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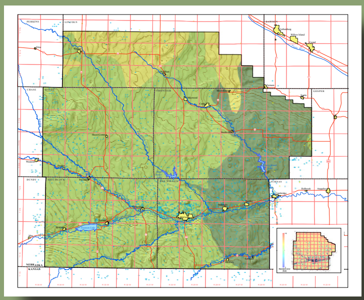
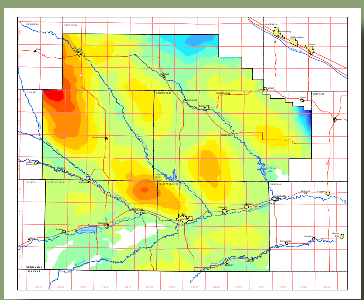
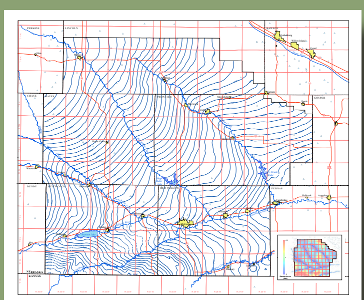
Maps showing the Physical Hydrogeology and Changes in Saturated Thickness (Predevelopment to Spring 2016 and Spring 2011 to Spring 2016) in the Middle Republican Natural Resources District, Southwestern Nebraska.

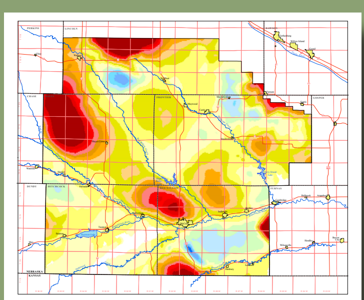
Jesse T. Korus Dr.
University of Nebraska-Lincoln, jkorus3@unl.edu

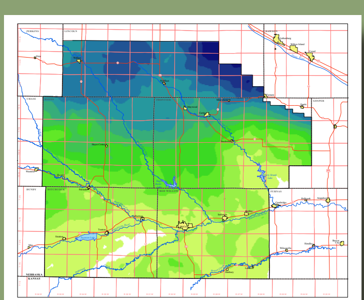
Leslie M. Howard
University of Nebraska - Lincoln, lhoward3@unl.edu











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Conservation and Survey Division
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Resource Atlas Number 12

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Phone: 402-472-3471
Fax: 402-472-2946
Email: snrsales@unl.edu
Website: nebraskamaps.unl.edu

Contents and Figures

Abstract 2
Introduction 2
    Purpose and Scope 2
    Previous Hydrogeologic Maps 3
Physical Setting 3
    Physiography and Soils 3
    Geology 4
    Hydrogeology 5
Data Sources and Analysis 5
    Borehole Logs 5
    Estimation of Hydraulic Conductivity and Transmissivity 6
    Groundwater Levels 6
Geostatistical Methods 7
Post-Processing 8
Results 8
    Base of the Principal Aquifer (Plate 1) 8
    Predevelopment Water Table (Plate 2) 9
    Predevelopment Saturated Thickness (Plate 3) 9
    Spring 2016 Water Table: Method A (Plate 4) 9
    Spring 2016 Saturated Thickness: Method A (Plate 5) 9
    Change in Saturated Thickness: Predevelopment to Spring 2016 (Plate 6) 9
    Percent Change in Saturated Thickness: Predevelopment to Spring 2016 (Plate 7) 9
    Spring 2011 Water Table (Plate 8) 10
    Spring 2011 Saturated Thickness (Plate 9) 10
    Spring 2016 Water Table: Method B (Plate 10) 10
    Spring 2016 Saturated Thickness: Method B (Plate 11) 10
    Change in Saturated Thickness: Spring 2011 to Spring 2016 (Plate 12) 10
    Percent Change in Saturated Thickness: Spring 2011 to Spring 2016 (Plate 13) 10
    Transmissivity of the Principal Aquifer (Plate 14) 11
Limitations and Intended Use 11
Explanation of Digital GIS Files 12
References 13

Figure 1 Generalized stratigraphic column showing the stratigraphic units present beneath the Middle Republican Natural Resources District 4
Figure 2 Decision tree used to assign quality-assessment ranks to boreholes 6
Table 1 Generalized Geologic and Hydrostratigraphic Framework of Nebraska 7
Table 2 Explanation of GIS files 12

Abstract

This report accompanies fourteen new maps summarizing the hydrogeology and changes in saturated thickness in the Middle Republican Natural Resources District (MRNRD). The purpose of these maps is to assist the MRNRD in their groundwater management programs and in planning and installing an observation well network. Maps include:

- base of the principal aquifer;
- water table surfaces for predevelopment, Spring 2011, and Spring 2016;
- saturated thicknesses for predevelopment, Spring 2011, and Spring 2016;
- changes in saturated thickness (both in absolute magnitude and in percent) from predevelopment to Spring 2016 and from Spring 2011 to Spring 2016;
- transmissivity.

