Nebraska Statewide Groundwater-Level Monitoring Report

2021

Aaron R. Young, Mark E. Burbach, Leslie M. Howard, Susan Olafsen Lackey and R.M. Joeckel

Conservation and Survey Division
School of Natural Resources

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Nebraska Water Survey Paper Number 90

Institute of Agriculture and Natural Resources
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FOREWORD

Nebraska Water Issues of Interest

R.M. Joeckel, Nebraska State Geologist and Director of the Conservation and Survey Division; Senior Associate Director, School of Natural Resources

Surface water

Record cold during February 2021 led to ice-jam flooding on the Platte River near Schuyler on February 28 and around Fremont during March 3–5 (Campbell, 2021; Lundgren, 2021a, b; Schnell, 2021). Severe storms on July 9–10 caused the release of millions of gallons of untreated wastewater into the Missouri River at Omaha (KMTV Staff, 2021). Exceptional flash flooding occurred in urban Omaha, and elsewhere in eastern Nebraska, during an intense rainstorm on the evening of August 7 (Cole, et al., 2021; Jones, 2021). Nevertheless, deepening drought strongly reduced managed flows in the Missouri River through the summer and beyond (6 News Staff, 2021; Associated Press, 2021). State and local governments expected to receive an additional $65 million in federal funding for infrastructure damaged during the historic March 2019 floods (Walton, 2021). Also, the Federal Emergency Management Agency announced in April that it will provide $50 million for the decommissioning of the destroyed Spencer Dam on the Niobrara River (Salter, 2021).

Groundwater, water-supply, and environmental issues

The AltEn ethanol plant at Mead, which had been the focus of concerns about surface- and groundwater contamination in 2020, was shut down on February 8 by order of the Nebraska Department of Environment and Energy and began cleanup efforts after the receipt of a discharge management plan from the AltEn Facility Response Group (AFRG) later in that month (Nebraska Department of Environment and Energy, 2021). During very early remediation efforts, a digester-tank pipe burst, and the breaching of a contaminant berm produced a spill that rapidly traveled at least 4 mi (6.4 km) along local waterways, killing fish and wildlife; another breach occurred at the end of August (Dunker, 2021a; NTV News, 2021). By September, groundwater testing had identified traces of two insecticides and a fungicide—compounds used in treating seeds like the seed corn consumed at the AltEn plant—in a private well 6 miles (10 km) downgradient (Dunker, 2021b). AFRG submitted additional remedial action, management, and winterization plans in late 2021 (Nebraska Department of Environment and Energy, 2022). The total costs of unrelated groundwater remediation at the nearby Nebraska Ordnance Plant Superfund Site reached $140 million in 2021 (Dunker, 2021c).

Lyons continued to experience discolored domestic water due to iron and manganese from delayed replacement of the city's more than four-decades-old filter beds (Bonderson, 2021). Short-term discoloration of water by iron and manganese occurred during maintenance of Lincoln's water supply (10/11 NOW, 2021). Summer brought a ban on lawn watering in rural Lancaster County (Wiltsey, 2021a), and a water-conservation order in Fairbury (Hopkins, 2021).

In late August, the Environmental Protection Agency (EPA) announced that $263,000 in grant funding under the Water Infrastructure Improvements for the Nation (WIIN) Act would be available to improve drinking water in underserved and disadvantaged communities in the state (United States Environmental Protection Agency, 2021a). EPA also announced in early December that more than $63 million would be received by Nebraska through the State Revolving Fund for upgrading water infrastructure, dealing with drinking-water water contaminants, and creating water-related jobs (United States Environmental Protection Agency, 2021b).

Legislation

The Biden administration canceled permits for the Keystone XL Pipeline extension project in January 2021 after twelve years of environmental concerns. Nevertheless, there are still dozens of related lawsuits in Nebraska (Wiltsey, 2021b). LB 507, which prohibits the use of treated seed corn in agricultural ethanol production if byproducts thereof are unsafe for land application or consumption by livestock, was signed by Governor Ricketts on May 5, and was amended near the end of the same month (Nebraska Legislature, 2021a). The introduction of this bill was prompted by recent events at the AltEn ethanol plant at Mead. LB 650, which was approved by Governor Ricketts on May 26, is a landmark piece of legislation that regulates underground carbon dioxide injection and storage in Nebraska. Among its many regulatory statements, LB650 states that permits for doing so will only be issued if operations "will not endanger surface waters or underground sources of drinking water" (Nebraska Legislature, undated, 2021b). Governor Ricketts submitted a letter to the EPA in September maintaining the state's authority to manage water despite the Biden administration's redefinition of "Waters of the United States" within the Clean Water Act (Anonymous, 2021).

SELECT RECENT PUBLICATIONS INVOLVING CSD PERSONNEL

Burbach M.E., 2021. Does stakeholder engagement improve groundwater management? *Water Economics and Policy* 7 (2), 2150008.

Delozier, J., and **Burbach, M.E.,** 2021. Boundary spanning: Its role in trust development between stakeholders in integrated water resource management. *Current Research in Environmental Sustainability* 3, 100027.

Diffendal, R.F. Jr., **Olafsen Lackey, S.**, **Hallum, D.R.,** 2021. Geology and Hydrogeology of Northeastern Nebraska: Geology, Water Management and Geological Hazards, Nebraska Geological Society Field Trip 2021, Guidebook No. 38, University of Nebraska–Lincoln, Conservation and Survey Division, 32 pp.

