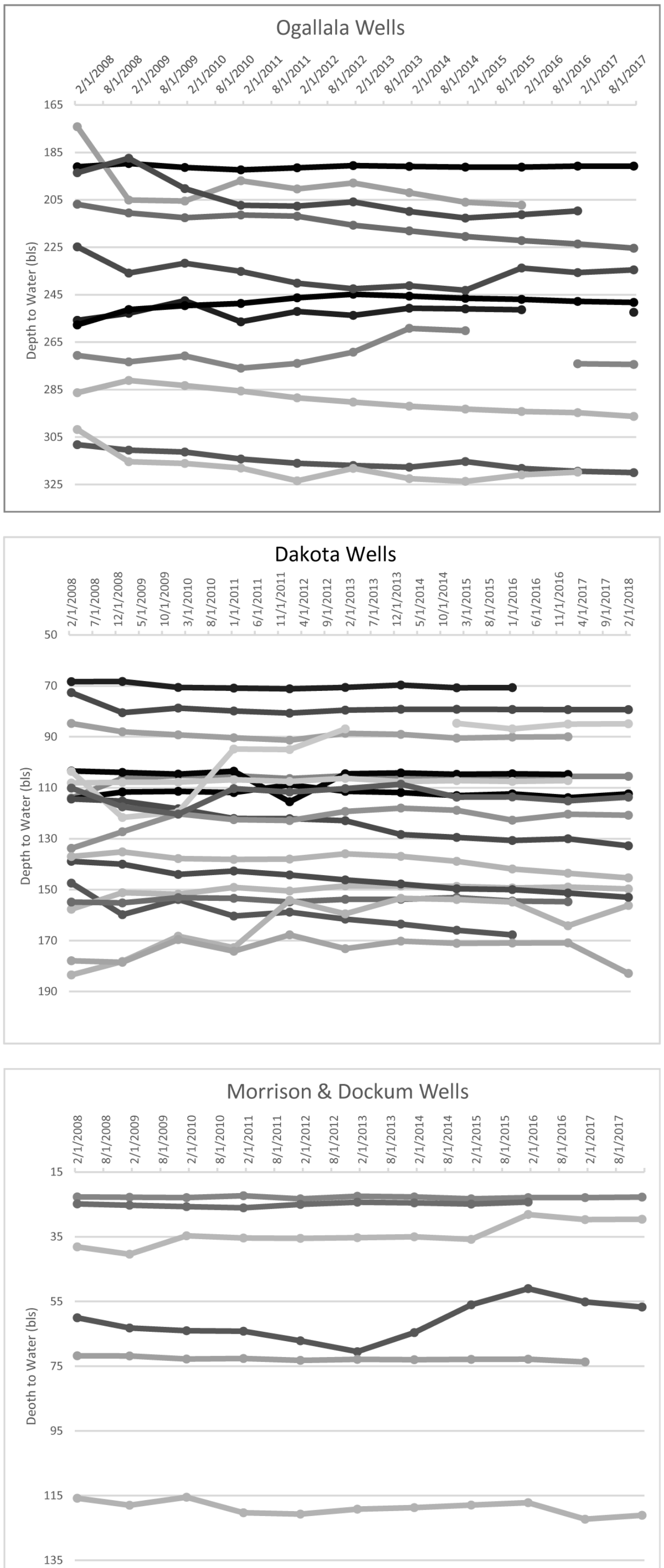

FIGURE 4. Stacked hydrographs for primary hydrostratigraphic units showing overall patterns of well behavior in Ogallala, Dakota and Morrison-completed wells. Dry Cimarron wells are generally completed in alluvium and locally, the top of the Dockum Group.

per year (Fig. 5). This pattern has held steady through January 2019 and is the result of a concerted effort on the part of the farming communities to conserve groundwater by altering cropping management strategies.

Wells in the central and western portions of the county, outside of the Sedan and Seneca areas, show a mix of steady declines and variable behavior. Rising water tables, as seen in Figure 5, occur in wells that are adjacent to drainages and generally relatively shallow. In addition, water table increases locally in the Sedan area are not necessarily true recharge events, but recovery of deep cones of depression developed over years to decades. Wells in the Dry Cimarron display significant variability in water level from year to year and increased water table elevations generally correspond to higher flow in the Dry Cimarron and its main tributaries. These wells are shallow and often drilled adjacent to drainages in an unconfined alluvial aquifer.