A series of comprehensive datasets was assembled from borehole logs and groundwater-level measurements. Borehole logs were assessed for quality using systematic procedures. Maps were generated using ordinary kriging (base of aquifer, transmissivity) and co-kriging (water table surfaces), and raster files were subtracted to derive the saturated thickness and change maps. Saturated thickness decreased as much as 35 ft from predevelopment to 2016, and as much as 10 ft from 2011 to 2016. Percentage decreases were as much as 40% from predevelopment to 2016 and as much as 10% from 2011 to 2016. Increases in saturated thickness occurred near surface water development projects north of the MRNRD, and were as much as 36 ft (15%) from predevelopment to 2016. Increases from 2011 to 2016 occurred in a few small areas, and were as much as 3 ft (5%). The calculated change in saturated thickness was highly variable between the two time periods in areas of sparse data and where the aquifer is thin. Digital GIS files are provided as part of this report for use in models, maps, and related hydrogeologic analyses.

Introduction

Purpose and Scope

The Middle Republican Natural Resources District (MRNRD) is one of 23 locally governed Natural Resources Districts (NRDs) in Nebraska. The NRDs are responsible for developing, managing, and conserving groundwater and a variety of other natural resources such as soil and wildlife habitat. NRDs rely on hydrogeologic maps and other information to develop management plans and monitoring programs for groundwater and interconnected surface water. The last comprehensive hydrogeologic assessment of the MRNRD (excluding the area south of the Republican River) was published in 1992 (Goeke et al. 1992). Groundwater conditions, data availability, and mapping methods have changed dramatically since that publication. Moreover, the MRNRD seeks to improve their monitoring program by installing new groundwater-level observation wells at strategic locations informed on the basis of hydrogeologic characteristics, changes in saturated thickness, and gaps in data coverage. This current study provides a series of up-to-date maps for the MRNRD showing aquifer properties, including base of the principal aquifer, water table elevation, saturated thickness, and transmissivity.

Previous Hydrogeologic Maps

Several maps were published before the 1970s for localized areas defined by drainage basins covering parts of the MRNRD. Water table elevation and saturated thickness maps were published by Johnson (1960) for the northern part of the MRNRD, north of the Republican River and east of Blackwood Creek. The water levels used to construct the maps were taken from measurement campaigns during 1948–1952. Cardwell and Jenkins (1963) mapped portions of the Frenchman Creek Basin. These maps included bedrock geology, surficial geology, and water table elevation. Groundwater levels used to map the water table were measured during the summer of 1952.

In 1979, the Conservation and Survey Division (CSD) at the University of Nebraska-Lincoln published a series of maps for the entire state of Nebraska showing the basal surface of the principal aquifer and the water table elevation based on 1979 readings (CSD 1979). The water table map was later updated to reflect groundwater levels as they existed in 1995 (Summerside et al. 2001).

The first comprehensive, regional studies of the High Plains/Ogallala aquifer system (HPA) were completed in the early 1980's (Pettijohn and Chen 1983a, 1983b; Gutentag et al. 1984). Maps contained in these reports include geologic units in the aquifer, bedrock units underlying the aquifer, aquifer properties, water table elevation maps, and changes in saturated thickness from predevelopment to 1980. These maps are presented at a regional scale and show hydrogeologic features generalized over the entire state, or in the case of the maps in Gutentag et al. (1984), over the eight-state area of the HPA.

Eversoll et al. (1988) published a geologic map covering an area encompassing all of the MRNRD. The map shows the distribution of geologic units as well as the elevation of the bedrock surface, which was defined as the top of the Ogallala Group, or where the Ogallala is absent, the top of the White River Group or Cretaceous geologic units.

A hydrogeologic study specific to southwest Nebraska, including parts of the MRNRD north of the Republican River, was completed in 1992 (Goeke et al. 1992). It gives detailed descriptions of the area, including climate, land use, surface water, soil water, groundwater, and water quality. It also includes maps of the base of the aquifer, water table elevation, saturated thickness, and transmissivity. Water-level data were measured in wells during the springs of 1977 and 1978. Geologic data for these maps were assembled from test holes drilled by the Conservation and Survey Division prior to 1980. The density of the test-hole data was about one data point per 36 mi^2.

Several recent publications contain maps for all or parts of the MRNRD. Korus et al. (2013) published a revised water table elevation map for the High Plains aquifer in Nebraska using 25,000 measurements taken during the springs of 2000 to 2012. McGuire (2017) published a map showing changes in water levels in the High Plains aquifer in the Republican River Basin in Colorado, Kansas, and Nebraska from 2002 to 2015. Divine and Eversoll (2018) published hydrogeologic maps for Red Willow County.

Physical Setting

Physiography and Soils

The MRNRD lies generally within the Plains and Dissected Plains topographic regions of Nebraska (Korus et al. 2013). The main topographic elements are low-relief, loess-mantled uplands with deep, silty loam to silty clay loam soils (Mollisols). Some upland areas in the northwestern part of the MRNRD are overlain by sand dunes with undulating, hummocky topography. Soils atop dunes are weakly developed and highly permeable (Entisols). The uplands are locally dissected by river valleys, tributary streams, and numerous small drainages. These areas are characterized by steep-sided canyons and valley side-slopes with thin soils susceptible to erosion. Bottomland and terraces along river valleys are generally flat to gently sloping with silty soils. Additional details of the soils and land use characteristics can be found in Goeke (1992) and NRCS, USDA (2006; 2018).

Geology

Although older bedrock units are present beneath the area, Cretaceous units make up the lower confining unit of the aquifer system over most of the study area (Figure 1; Plate 1). The oldest of these Cretaceous units is the Niobrara Formation, which comprises marine shale, chalk, marl, and chalky limestone, with thin beds of bentonite (Divine et al. 2017). The Niobrara Formation varies in thickness from 50 to 500 feet in the MRNRD (Burchett, 1992; Goeke et al. 1992).