Gilmore, T.E., Cherry, M., Gastmans, D., Humphrey, E., & Solomon, D. K., 2021. The $^{3}H/^{3}He$ Groundwater age-dating method and applications. *Derbyana* 42. [https://revistaig.emnuvens.com.br/derbyana/article/view/740].

Hallum, D., 2020. Hydrogeologic Framework and Water Balance Investigation of Land Near the Gothenburg Canal System. Lincoln, NE, University of Nebraska-Lincoln, Conservation and Survey Division, Open File Report 208, 42 pp.

Kambhu A., Li, Y, **Gilmore, T.E.**, Comfort, S., 2021. Modeling the release and spreading of permanganate from aerated oxidant candles in a laboratory flow tank. Journal of Hazardous Materials [https://doi.org/10.1016/j.jhazmat.2020.123719].

Korus, J. T., Joeckel, R. M., Abraham, J. D., Hoyer, A.-S., Jorgenson, F., 2021. Reconstruction of pre-Illinoian ice margins and glaciotectonic structures from airborne electromagnetic (AEM) surveys at the western limit of Laurentide glaciation, Midcontinent U.S.A. Quaternary Science Advances 4, 15 pp. [https://doi.org/10.1016/j.qsa.2021.100026].

Ma, N., **Szilagyi, J.**, Zhang, Y., 2021. Calibration-free complementary relationship estimates terrestrial evapotranspiration globally. Water Resources Research 57 (9) [doi: 10.1029/2021WR029691].

Shrestha, N., Mittelstet, A.R., **Gilmore, T.E.**, Zlotnik, V., & Neale, C.M. 2021. Effects of drought on groundwater-fed lake areas in the Nebraska Sand Hills. *Journal of Hydrology: Regional Studies* 36, 100877. https://doi.org/10.1016/j.ejrh.2021.100877

Wells, M J., **Gilmore, T.E.**, Nelson, N., Mittelstet, A., and Böhlke, J.K, 2021. Determination of vadose zone and saturated zone nitrate lag times using long-term groundwater monitoring data and statistical machine learning, *Hydrology and Earth System Science* 25: 811–829 [https://doi.org/10.5194/hess-25-811-2021].

Westrop, J.P., Snow, D.D., and Weber, K.A., 2021. Mobilization of naturally occurring uranium under intensely managed farmland, p. 215-233 in: Ray, C., Muddu, S., and Sharma, S. (eds), *Food, Energy, and Water Nexus. A Consideration for the 21st Century.* Springer Nature.

Wilkening, E., Heeren, M.D., **Hallum, D.**, Schellpeper, J., and Martin, D.L., 2021. Impact of irrigation technologies on withdrawals and consumptive use of water. ASABE Annual International Meeting, Paper No. 2101114, 11 pp [DOI: https://doi.org/10.13031/aim.2101114].

INTRODUCTION

Groundwater-level information is valuable to citizens and stakeholders.
It quantifies the availability of groundwater and informs management decisions.

This report is a synthesis of groundwater-level monitoring programs in Nebraska. It is a continuation of the series of annual reports and maps produced by the Conservation and Survey Division (CSD) of the University of Nebraska in cooperation with the U.S. Geological Survey (USGS) since the 1950s. Groundwater-level monitoring began in Nebraska in 1930 in an effort to survey the state's groundwater resources and to observe changes in its availability on a continuing basis. The CSD and USGS cooperatively developed, maintained, and operated an observation-well network throughout the state. These two agencies were responsible for collecting and archiving this information, and for making it available to the citizens.

Although CSD and USGS still occupy the central role in the statewide groundwater-level monitoring program, other agencies have assumed the responsibilities of building and maintaining observation networks and measuring groundwater-levels. The CSD and USGS continue to operate some of the original observation wells, but today the majority of measurements are made by agencies such as Natural Resources Districts (NRDs) (Fig.1), U.S. Bureau of Reclamation, U.S. Fish and Wildlife Service, and Public Power and Irrigation Districts. Because these agencies are located throughout the state, they are able to implement groundwater-level monitoring programs using local field staff, landowner contacts, taxing and regulatory authority, and first-hand knowledge of local conditions. Collectively, these agencies have developed an extensive network of observation wells throughout the state.

The CSD provides vital technical expertise to these agencies as they develop and implement groundwater-level monitoring plans. The CSD evaluates the adequacy and accuracy of the groundwater-level data and provides the statewide assessment of groundwater-level changes across many of the state's aquifers (Figs. 2–3).

The CSD has long provided technical services to stakeholders by integrating groundwater-level change data with multiple data sets in order to:

1) Determine the amount of groundwater in storage and its availability for use.
2) Assess the water-supply outlook by identifying changes in the volume of groundwater in storage.
3) Identify areas in which changes in groundwater levels may have an economic impact.
4) Assist state and local agencies in the formulation and administration of resource-management programs.
5) Determine or estimate the rate and direction of groundwater movement, specific yield of aquifers, base flow of streams, sources and amounts of groundwater recharge, and locations and amounts of groundwater discharge.
6) Assess the validity of hydrogeologic interpretations and the assumptions used in developing models of groundwater systems.

The need for this essential information only escalates as water-use pressures steadily increase. The CSD strives to meet this challenge by focusing on fundamental data, building collaborative relationships with the agencies that depend on the information, and providing scientifically accurate information in a timely manner.