WATER CHEMISTRY

Analyses of water samples for major ion chemistry and isotopes helps provide insight into the aquifer systems being utilized in different parts of the county. Major cations and anions were used as primary means of characterizing the groundwater quality and for discerning contributions of water to a specific well from different geologic units. Tritium and ^{14}C isotopes are used as a means of assessing potential modern recharge and constraining average residence time of groundwater respectively.

Major ion chemistry and water types

Samples were analyzed from 41 wells and three springs, with an additional 10 samples as duplicates, resulting in Ca, Mg, and Na as dominant cations and HCO_3, and SO_4 as dominant anions (Fig. 6; Table 1). Note that not all of the wells sampled for water chemistry are part of the original 50 USGS wells, but include wells that were added on behalf of individual landowners later in the progression of the project. Of the 54 samples, 27 are Ca-Mg-HCO_3, 13 are Na-HCO_3, seven are Ca-Mg-SO_4 and the remaining seven are mixed cation-mixed anion type. The Ca-Mg-HCO_3 types correspond to wells completed through the Dakota Group, Ogallala Formation, Quaternary alluvium and springs exiting from Quaternary basalt flows. Ca-Mg-HCO_3 waters have been used as an indicator of shorter residence time of groundwater in aquifer systems, due to the lack of other cations and anions indicating too short a time for significant dissolution.

The Na-HCO_3 type waters occur in wells completed through the Dockum Group, Morrison Formation, Quaternary basalts and one spring occurring at the base of a basalt flow. Samples with Na-HCO_3 waters also correlate well to higher total dissolved solid (TDS) values. Exceptions to this include three samples collected from southern Union County near Tramperos Creek. These wells are completed in Morrison Formation that occurs as a paleoridgeline within ten feet of the land surface, trending northwest-southeast. Samples from these wells