The Pierre Shale overlies the Niobrara Formation in the central and western MRNRD and is composed of shale with minor shaly chalk, siltstone, sandstone, and bentonite. The Pierre Shale is absent in the eastern MRNRD where it has been eroded atop the Chadron-Cambridge Arch (Condra and Reed, 1959), but is more than 1000 ft. thick in the western MRNRD (Shurr 1977). The top of this unit is commonly a well-developed, yellowish or reddish paleosol or weathered zone that grades to dark gray with depth.

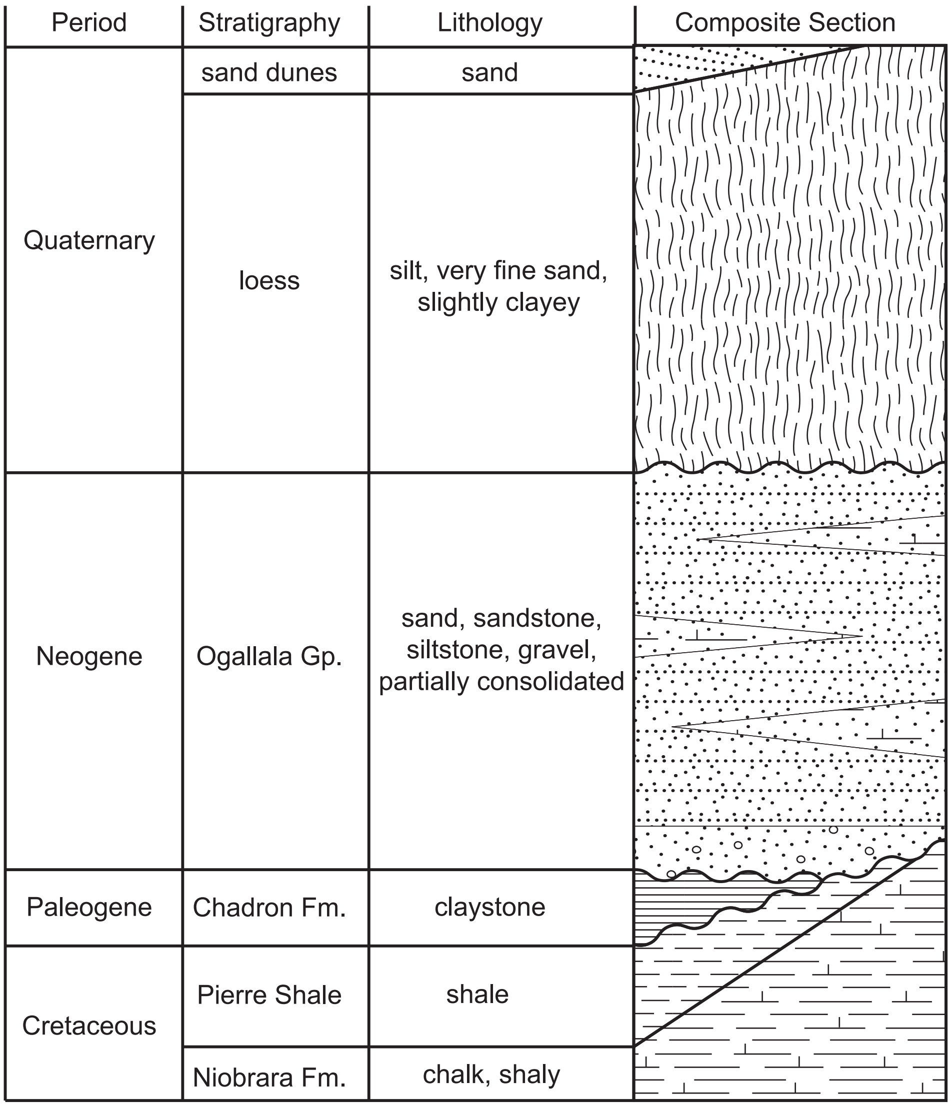

Figure. 1. Generalized stratigraphic column showing the stratigraphic units present beneath the Middle Republican Natural Resources District.

The Pierre Shale is overlain by the Chadron Formation of the White River Group (Paleogene) in parts of the northern MRNRD. The Chadron Formation is composed primarily of claystone, but some minor sandstone and siltstone exist locally. The maximum thickness of the Chadron encountered in test holes in the MRNRD is 77 ft. It is discontinuous throughout the northern part of the study area and is completely absent in the central and southern parts.

The Ogallala Group (Neogene) comprises semi-consolidated sand and silt, sandstone, siltstone, and minor gravel and conglomerate, and is the principal aquifer in the study area. The silt and sand are calcareous, and the sandstone is predominantly carbonate-cemented, although some silica-cemented sandstone layers exist. Volcanic ash beds occur locally (Eversoll et al., 1988). Rare carbonate and diatomite are known from the Ogallala nearby (Joeckel et al., 2004; 2014). The base of the Ogallala is a gently sloping, eastward-dipping surface. Outcrops of the Ogallala can be observed along valley margins, in gulleys and ravines, and along the shores of some man-made reservoirs such as Hugh Butler Lake. Except for a few, local remnants, the Ogallala is absent beneath the valleys of the Republican River and the lower portions of its main tributaries (Eversoll et al. 1988).