Purpose and Methods

The vast majority of groundwater used in Nebraska is pumped from the High Plains Aquifer (HPA), although there are multiple aquifers in the state (Fig. 2, 3). The HPA underlies parts of eight states, including South Dakota, Wyoming, Nebraska, Colorado, Kansas, Oklahoma, Texas, and New Mexico. In total, Nebraska

Figure 1. Nebraska Natural Resources Districts

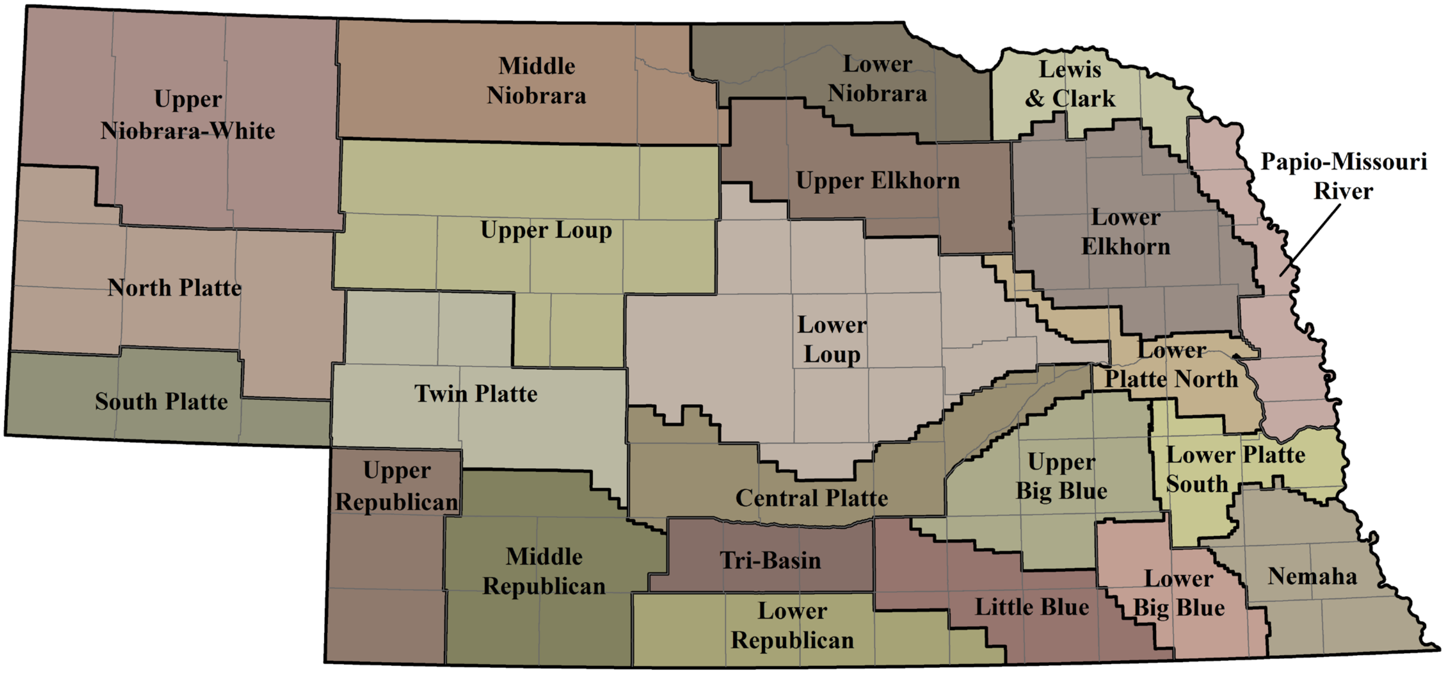
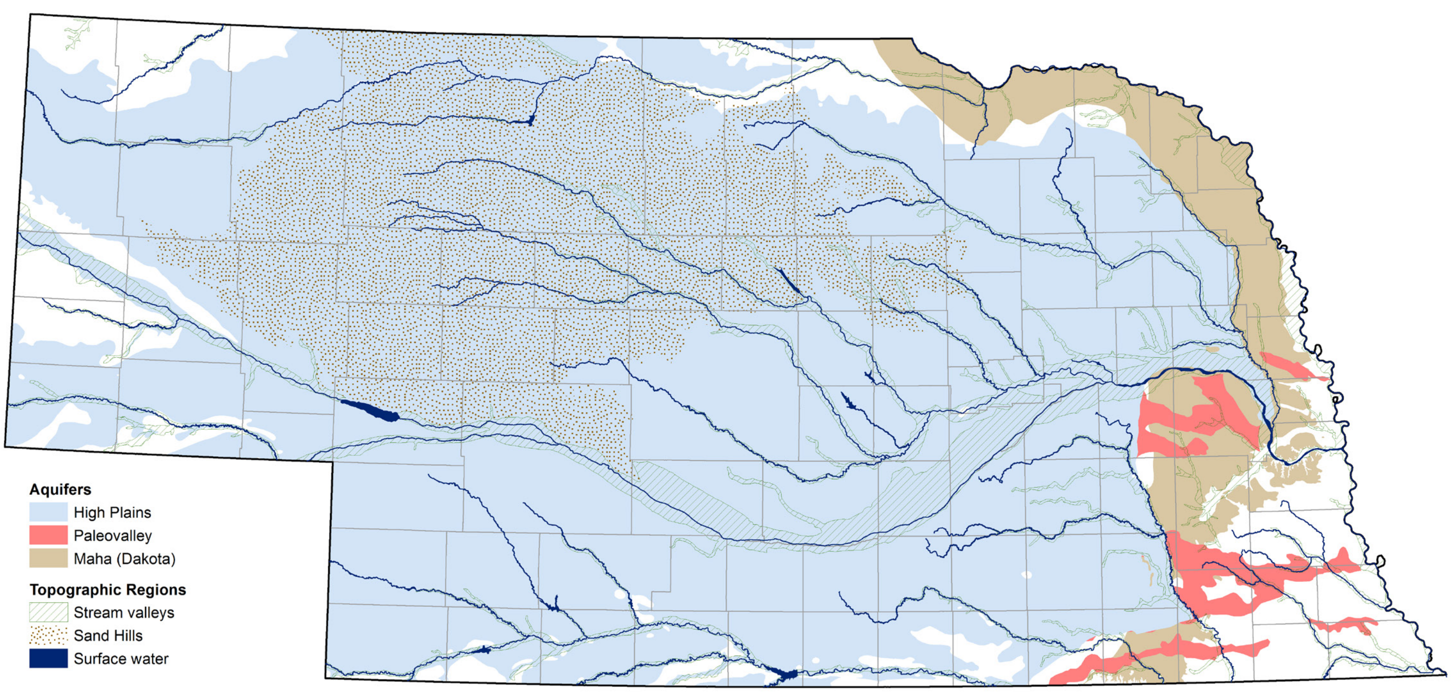