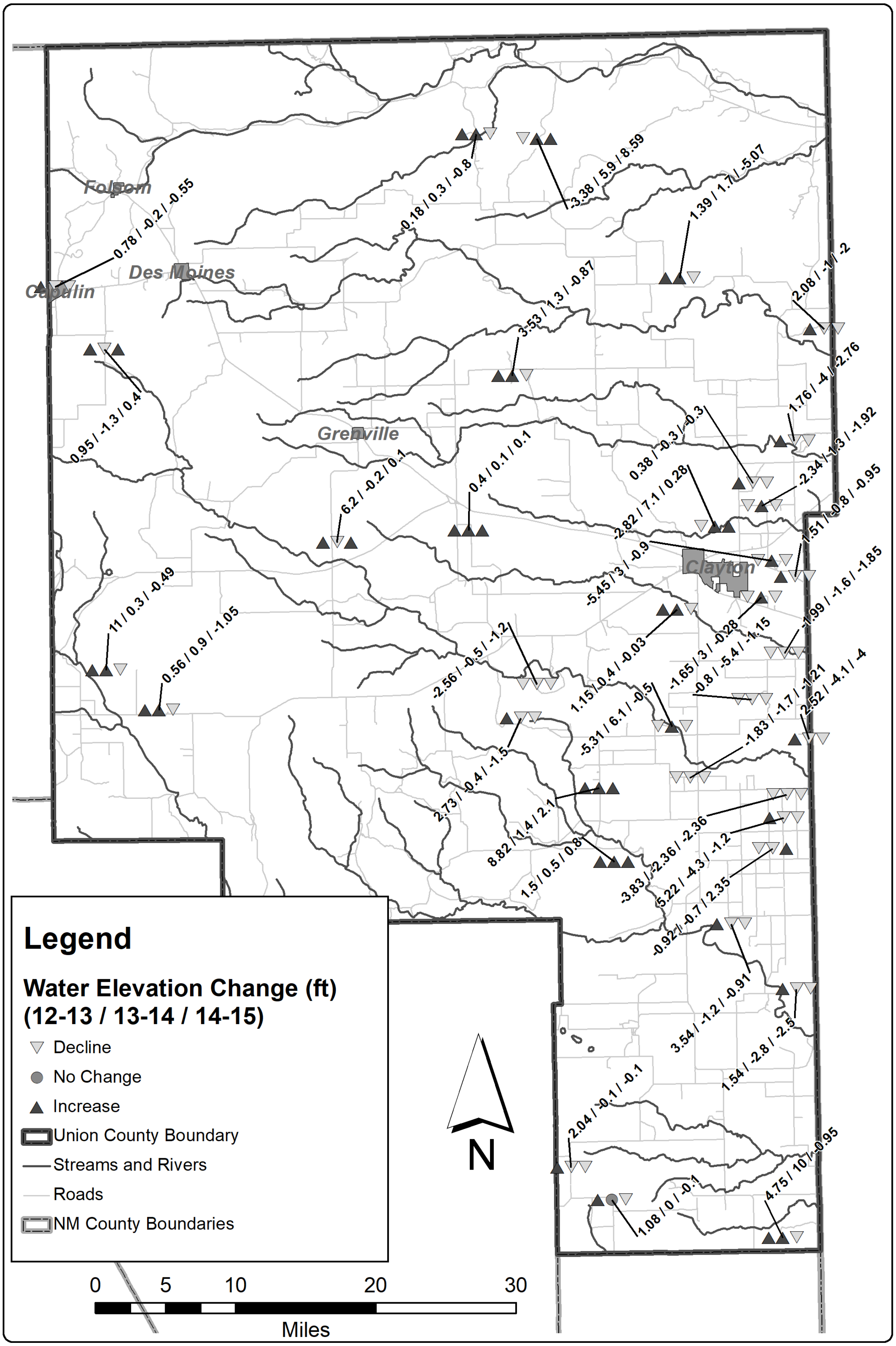

FIGURE 5. Groundwater level change map showing change in water level from January 2012 to 2013 (left-hand value), January 2013 to January 2014 (center value) and January 2014 to January 2015 (right-hand value). Note the areas of highest groundwater level decline are located where center-pivot irrigation is most prominent. Beginning in January 2015, water level declines around Sedan began to decrease.

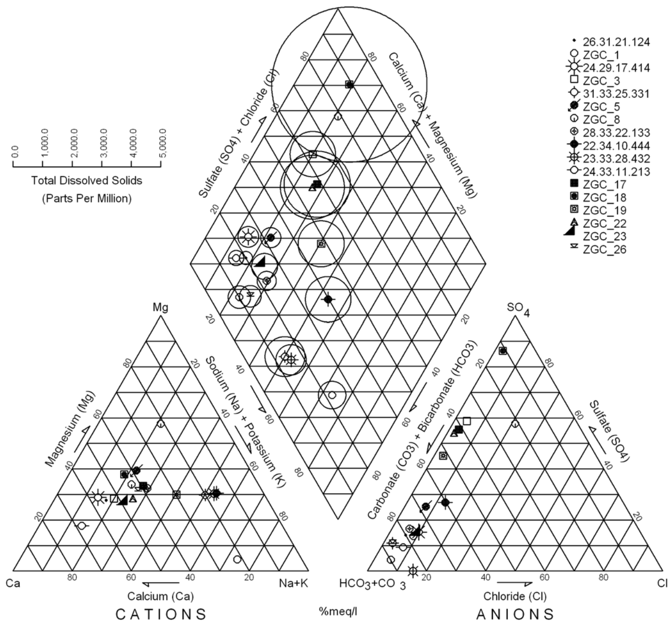

FIGURE 6. Piper diagram showing major cation and anion components for wells representing the major water types observed in Union County.

have Na+HCO_3 waters, but lower TDS values compared to other water samples from Morrison waters (Table 1). Morrison Formation sandstones are arkosic, and feldspar presumably contributes to the presence of Na through the hydrolysis of feldspar to clay.

The Ca-Mg-SO_4 water type occurs in one well that is partially completed in the Bell Ranch Formation, as well as in wells penetrating black shale lenses in the Dakota Group and/or the Graneros Shale, or in wells along the length of the Dry Cimarron. Dry Cimarron wells are generally shallow and completed through alluvial deposits that contain gypsum mobilized from rock units exposed along canyon walls and tributaries. The presence of sulfate in these waters reflects the occurrence of gypsum in these rock units and generally cooler groundwater temperatures.