The Ogallala is overlain by a thick (~ 100 ft) succession of late Pleistocene-early Holocene loesses and Holocene sand dunes. Loess units consist predominantly of silt, clayey silt, and very fine sand. Holocene sand dunes are present locally atop the loess in parts of Hayes County and in most of southwestern Lincoln County. River valleys contain ~ 65 – 100 ft of sandy to silty alluvium atop Cretaceous bedrock.

Hydrogeology

The Cretaceous units are generally impermeable and define the base of the aquifer system in most areas. Depth to Cretaceous bedrock is as much as 650 ft below ground surface in the northern part of the MRNRD, but these units exist at or near the surface in some areas along the margins of the Republican River valley and its tributaries. The Niobrara Formation directly underlies the principal aquifer in the eastern one-third of the MRNRD where the Pierre Shale is absent. The Niobrara Formation is primarily a confining unit, but relatively high porosity and permeability may exist locally within the weathered zone at the top of the unit. It is possible that this part of the unit could yield water to wells, especially if it exists at shallow depths (<100 ft.) (Divine and Sibray, 2017). There are no wells, however, known to draw water from the Niobrara in the MRNRD. The Pierre Shale is the confining unit at the base of the aquifer over most of the western two-thirds of the MRNRD. The Chadron Formation is the basal confining unit in parts of the northern MRNRD.

The Ogallala Group is the principal aquifer in the MRNRD. The entire Ogallala Group is saturated in Lincoln County, but south of there the water table is below the top of the Ogallala. The Ogallala is mostly unsaturated in part of the uplands in southeastern Red Willow County and southeast of Harry Strunk Lake in Frontier County. Hydraulic properties vary greatly over short distances, both vertically and laterally, due to the heterogeneity of the deposits and the varying degrees of cementation. Thick (> 30 ft) hydrostratigraphic units have been mapped at scales of 100’s of km^2 in Kansas using driller’s logs (Macfarlane 2009). It is likely that similar techniques could be applied to the present study area to map patterns of heterogeneity, but no such studies have yet been conducted.

Alluvial deposits in the Republican River valley and the lower portions of its main tributaries support approximately 800 irrigation wells. Cross sections through the Republican River valley by Goeke et al. (1992) and Divine et al. (2018) show that the alluvial aquifer is likely in hydrologic connection with the Ogallala aquifer because the alluvial sediments either abut the Ogallala or overlie it.

Data Sources and Analysis

Borehole Logs

Elevations of the base of the principal aquifer were interpreted from descriptions of geologic materials encountered in boreholes. Data were assembled from CSD test holes, water well records from the Department of Natural Resources, and water well records from the Kansas Geological Survey. Data was obtained for the Middle Republican Natural Resources District (MRNRD) and the surrounding area within a minimum of 3 miles of the MRNRD boundary. For each borehole or well used in the analysis, the land surface elevation was extracted from a 10-meter digital elevation model (DEM) obtained from the U.S. Geological Survey (USGS).

The quality of information contained in each borehole log was ranked based on several criteria (Fig. 2). The criteria relate to the depth of the borehole, the source of the lithology description, the quality of the description, and the quality of the location information. Rank 1 is assigned to the highest quality borehole data, and rank 5 is assigned to the lowest quality. The rank provided a guide for determining which boreholes should be omitted from the dataset during later analysis and interpolation. All rank 5 boreholes were omitted because they either did not fully penetrate the geologic

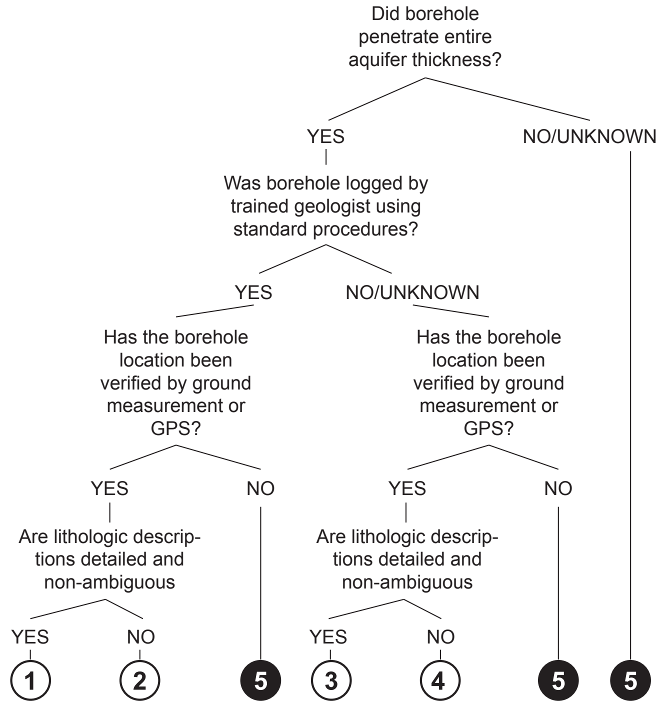

Figure 2. Decision tree used to assign quality-assessment ranks to boreholes.

units of interest or they lacked accurate location information. Oil and gas wells from the Nebraska Oil and Gas Conservation Commision (NOGCC) were reviewed for information on stratigraphy and lithology, but these data proved to be unreliable so they were not included in the present study.