Figure 2. Important Aquifers and Topographic Regions of Nebraska



Note: The aquifer units shown here may contain little or no saturated thickness in some areas.

Figure 3. Generalized Geologic and Hydrostratigraphic Framework of Nebraska

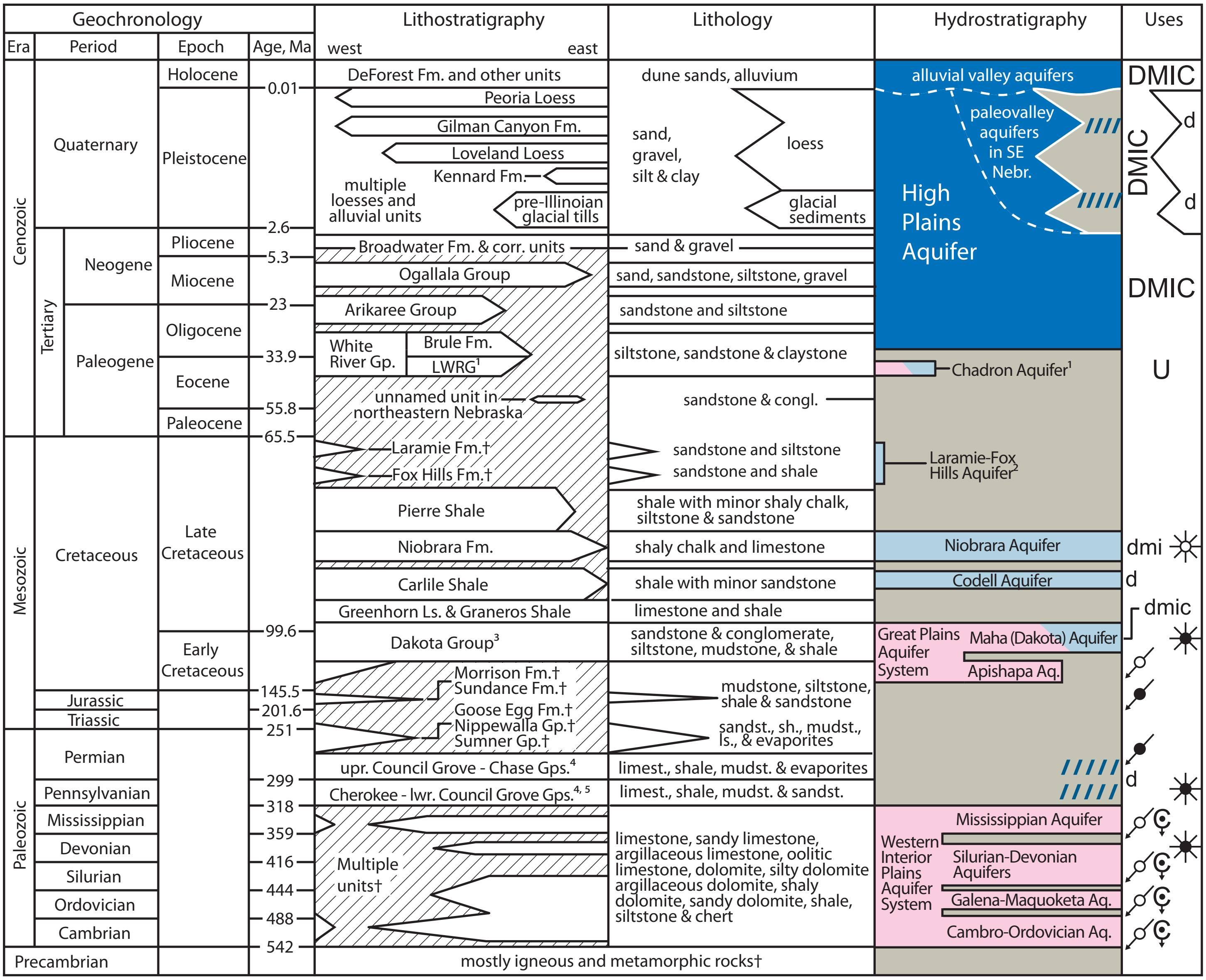


Diagram is not to scale relative to geologic time and stratigraphic thicknesses.