The mixed cation-mixed anion type waters occur in wells that potentially intersect more than one hydrostratigraphic unit, such as Morrison + Dakota, as well as in shallow wells in the Dry Cimarron valley, which may be due to the contribution of a wider variety of ions from surrounding rock units. Outcrops of Dockum Group, Bell Ranch, Morrison Formation and black shales in the Cretaceous sequence have presumably all contributed to the sediments deposited along the floor of the valley and thus to the waters in the shallow alluvial aquifer.

Groundwater residence time and recharge potential

In order to assess the average residence time of various groundwater sources in the county and determine potential for modern recharge of the various aquifers utilized in the county, several samples were analyzed for ^{14}C and tritium (Fig. 7; Table 2). As described by Bethke and Johnson (2008), the age of groundwater is related to the rate of water molecule migration through the subsurface. Given that water molecules may enter and leave a given hydrostratigraphic unit via cross-formational flow and that groundwater masses will exchange water molecules with other groundwater masses, water molecules that entered the system as one mass will end up dispersed. Thus, ^{14}C values are taken to indicate an average residence time and not an absolute age of a groundwater mass. In addition, the presence of limestone in hydrostratigraphic units, such as the Morrison Formation or Graneros Shale, may cause artificially "older" ^{14}C results due to the presence of ^{12}C in the limestone. The ^{14}C activities reported in this study have not been corrected yet for potential dead carbon inputs. The majority of ^{14}C values obtained from wells around Union County returned residence times of greater than 800 years. In the Dry Cimarron, one sample from a well in the Dry Cimarron valley returned a residence time of less than 600 years, suggesting generally younger waters when coupled with tritium values.

Tritium is a radioactive isotope of hydrogen with a short half-life of 12.3 years and is most commonly used to determine relative age of waters less than 70 years old (Clark and Fritz, 1997). Tritium is produced as a natural byproduct of cosmic radiation interaction with the upper atmosphere. It was also produced anthropogenically during thermonuclear bomb testing in the 1950s. Thus, the presence or absence of tritium in groundwater samples can be used to determine potential for modern recharge. In general, a groundwater sample with 5 to 15 tritium units (TUs) is considered to be modern groundwater, indicating that the hydrostratigraphic unit a well is drawing from can be replenished with appropriate quantities of precipitation. Samples with 0.8 to 4.9 TUs are a mixture of modern and older waters and samples with less than 0.8 TUs indicate older waters. However, it should be noted that "older" does not necessarily equate to paleowaters, which are generally considered to be significantly older (e.g., Pleistocene). In fact, preliminary stable isotope data suggests few wells in the region are drawing from paleowaters (Blumenberg, 2018).

Tritium values show little to no detectable amounts other than in wells in the Dry Cimarron and in shallow wells adjacent to drainages where reasonably elevated levels of tritium occur. As noted previously, one caveat for utilizing tritium values is the penetration of multiple hydrostratigraphic units may result in extraneously high or low measurements of tritium due to mixing of waters. However, the overall pattern derived from both the ^{14}C and tritium analyses is a lack of volumetrically significant modern recharge for areas of the county outside the Dry Cimarron and its major tributaries with the exception of wells located adjacent to Tramperos Creek in southern Union County, which show mixed modern and older waters.

DISCUSSION

At the onset of the current effort to understand the groundwater resources of Union County, a common observation made by inhabitants of the area was that most of the wells in the area were completed in the Ogallala Formation and that "there are oceans of water down there". Careful re-examination of Baldwin and Muehlberger's original field maps, as well as devel-

TABLE 1. Table showing water sample major element chemistry results in mg/L. Abbreviations: (2) indicates duplicate sample collected at a later date, TDS = total dissolved solids (calculated). Decimal IDs are wells in the USGS NWIS system. Qal = Quaternary alluvium, Qb = Quaternary basalt, To = Ogallala Formation, Kg = Graneros Shale, Kd = Dakota Group, Jm = Morrison Formation, Je = Exeter Sandstone, Jbr = Bell Ranch Formation, Trd = Dockum Group. To/Kd = combined Ogallala/Dakota, Kd/Kg = combined Graneros/Dakota, Kd/Jm = combined Dakota/Morrison, Qal/Trd = alluvium overlying shallow Dockum Group (Dry Cimarron wells). Z= duplicate sample.