Estimation of Hydraulic Conductivity and Transmissivity

Estimates of hydraulic conductivity *(K)* were derived from lithologic descriptions using a table that relates geologic materials to hydrogeologic properties (Appendix A). These relationships have been derived from previous studies, aquifer tests in Nebraska, as well as values from the literature (Piskin, 1971). The table was developed by CSD geologists over many years and has been used in numerous hydrogeologic studies in Nebraska. It is considered by local hydrogeologists to be a useful approximation of *K* for aquifers in this region (Goeke et al. 1992; Summerside et al. 2005).

Transmissivity, *T*, for each borehole is calculated by summing the transmissivity for each saturated unit described on the lithologic log. It is expressed as:

$$T = \Sigma(K_i b_i)$$

where K_i is the hydraulic conductivity of an individual layer and b_i is the thickness of the layer (e.g. Javandel and Witherspoon 1969; Freeze and Cherry 1979). After a transmissivity value is calculated for each borehole, the transmissivity across the aquifer can be interpolated.

Groundwater Levels

Water-level data used to make the accompanying maps are within the Middle Republican NRD and at least a surrounding six-mile buffer. Data were assembled from a wider buffer in the northeastern corner of the study area because data were sparse within the six-mile buffer. Water-level data for Nebraska were obtained from the Conservation and Survey Division groundwater-level database (CSD, undated). Geographic coordinates for wells in the MRNRD were obtained from a database updated and maintained by the MRNRD. Water-level data for Kansas were obtained from the U.S. Geological Survey National Water Information System (NWIS; USGS undated).

Water-level data represent measurements of the depth to water in wells using an electric, steel, or fiberglass tape. Groundwater levels are measured generally during the spring when most irrigation wells are idle. One well (USGS ID 405557100564501) is located near the Nebraska Cooperative Republican Platte Enhancement (NCORPE) augmentation wells, which were pumped during the winter of 2016. The spring measurement reflects drawdown from the pumping. The fall 2015 measurement, however, was not affected by the pumping and so this measurement was used to represent the static water level at that site. A few measurements from other wells were taken during the late fall of 2015 or early summer of 2016. Most (93%) of the measurements were made during the period from March to early June. If several measurements were made in the same well for any given year (defined as October 1 to September 30), the earliest of these measurements was used as the representative value for that year.

Measurements are reported to the CSD and USGS by local, State, and Federal agencies. These data have been checked for quality and consistency (Young et al. 2016; McGuire 2017). Some wells were omitted from the dataset because of discrepancies in the locations of the wells or because the data was highly anomalous compared to local pumping practices and surrounding wells.

To facilitate direct comparisons of the water table surfaces from two periods, only those wells with measurements for both periods were used to generate surfaces. The Spring 2016 water table was mapped using two methods. Method A employed only those wells which were measured in 2016 and contained an estimate of the water level prior to large-scale irrigation development (i.e. predevelopment). Method B employed only those wells that were measured in both 2011 and 2016. Method B resulted in a greater number of data points, and is therefore considered a more reliable estimate of the water table surface as it existed in 2016.

The groundwater-level database used in this study also contains point data defining imposed heads along streams. These values are the inferred head elevations at the point where the water table meets the paths of perennial streams. Using stream elevations in the interpolation helps prevent the estimated water table surface from lying above the land surface in stream valleys (Guekie simo et al. 2016).

Geostatistical Methods

Geostatistical analyses were completed using ESRI Geostatistical Analyst™ tool in ArcMap™ 10.5.1. Ordinary kriging and cokriging methods were used to generate interpolated surfaces from point data. Various textbooks provide detailed treatment of these methods (e.g. Davis 1986; Isaaks and Srivastava 1989).

The water table surfaces were interpolated using cokriging. Hyraulic-head elevation was the primary variable and land surface elevation was the secondary variable. Comparison of results generated via ordinary kriging with those from cokriging showed that cokriging produced more realistic results. For example, it reduced the size and number of areas where the estimated water table elevation was higher than the land surface elevation. The advantages of cokriging for water table mapping have been described by several authors (Hoeksema et al. 1989; Boezio et al. 2006; Ahmadi and Sedghamiz 2008; Guekie simo et al. 2016).

Outliers were identified by reviewing experimental variograms for each dataset. Outliers were checked for errors, which were corrected if possible. Anomalous data were removed from the dataset. For borehole data, the ranking scheme provided the basis for determining whether or not to omit certain outliers. Outliers corresponding to boreholes with lower-quality rankings were more likely to be eliminated from the dataset.

A best fit variogram model was obtained for each dataset by systematically adjusting the kriging parameters to minimize the mean squared error and obtain a mean squared deviation ratio as close to one as possible (Oliver and Webster 2014). Parameters that were adjusted included model type (i.e. Exponential, Power, Gaussian, Stable), range, lag size, and number of bins. The final parameters and errors of the kriging and cokriging analyses are shown in Table 1. The prediction standard error (PSE) is shown as an inset on the maps in this report. PSE is the square root of the variation associated with the difference between the true and predicted value. It describes the uncertainty associated with the prediction maps.

Table 1. Parameters and results of kriging and cokriging interpolations.