Hydrostratigraphic characteristics and water quality

- primary aquifers with good quality water
- secondary aquifers with good quality water
- secondary aquifers with generally poor quality water
- //// aquitards with local low-yield aquifers
- aquitards

[1] lower White River Group - includes Chamberlain Pass and Chadron Formations according to some authors; "Chadron Aquifer" historically refers to aquifer in lower White River Group

[2] important aquifer in Colorado, but present in Nebraska only in extreme southwestern Panhandle

[3] Dakota Formation in adjacent states

[4] includes correlative units with different names in northwest Nebraska

[5] Cherokee, Marmaton & Pleasanton Groups are not exposed in Nebraska

†present only in subsurface

Groundwater uses and related aspects

D	major domestic use	I	major irrigation use
d	minor domestic use	i	minor irrigation use
M	major municipal use	C	major commercial/industrial use
m	minor municipal use	c	minor commercial/industrial use

- units used for wastewater injection
- units with potential use for wastewater injection
- U unit mined for uranium by in-situ leaching (Dawes Co.)
- unit with potential use for carbon sequestration
- unit producing petroleum or natural gas
- unit with natural gas potential

From Korus and Joeckel, 2011

overlies approximately 64,600 mi^2 of the HPA, or 36% of the total aquifer by area. By volume as of 2009, Nebraska has approximately 2.040 billion acre-feet of saturated sediments, or 69% of the total volume of the HPA (McGuire et. al., 2012). The greatest area of saturated thickness in the HPA, nearly 1,000 feet, is located under the western portion of the Nebraska Sand Hills (c.f. Korus et. al. 2013, pp. 44).

Although Nebraska is fortunate to have such vast supplies of groundwater, any groundwater supply is vulnerable to depletion through overpumping. According to the 2017 U.S. Census of Agriculture, Nebraska leads the nation in irrigated acres with more than 8.6 million acres. Without proper oversight, irrigation pumping on this scale can rapidly deplete aquifers and lead to large-scale economic hardship. The present report illustrates the changes in groundwater levels in Nebraska at different time scales, resulting from both natural and anthropogenic influenced changes. This information is important to both state and local lawmakers in assessing the current state of Nebraska's groundwater resources, and to local producers in making land management decisions.

This report summarizes changes in Nebraska's groundwater levels over periods of one, five, and ten years prior to 2021, as well as from 1981 to 2021, predevelopment to 1981 and predevelopment to 2021. Nineteen eighty-one was selected as a fixed year, as groundwater-level declines in many parts of the state reached a maximum in 1981. These changes are depicted in maps that delineate regional trends on a statewide basis. **We stress that the maps presented in this report provide overviews of the general locations, magnitudes, and extents of rises and declines. Local conditions, which may vary considerably, are not depicted in these maps and, indeed, cannot be represented with accuracy at the scale of these maps.** The reader is referred to Figures 1 through 4 for the boundaries of NRDs and the locations of rivers, aquifers, and counties mentioned in the text.