ZGC ID	Na	K	Ca	Mg	Cl	HCO_3	SO_4	TDS	Inferred Hydrostratigraphic Unit(s)
18.34.15.422	58.0	6.2	37.0	30.0	47.0	140.0	71.0	389.2	Jm and/or Trd
18.36.35.111	20.0	3.3	32.0	28.0	20.0	160.0	31.0	294.3	To/Kd
19.36.23.244	46.0	7.8	29.0	39.0	34.0	150.0	70.0	375.8	Kd and/or Jm
22.34.10.444	140.0	5.2	37.0	43.0	46.0	370.0	130.0	771.2	Jm
22.34.10.444(2)	140.0	5.1	35.0	41.0	46.0	350.0	120.0	737.1	Jm
23.33.28.432	76.0	5.4	22.0	24.0	37.0	350.0	0.0	514.4	Jm
24.29.17.414	18.0	1.4	65.0	20.0	15.0	200.0	32.0	351.4	Kd
24.33.11.213	12.0	1.5	53.0	8.4	8.3	160.0	14.0	257.2	To/Kd
25.28.34.344	40.0	4.6	47.0	27.0	9.9	280.0	20.0	428.5	Kd
26.31.21.124	13.0	2.5	39.0	12.0	5.6	130.0	18.0	220.1	Kd
28.28.10.222	30.0	2.9	91.0	35.0	38.0	300.0	65.0	561.9	Kd
28.28.10.222(2)	32.6	2.5	72.1	27.3	32.0	289.8	14.3	470.6	Kd
28.33.22.133	32.0	3.5	39.0	20.0	8.5	190.0	32.0	325.0	Kd
28.37.05.233	29.0	4.4	68.0	26.0	53.0	130.0	130.0	440.4	To/Kd
29.28.18.322	64.0	8.3	47.0	38.0	17.0	240.0	130.0	544.3	Qb
31.33.25.331	110.0	7.9	40.0	36.0	8.8	430.0	43.0	675.7	Je
31.33.25.331(2)	59.0	7.7	46.0	34.0	4.1	290.0	84.0	675.7	Je
31.37.18.424	190.0	9.4	52.0	56.0	30.0	400.0	350.0	1087.4	Qal/Trd
ZGC_1	160.0	4.0	7.3	8.3	21.0	320.0	73.0	593.6	Jm
ZGC_2	34.0	2.1	83.0	30.0	5.8	310.0	69.0	533.9	Qal
ZGC_2 (2)	38.2	1.8	79.4	29.8	5.4	390.4	16.2	561.2	Qal
ZGC_3	52.0	2.1	120.0	40.0	16.0	240.0	300.0	770.1	Kd/Kg
ZGC_3 (2)	56.7	1.6	108.4	36.2	14.9	297.7	286.6	802.1	Kd/Kg
ZGC_4	12.0	2.7	53.0	16.0	14.0	170.0	20.0	287.7	To
ZGC_4 (2)	17.3	2.7	46.9	14.8	6.4	210.5	21.7	320.3	To
ZGC_5	25.0	4.5	42.0	26.0	11.0	180.0	53.0	341.5	To
ZGC_6	18.0	3.9	68.0	9.2	8.0	150.0	62.0	319.1	To
ZGC_7	38.0	3.8	64.0	14.0	16.0	180.0	73.0	388.8	To
ZGC_8	27.0	4.5	48.0	23.0	9.6	260.0	10.0	382.1	Kd
ZGC_9	25.0	3.8	37.0	20.0	12.0	180.0	25.0	302.8	Kd
ZGC_10	33.0	5.4	84.0	35.0	54.0	200.0	87.0	498.4	To/Kd
ZGC_12	56.0	3.8	48.0	19.0	4.9	270.0	44.0	445.7	Kd/Jm?
ZGC_13	12.0	3.7	49.0	24.0	33.0	150.0	29.0	300.7	Kd
ZGC_13 (2)	16.1	4.2	46.2	24.0	31.2	187.9	29.9	339.5	Kd
ZGC_14	38.0	2.8	21.0	22.0	8.0	190.0	53.0	334.8	Qb (spring)
ZGC_15	18.0	6.2	44.0	14.0	4.2	180.0	7.4	273.8	Qb (spring)
ZGC_16	37.0	4.8	57.0	24.0	8.0	200.0	79.0	409.8	Qb (spring)
ZGC_17	110.0	2.8	140.0	72.0	17.0	380.0	400.0	1121.8	Qal/Trd
ZGC_18	170.0	13.0	360.0	190.0	37.0	260.0	1600.0	2630.0	Jbr
ZGC_19	110.0	3.9	72.0	44.0	11.0	320.0	220.0	780.9	Qal/Trd
ZGC_20	43.0	3.5	77.0	28.0	7.1	250.0	140.0	548.6	Qal/Trd
ZGC_21	230.0	8.8	45.0	41.0	62.0	450.0	230.0	1066.8	Jm
ZGC_22	154.0	7.6	30.8	21.1	17.2	398.0	149.0	777.7	Kd/Jm
ZGC_22 (2)	164.3	6.0	28.8	20.5	15.7	419.1	159.2	813.6	Kd/Jm
ZGC_23	92.9	4.5	134.8	51.8	10.0	380.6	389.6	1064.2	Qal/Trd
ZGC_23 (2)	90.3	4.1	139.0	53.0	11.6	397.0	388.0	1083.0	Qal/Trd
ZGC_24	32.3	2.9	56.0	18.2	22.3	269.0	39.1	439.79	Kd
ZGC_25	66.8	5.5	116.0	54.9	12.9	398.0	308.0	962.1	Qal/Trd
ZGC_25 (2)	81.6	4.1	207.1	79.0	17.2	412.4	648.2	1449.6	Qal/Trd
ZGC_26	20.3	3.1	53.0	15.5	16.3	208.0	40.8	357.0	To/Kd
ZGC_27	26.6	4.0	39.7	18.0	5.4	248.0	24.5	366.2	Kd
ZGC_28	12.7	2.3	36.8	11.0	5.3	165.0	19.9	253.0	Kd
ZGC_29	32.0	3.9	33.6	17.1	10.5	203.1	7.0	307.2	Kd/Jm
ZGC_30	76.2	4.5	50.5	24.1	10.6	348.9	85.8	600.6	Kd/Jm