Data set[1]	Samples	Units[2]	Method	Model	Lag distance	Lags	Major range	Nugget	Partial Sill	M E[3]	RMS E[3]	M SE[3]	RMS SE[3]	Avg SE[3]
BoA	3640	ft. a.s.l.	Ordinary with trend removal	Stable	1000	23	5,606	196.5	65.2	-0.028	23.165	-0.001	1.442	15.831
WT PDV	511	ft. a.s.l.	Cokriging	Stable	33,068	12	247,815	58.63	58,630	1.032	16.724	0.116	1.579	9.385
WT 2016a	511	ft. a.s.l.	Cokriging	Stable	33,068	12	247,815	57.39	57,390	0.795	15.800	0.127	1.451	9.285
WT 2011	616	ft. a.s.l.	Cokriging	Stable	36,402	12	251,890	56.46	54,784	1.690	19.273	0.176	2.049	9.005
WT 2016b	616	ft. a.s.l.	Cokriging	Stable	36,402	12	251,890	56.38	54,689	1.699	19.640	0.175	2.085	8.999
T	3630	gallons per day per foot	Ordinary kriging	Stable	5700	12	11,691	0.001	0.004	-0.0004	0.07	-0.004	1.118	0.062

[1] Abbreviations for data sets: BoA (base of aquifer), WT PDV (predevelopment water table), WT 2016a (2016 water table using only those wells with predevelopment water levels [Method A]), WT 2011 (2011 water table), WT 2016b (2016 water table using only those wells with 2011 water levels[Method B]), *T* transmissivity.

[2] ft. a.s.l.: feet above sea level

[3] Abbreviations for errors: M E (mean error), RMS E (root-mean-square error), M SE (mean standardized error), RMS SE (root-mean-square standardized error), Avg SE (average standard error)

Post-Processing

Several post-processing procedures were applied to raster output files generated from the geostatisical interpolations. The final steps for all files included a smoothing operation using the Focal Statistics tool in ArcMap™ 10.5.1. Then each grid was clipped to the MRNRD boundary. For the base of aquifer and water table maps, contour lines were generated from the final raster file after all processing steps were complete.

The initial model for the base of the principal aquifer was higher than the land surface elevation in less than 0.2% of the model area. These errors typically occur along valley sides with large changes in land surface elevation. For those areas, a limit filter was executed such that the elevation of the base of aquifer was replaced with the value for the land surface elevation. Similarly, the initial models for the water table surfaces were higher than the land surface in a few areas near streams. For the predevelopment water table, this error occurred in about 13% of the raster cells within the entire model area, although many of the errors occurred outside the MRNRD boundary. For the 2016a, 2016b, and 2011 water table models, about 3% of the raster cell values were in error. A limit filter replaced the water table elevation in these cells with the land surface elevation. The water table surfaces were also lower than the base of aquifer in about 6% of the raster cells for all water table models. These errors occurred in areas near the Republican River where groundwater-level data are sparse and the aquifer is very thin. A limit filter replaced the water table elevation in these cells with that of the base of aquifer.

Saturated thickness maps were computed by subtracting the base-of-aquifer elevation from the water table elevation. Changes in saturated thicknesses were computed by subtracting the 2016 saturated thickness from the saturated thickness in the previous period (predevelopment or 2011). The percent change in saturated thickness was computed by dividing the change in saturated thickness by the saturated thickness from the earlier period (predevelopment or 2011). Because the saturated thickness is very thin in some areas, a small change in the water table elevation resulted in some very large percent changes, especially on the margins of the aquifer in the southern MRNRD. Maximum and minimum values were set for each raster by examining a histogram of values and determining a cut-off for outliers. Values above and below these limits were replaced with the maximum and minimum values using a bandpass filter.

Results

Base of the Principal Aquifer (Plate 1)

The base of the aquifer is defined by one of three geologic units, depending on location. The distribution of these units was modified from Goeke et al. (1992). The extent of the White River Group was changed on the basis of descriptions in driller's logs and CSD test holes.

The base of the aquifer is generally a low-relief surface that slopes gently east-northeast. Several low-relief ridges and troughs are identified. One ridge extends from west-central Hayes County to east-central Frontier County. The crest of the ridge is irregular and discontinuous. Nonetheless, it generally separates a southern area where the slope of the surface is toward the Republican River and a northern area that slopes toward the Platte River. A low-relief trough trends west-east from southern Lincoln County near Wallace to northern Frontier and southern Lincoln County near Curtis, Moorefield, and Farnam. Another gentle, west-east trough extends from central Hayes County to southwestern Frontier County near Hugh Butler Lake. The base of the aquifer is highly irregular in Hitchcock and Red Willow Counties where it has been reshaped by erosion under recent stream valleys.

The largest uncertainties in the interpolated base of the aquifer are in the north where borehole data is sparse. Uncertainties are lower in the valleys where numerous boreholes have been drilled to the Cretaceous units under the aquifer.

Predevelopment Water Table (Plate 2)

The interpolated water table surface represents average static water level conditions prior to large-scale irrigation development (before 1960). A total of 511 data points were used in the analysis, including 212 measurements from observation wells and 299 imposed heads along stream courses. Prediction errors ranged from 2 – 13 ft, with the highest errors in the southwestern corner of the MRNRD.

The water table surface generally slopes southeastward north of the Republican River. Contours bow gently southeastward between streams, indicating the streams were generally gaining. South of the Republican River, the water table surface slopes northeastward, although data is sparse in this area. Some of the irregularities in the water table in this area are due to the effects of filtering during post-processing (described above). The contours south of Trenton, for example, match the contours on the base of the aquifer because there is little or no saturated thickness in this area.

Predevelopment Saturated Thickness (Plate 3)

Saturated thickness before irrigation development varied from as much as 500 ft in the northeast to little or no saturated thickness south of the Republican River. The areas of little or no saturated thickness are those areas where the interpolated water table elevation was equal to or less than the elevation of the base of aquifer.