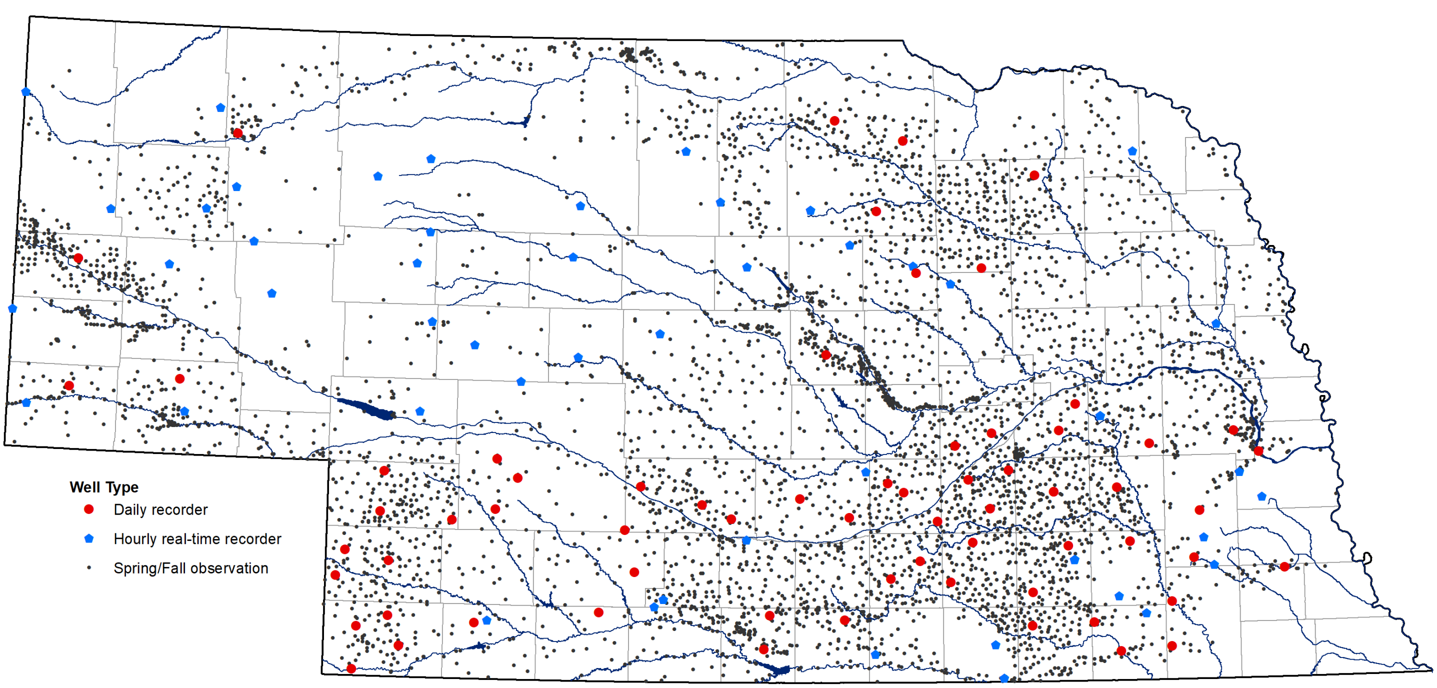
The one-, five-, and ten-year changes are presented in the spring 2020 to spring 2021, spring 2016 to spring 2021, and spring 2011 to spring 2021 maps, respectively. Groundwater levels measured from thousands of wells throughout the state during the spring of 2021 (Fig. 5) were compared to levels measured in the same wells in the spring of the preceding target year. A spreadsheet of wells used for mapping are available for download at http://snr.unl.edu/data/water/groundwater/gwlevelchangemaps.aspx. For the one-, five-, and ten-year change maps, contours were generated using computer interpolation. These contours were incorporated into the final maps in areas where the principal aquifer is geographically continuous and in relatively good hydraulic connection, and where data density is comparatively high. In areas not meeting these criteria, the computer-generated contours were manually edited at various scales in order to conform to hydrogeologic boundaries that prevent the flow of groundwater. Such boundaries include: (1) areas where relatively impermeable bedrock units outcrop or exist in the shallow subsurface, such as southeastern Nebraska and in areas of Scotts Bluff County, (2) valley boundaries in eastern Nebraska where alluvial aquifers are a major source of groundwater but upland areas between them lack a primary aquifer, and (3) areas where the HPA is separated by deeply entrenched parts of the Niobrara, Republican, and Platte River valleys. For the spring 1981 to spring 2021 map, computer interpolation was impractical because data were sparse in many areas. Accordingly, contours were drawn manually at a scale of 1:500,000 to incorporate the major hydrogeologic boundaries listed above.

For the predevelopment to spring 2021 and predevelopment to spring 1981 maps, groundwater levels from wells measured in 2021 and 1981 were compared to estimated predevelopment groundwater levels in the same wells. An estimated predevelopment groundwater level is the approximate average groundwater level at a well site prior to any development that significantly affects groundwater levels. Predevelopment groundwater levels are generally presumed to be those that predated intensive groundwater irrigation. Such intensive use of groundwater began during the approximate period 1930 to 1960, although not synchronously across the state. Predevelopment map contours were drawn manually with the aid of previously existing maps for similar time periods and with knowledge of major hydrogeologic boundaries.

Areas of sparse data are shown with a hatched pattern on all maps (e.g., Fig. 7). A point density interpolation was used to determine the number of observation points within a 6-mile (approximately 10-kilometer) search radius. Areas of sparse data were defined as areas with zero observation points within the search radius.

Figure 4. Counties, Major Cities, and Streams of Nebraska

Figure 5. Location of Observation Wells by Type



Sources: U.S. Geological Survey, Nebraska Water Science Center; U.S. Bureau of Reclamation, Kansas-Nebraska Area Office; Nebraska Natural Resources Districts; Central Nebraska Public Power and Irrigation District; Conservation and Survey Division, School of Natural Resources, University of Nebraska-Lincoln

Precipitation maps were prepared by comparing total precipitation over the time period of interest to the 30-year normal provided by the National Climate Data Center (www.ncdc.noaa.gov). The 30-year normal currently in use is calculated on the basis of average annual precipitation during 1981-2010. A precipitation surface is generated using the inverse distance weighted interpolation method in ArcGIS with a 1,640 ft (500 m) cell size. The resulting surface is classified with a defined interval of ten percent and contoured. The resulting contours are smoothed and then converted to polygons.