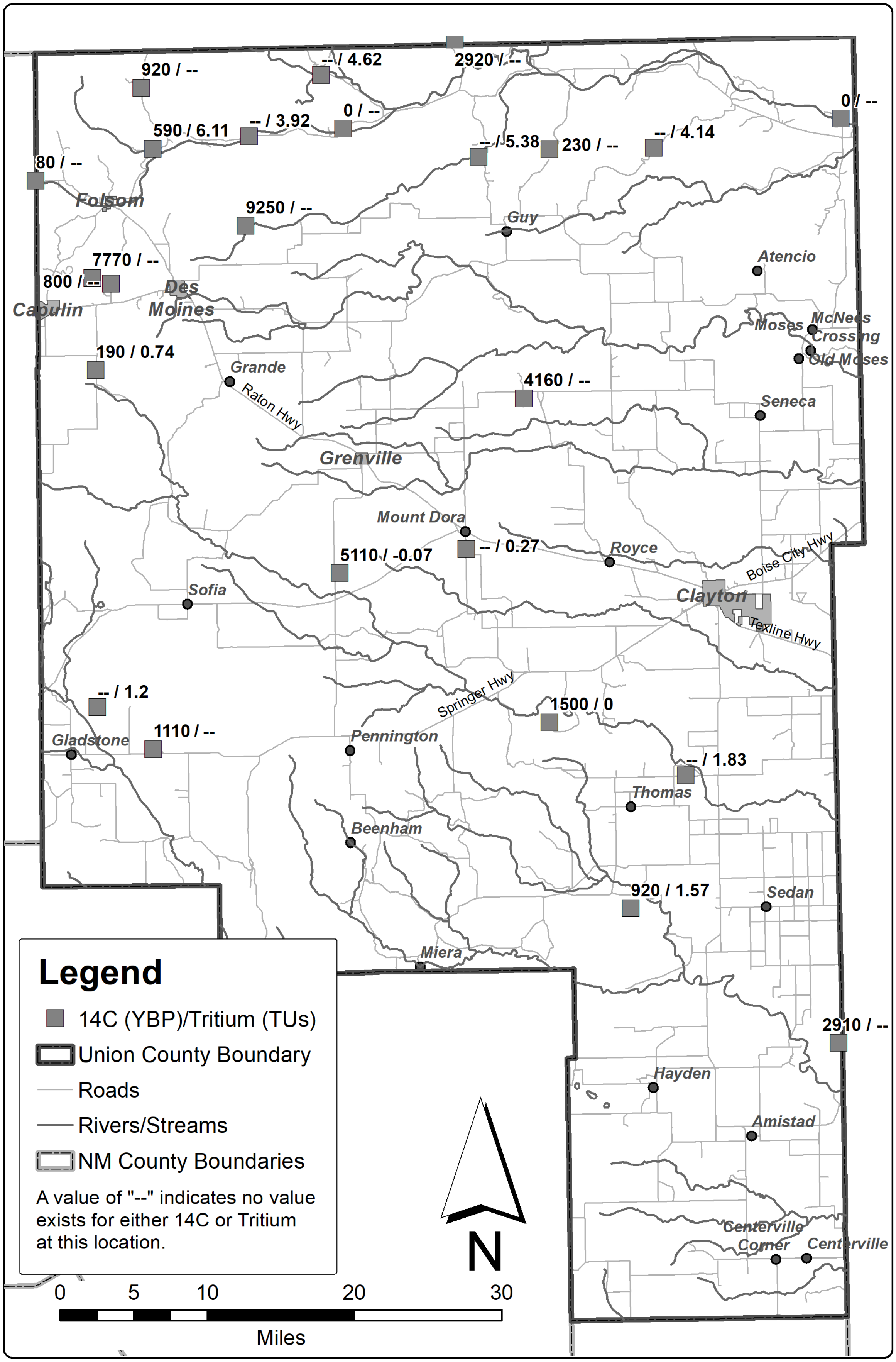

FIGURE 7. Map of Union County showing ^{14}C and tritium results for selected wells. YBP = years before present. TUs = tritium units.

TABLE 2. Table showing ^{14}C and tritium results. Abbreviations: pMC = percent modern carbon, YBP = years before present, TU = tritium units, (ND) = non-detectable. Hydrostratigraphic unit abbreviations are the same as for Table 1.

ZGC ID	pMC	pMC error	Apparent ^{14}C Age	Tritium (TU)	Trititum error	Inferred Hydrostratigraphic Unit(s)
24.29.17.414	87.1	0.3	1110			Kd
28.28.10.222	97.7	0.4	190	0.74	0.09	Kd
28.33.22.133	59.6	0.2	4160			Kd
31.33.25.331	97.2	0.4	230			Je
31.37.18.424	101.4	0.4	0			Qal/Trd
ZGC_2	92.9	0.3	590	6.11	0.2	Qal
ZGC_3	89.2	0.3	920			Kd/Kg
ZGC_8	38.0	0.2	7770			Kd
ZGC_9	90.5	0.3	800			Kd
ZGC_12	31.6	0.2	9250			Kd/Jm?
ZGC_14	99.0	0.4	80			Qb (spring)
ZGC_17	102.5	0.4	0			Qal/Trd
ZGC_19				5.38	0.18	Qal/Trd
ZGC_23				4.62	0.15	Qal/Trd
ZGC_24				1.20	0.09	Kd
ZGC_25				3.92	0.13	Qal/Trd
ZGC_26				1.83	0.09	To/Kd
ZGC_27				0.27	0.09	Kd
ZGC_28	52.9	0.2	5110	-0.07 (ND)	0.09	Kd
ZGC_29	89.2	0.3	920	1.57	0.09	Kd/Jm
ZGC_30	83.0	0.3	1500	0.00	0.09	Jd/Jm
ZGC_31	69.6	0.3	2910			To
ZGC_32	69.5	0.3	2920			Qal/Trd
ZGC_33	99.1	0.4	70			Qal/Trd
ZGC_34	102.1	0.4	102			Qal/Trd
ZGC_35				4.14	0.14	Qal

opment of groundwater quantity and quality data sets, indicate that this assumption is unfortunately not true. In addition, the hypothesis of Cooper and Davis (1967) is also incorrect in that the source of all recharge to the Ogallala and other bedrock units is precipitation falling on outcrops of these units.