Spring 2016 Water Table: Method A (Plate 4)

The purpose of this map is to compute changes in saturated thickness between predevelopment and 2016. As such, only those wells that contain both predevelopment and 2016 water-level measurements were used to generate this water table surface, so the locations of the data points are the same in both maps. Prediction errors ranged from 2 – 12 ft with a distribution similar to the predevelopment water table map.

The overall shape of the contours is similar to the predevelopment water table. A notable difference, however, is that the gentle southeastward bow of water table contours between streams is less pronounced than in the predevelopment map. Contours are straight or slightly bowed westward in the area between Frenchman Creek and Red Willow Creek between Hayes Center and McCook.

Spring 2016 Saturated Thickness: Method A (Plate 5)

Saturated thickness computed using the 2016 water table (method A) shows a similar overall pattern to the predevelopment saturated thickness. However, the aquifer has become thinner throughout most of the MRNRD, except in northeastern parts of the district.

Change in Saturated Thickness: Predevelopment to Spring 2016 (Plate 6)

Saturated thickness decreased throughout most of the MRNRD from predevelopment to 2016. The largest decreases were in northwestern Hayes County, where groundwater levels declined 30 – 35 ft. Declines of more than 15 ft occurred in a large area west of Hayes Center to near the northwestern corner of the MRNRD. Saturated thickness declined between 5 – 20 ft. in the area between Indianola and Stockville.

Saturated thickness declined 15 – 30 ft in an area north of McCook and Culbertson. These declines are related to cessation of flows in the Culbertson Extension Canal and in the Hitchcock and Red Willow (H&RW) canal system in 2002. Water was diverted into these canals from the 1950's to 2002, providing a source of artificial recharge to the area. During this period, many irrigation wells were installed in the same area. These wells continued to extract groundwater after 2002, despite the loss of the canal recharge. As a result, the water table has declined rapidly.

Increases in saturated thickness occurred in some areas. Northeast of Wellfleet, increases are related to a large groundwater mound that has formed in Lincoln County from seepage through Sutherland Canal, Sutherland Reservoir, and Lake Maloney north of the MRNRD (Goeke et al. 1992; Young et al. 2016). The increased thickness in the easternmost part of the MRNRD near Eustis resulted from seepage through the Tri-County Canal and related storage reservoirs in Dawson and Gosper Counties (Goeke et al. 1992; Young et al. 2016).

Percent Change in Saturated Thickness: Predevelopment to Spring 2016 (Plate 7)

The percent change in saturated thickness from predevelopment to 2016 shows a much different pattern than the magnitude of change. The area of large magnitude (30 – 35 m) decline in Hayes County represents 5 – 15% less saturated thickness in 2016 than in predevelopment. The area north of McCook and Culbertson, however, has been reduced by 15 – 40% since predevelopment, despite experiencing declines of less than 30 ft.

The areas south of the Republican River and near Harry Strunk Lake show widely varying changes. These areas correspond to areas of little or no saturated thickness and so changes of just a few feet represent very large percentage changes.

Spring 2011 Water Table (Plate 8)

The 2011 water table was interpolated using 616 data points, including 317 measurements from wells that were measured in 2011 and again in 2016, as well as 299 imposed heads along stream courses. Prediction errors ranged from 2 – 11 ft. Errors are highest in the northeast and south of the Republican River. Error in the southwest corner of the MRNRD is lower than in the predevelopment and 2016 (method A) maps, primarily because several additional observation wells were available for that area in the 2011 map.

Contours show a pattern of southeastern groundwater flow north of the Republican River and northeastern flow south of the Republican River. The water table slopes southward in the easternmost MRNRD east of Stockville. Contours bow gently southeastward between streams, except for the area between Frenchman Creek and Red Willow Creek east of Palisade.

Spring 2011 Saturated Thickness (Plate 9)

Saturated thickness in 2011 varied from as much as 550 ft in Lincoln County northeast of Moorefield, to little or no saturated thickness south of Trenton and Culbertson, and near Harry Strunk Lake. The increase in maximum thickness over the 2016 (Method A) map is due to the use of additional observation wells in the northeast for mapping the 2011 water table.

Spring 2016 Water Table: Method B (Plate 10)

The 2016 water table (Method B) was interpolated using data from the same set of wells and imposed heads as the 2011 water table. Prediction errors ranged from 2 – 11 ft and are nearly identical to the 2011 map. Notable differences in the contours occur north of Highway 23, where the slope of the water table changed from east-southeast to east. In the entire area between Frenchman Creek and Red Willow Creek, the eastward bow of contours became more subdued between 2011 and 2016. North of Culbertson the 2016 contours bow slightly westward between the streams.

Spring 2016 Saturated Thickness: Method B (Plate 11)

The range and pattern of saturated thicknesses are similar across the MRNRD in 2011 and 2016. Minor differences can be observed north of Highway 23, west of Hayes Center, and north of McCook.

Change in Saturated Thickness: Spring 2011 to Spring 2016 (Plate 12)

Changes in saturated thickness ranged from a decrease of 14.4 ft to an increase of 3 ft. The largest decreases occurred north of Highway 23 in Lincoln County, and northwest of Hayes Center in Hayes County. In those areas the water table dropped more than 4 ft. Declines of 2.5 – 4 ft were observed north of McCook, near Farnam, west of Beaver Creek near the Kansas border, and southeast of Bartley. Many areas of the MRNRD had between 0.4 and 2.5 ft of decline. A small area of increase in saturated thickness of as much as 3 ft was observed in Lincoln County southeast of Wallace. Other minor increases of 1 – 1.5 ft occurred near Moorefield and South of McCook and Indianola.