Factors Causing Groundwater-Level Changes

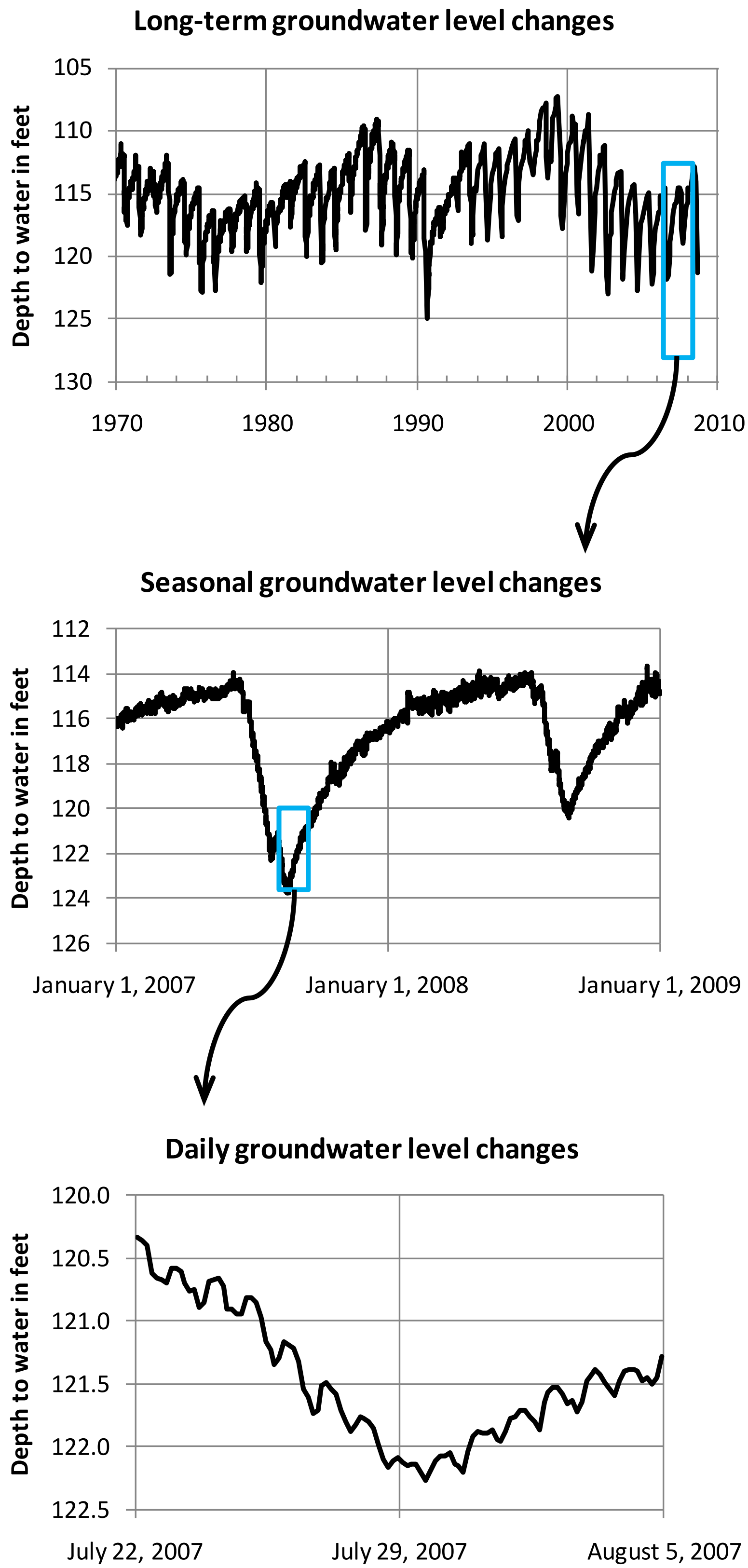
Long-term groundwater-level changes result from the changing balance between recharge to, discharge from, and storage in an aquifer. If recharge and discharge are in balance, such as they were before widespread irrigation development, groundwater levels are generally steady because the amount of water stored in the aquifer does not change. Minor changes in groundwater levels may occur due to natural variations in precipitation and streamflow, but generally the system is in equilibrium. If, however, the rate of recharge exceeds the rate of discharge over a long period, the amount of water stored in the aquifer increases and groundwater levels rise. Conversely, if the rate of discharge exceeds the rate of recharge for a long period, the amount of water in storage is depleted and groundwater levels decline. The magnitudes, locations, and rates of groundwater-level changes are controlled by many factors, including: the aquifer's storage properties, permeability, and saturated thickness; the locations, rates, and pumping schedules of wells; the locations and rates of artificial recharge areas; and the degree of hydraulic connection between the aquifer and surface water bodies.

It is a common misconception that the rate of recharge from precipitation can be used as a "safe yield" or "sustainable limit" on the rate of groundwater extraction from an aquifer (Bredehoeft, 1997). This concept is a gross oversimplification of hydrogeologic processes. The aquifer properties and all sources of recharge and discharge must be taken into consideration. Recharge is provided primarily by precipitation, but also by irrigation return flow and seepage from canals, reservoirs, and streams. Discharge occurs as baseflow to streams and lakes, evapotranspiration, and groundwater pumping. Groundwater levels, therefore, respond to a variety of natural and anthropogenic factors affecting recharge and discharge and are controlled largely by the physical properties of the aquifer. Limiting groundwater extraction to a rate equal to or less than the rate of recharge from precipitation will not prevent depletion of the aquifer. In fact, groundwater "mining" is prone to occur to one degree or another in any heavily pumped aquifer. A holistic, adaptive approach to groundwater management based on hydrologic mass balance is more appropriate. These strategies are discussed by several authors (e.g., Sophocleous, 1997, 1998, 2000; Alley and Leake, 2004; Maimone, 2004; Korus and Burbach, 2009a).

Groundwater-level changes can be observed at many different temporal scales (Fig. 6). Changes may occur over several minutes or hours in response to pumping, floods, or earthquakes. Long-term changes may occur due to the cumulative effects of pumping over many irrigation seasons, prolonged droughts or periods of high rainfall, or seepage from man-made water bodies. Similarly, groundwater levels can be observed at multiple spatial scales. For example, groundwater levels decline around the immediate vicinity of an individual well during pumping, but also from the cumulative effects of many irrigation wells pumped over many irrigation seasons at the scale of an entire regional aquifer. Groundwater levels rise along the banks of a stream during a flood, but they may also rise significantly over an entire drainage basin during a prolonged wet period. The temporal and spatial scales of observation must be taken into account when using the maps presented in this report.