The slow decline in well yields, as well as the increasing depth to the water table in the majority of wells in the county, is the first indicator that the "oceans of water" are simply not present. Geologic mapping and development of cross-sections from petroleum and water well log data indicate that the subsurface is considerably more complex than the landscape might otherwise indicate (Baldwin and Muehlberger, 1959; Rawling, 2013). The cumulative effect of a variety of structural and lithologic features results in a series of aquifer systems that are effectively partitioned from one another. Communication between aquifers is limited by the presence of low permeability zones such as thick mudstone sequences in the Morrison Formation or shale zones in the Dakota Group. In addition, lateral lithologic heterogeneity, folding of the Dockum Group, infilling of erosional landscapes, emplacement of volcanic features and the development of structural relief along the Clapham anticline and southeastern margin of the Bravo Dome, all contribute to a lack of lateral continuity. The ^{14}C and tritium results underscore that groundwater resources in most of Union County are not renewable on human timescales and thus the discharge of groundwater from wells for domestic and agricultural uses far exceeds the rate of potential recharge.

Producers have observed this lateral and vertical complexity when attempts to drill and develop new wells result in dry holes or considerably lower yield than observed in nearby established wells. In considering the complexity of the hydrostratigraphic units in the Union County area, it is not unreasonable to think that an older well that has a history of reasonable production is located in a relatively isolated "bathtub" and the attempt to drill a new well nearby that results in a dry hole indicates that the new well is located over a portion of the sequence dominated by mudstones and shales.

Combined water chemistry and residence time evaluations suggest the following patterns. Ogallala and Dakota wells generally have lower TDS values and $Ca+HCO_3$ water types, but low tritium and higher ^{14}C values that suggest moderately long residence times. Morrison wells show two patterns: 1) high TDS, $Na+HCO_3$ water types and low tritium values or 2) moderate TDS, $Na+HCO_3$ water types and moderate tritium values. Morrison wells exhibiting the first pattern generally have deeper water tables and consistently declining hydrographs, whereas those with the second pattern have shallower water tables (all are also located adjacent to Tramperos Creek with exposures of Morrison Formation) and variable behavior in their hydrographs, suggesting that these shallower wells can receive recharge. Dockum wells have high TDS values, mixed cation-anion water types, higher tritium values and lower ^{14}C values. These wells are all generally shallow and located in canyon bottoms and/or adjacent to the Dry Cimarron.

SUMMARY

Repeated regular static water level data, results from analysis of water samples for major element chemistry, tritium and ^{14}C, along with continued geologic mapping and well log information continue to shed light on the groundwater resources of Union County. The combination of lithologic heterogeneity, paleotopography and structural features in the subsurface results in an effectively partitioned system of aquifers. Water types, coupled with tritium results and average residence times, suggest that any volumetrically significant recharge to the various aquifers beneath Union County occurs much more slowly than human-induced discharge.

A unique feature of the work currently in progress to understand the aquifers of Union County is the development of the project by the stakeholders. The NESWCD started the well monitoring program and oversaw the addition of data sets including geologic mapping, well log data, installation of data loggers and analyses of water samples. The agricultural producers of the county have guided the continued growth of the project, with individual landowners contributing observations regarding well behavior over time, as well as assisting in determining appropriate wells to be used for long-term monitoring. This collaboration with landowners has led to difficult decisions being made regarding groundwater conservation.

Overall, the hydrogeology of Union County is complex and there is further data required to fully understand the hydrologic cycle of the area. Future work includes comparison of stable isotope data for select groundwater samples (Blumenberg, 2018) to precipitation samples currently being collected, as well as continued detailed geologic mapping and monitoring of static water levels. One goal of this project is to develop enough of an understanding of the aquifer systems in the county to assess potential locations for future well development, as well as areas to avoid in order to minimize continued diminishment of the groundwater resources in an area (e.g., Sedan).

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