Percent Change in Saturated Thickness: Spring 2011 to Spring 2016 (Plate 13)

The changes in saturated thickness north of Highway 23 and northwest of Hayes Center equate to 1 – 3% decrease from 2011 to 2016. Declines near Farnam are less than 1%. The declines north of McCook, west of Beaver Creek, and southeast of Bartley range from 3 – 10% of the 2011 saturated thickness. Increases of 2 – 5% occurred south of McCook and Indianola. Changes varied drastically along the areas of little or no saturated thickness, mostly because the aquifer is very thin and small-magnitude changes result in large changes in terms of percentage. The remainder of the MRNRD experienced only slight increases or decreases of less than 1%.

Transmissivity of the Principal Aquifer (Plate 14)

Estimated transmissivity ranges from 188 to more than 300,000 gallons per day per foot (gal/day/ft). The largest transmissivity values are in Lincoln County and in northeastern Hayes County. Transmissivities greater than 200,000 gal/day/ft are located in northern Frontier County and Lincoln County between Moorefield and Farnam. Moderately high transmissivities between 50,000 and 150,000 gal/day/ft are located in Hayes County, western and northern Frontier County, northernmost Hitchcock County, and northeastern Red Willow County. Transmissivity was not calculated for areas of little or no saturated thickness in 2016.

Limitations and Intended Use

Saturated thickness was computed from two interpolated surfaces: the water table and the base of the aquifer. Because both surfaces are interpolated from point data with varying density and quality, the actual saturated thickness may be significantly different than the calculated thickness in some areas. Furthermore, there are differences in the density of point data for the water table versus the base of aquifer. For these reasons, the areas of little or no saturated thickness should not be considered areas where the aquifer is absent. The map is not intended to replace site-specific assessment of groundwater conditions. A detailed examination of the groundwater system would be necessary to map the hydraulic boundary at the edge of the aquifer. Evidence such as the presence or absence of wells, springs, perennial stream reaches, and other information would be required to determine the actual limits of the aquifer at the resolution of the maps herein.

The 2016 water table was interpolated using two different data sets. Method A used only those wells with both predevelopment estimates and 2016 water level measurements. Method B used only those wells with measurements from both 2011 and 2016. About 100 fewer data points were used in Method A compared to Method B. Readers should therefore refer to the water table surface generated using method B for a more precise representation of the 2016 water table.

The transmissivity values here compare favorably with those used in the Republican River Compact Administration model (RCRA 2003). The RRCA values came from estimates that were adjusted during model calibration. The *T* values in the current mapping effort, however, are considerably higher than the initial estimates of Goeke et al. (1992, Figs. 24, 34). There are two primary differences between this study and the previous. First, the current study used additional water well records and test hole logs that were unavailable to previous researchers. Second, the current study derived *K* values from lithologic descriptions in driller's logs, whereas Goeke et al. (1992) used the reported well yield to derive transmissivity. It is possible that the current approach used here overestimates *K* compared to the well yield approach. This is because most driller's logs were recorded using non-standard terminology, and it is possible that many drillers overestimate the amount of sand and gravel encountered during drilling. It is also possible that the initial values of Goeke et al. (1992) were over-estimated. It is noted that Goeke et al. (1992, Fig. 36) present revised *T* estimates in the same report. The revised values were adjusted during model calibration, yielding a range of adjusted *T* values that closely resembles the range of values reported herein. This suggests that the *T* estimates in this study are reasonable and may be used as an initial estimate of *T* for groundwater model parameterization.

Explanation of Digital GIS Files

Digital GIS files are included in the electronic copy of this report. The coordinates system of all raster files is North American Datum 1983. Units refer to cell values in raster files.

Table 2. Explanation of GIS files

Model	File name	File type	Units
Base of the principal aquifer	btog	raster	feet above sea level
Predevelopment water table	wtpv	raster	feet above sea level
Predevelopment water table	wtpv_contours	polyline	feet above sea level
Predevelopment saturated thickness	stpv	raster	feet
Spring 2016 water table: method A	wt16p	raster	feet above sea level
Spring 2016 water table: method A	wt16p_contours	polyline	feet above sea level
Spring 2016 saturated thickness: method A	st16p	raster	feet
Change in saturated thickness: predevelopment to Spring 2016	stchg_pv_16	raster	feet
Percent change in saturated thickness: predevelopment to Spring 2016	stpct_pv_16	raster	percent
Spring 2011 water table	wt11	raster	feet above sea level
Spring 2011 water table	wt11_contours	polyline	feet above sea level
Spring 2011 saturated thickness	st11	raster	feet
Spring 2016 water table: method B	wt16	raster	feet above sea level
Spring 2016 water table: method B	wt16_contours	polyline	feet above sea level
Spring 2016 saturated thickness: method B	st16	raster	feet
Change in saturated thickness: Spring 2011 to Spring 2016	stchg_11_16	raster	feet
Percent change in saturated thickness: Spring 2011 to Spring 2016	stpct_11_16	raster	percent
Transmissivity of the principal aquifer	t16	raster	gallons per day per foot

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