The maps presented in this report were generally created at a scale of 1:557,000 or 1:500,000. **They are intended solely to identify regional conditions and trends at varying time scales throughout the entire state of Nebraska, and not at the local scale**. As such, these changes chiefly reflect the interplay between precipitation, groundwater pumping, and artificial recharge from reservoirs and canals.

Figure 6. Example of Groundwater-Level Changes at Different Temporal Scales



Data from Plymouth Recorder well, Jefferson County

CHANGES IN GROUNDWATER LEVELS, SPRING 2020 TO SPRING 2021

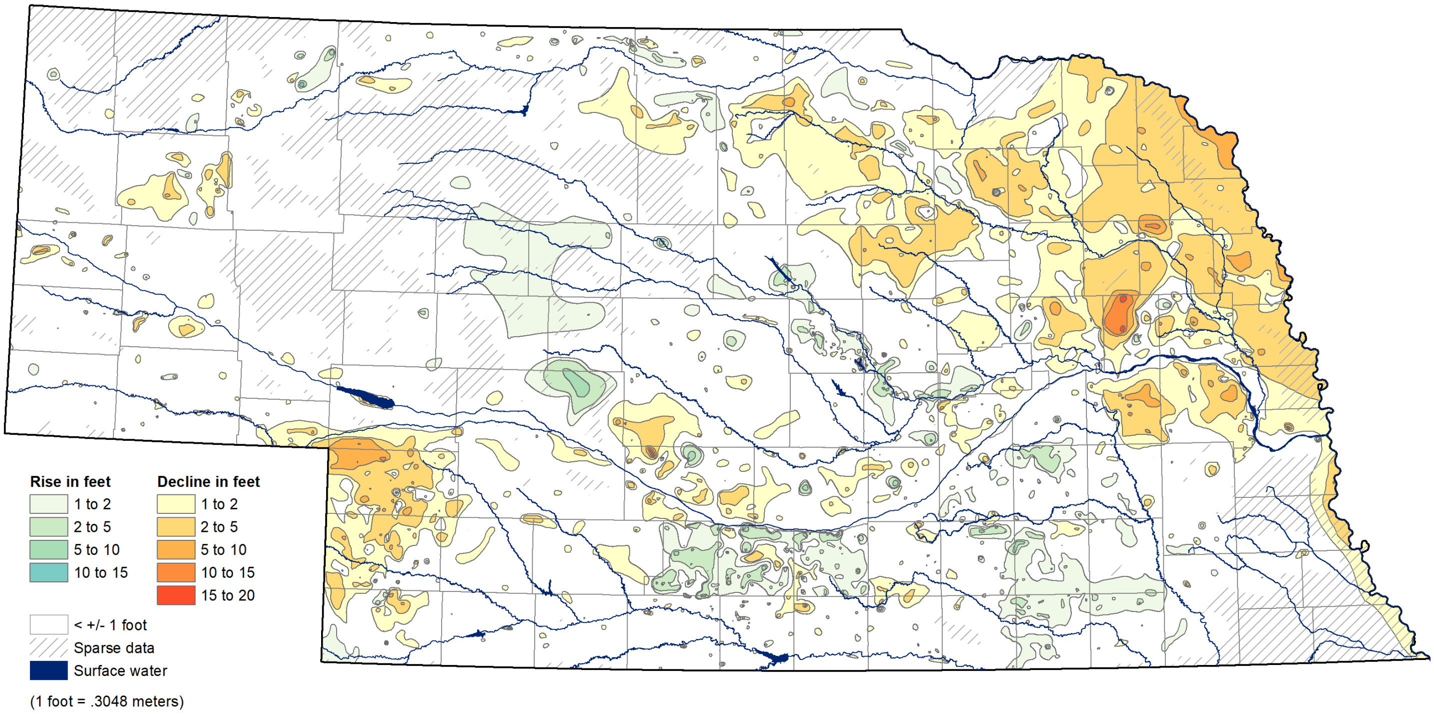
From the spring of 2020 to the spring of 2021, groundwater levels in Nebraska recorded an average decline of 0.44 feet.

Groundwater levels in Nebraska generally declined from the spring of 2020 to the spring of 2021. In total, 4,967 wells were measured consecutively in the spring of 2020 and spring 2021. Groundwater-level declines were recorded in 61% of measured wells, and 31% of all measured wells experienced a decline of greater than one foot (Fig. 7). Groundwater-level rises were recorded in 39% of measured wells, and 16% of all measured wells recorded a rise greater than one foot. Approximately 1% of measured wells had neither rises nor declines from the spring of 2020 to the spring of 2021. The average groundwater-level change for all measured wells in Nebraska in the spring of 2021 was a decline of 0.44 feet. From January 2020 to January 2021, precipitation values for Nebraska were well below the 30-year normal for 166 of 172 reporting stations in Nebraska (Fig. 8). Precipitation values ranged from 37% of the 30-year normal in the southern Panhandle to 119% in central Thayer County.

Following several years of continued annual groundwater-level rises, water-levels changes from 2020-2021 show a different pattern. Water levels continue to rise in the central sandhills, despite near normal precipitation levels. Locally, surface water levels in this area are still high following significant precipitation events in 2019, though levels have been receding from 2019-2020 highs. Other spatially continuous areas of water-level rises were recorded in central Nebraska, to the south of the Platte River despite well below-average precipitation in many of these areas.

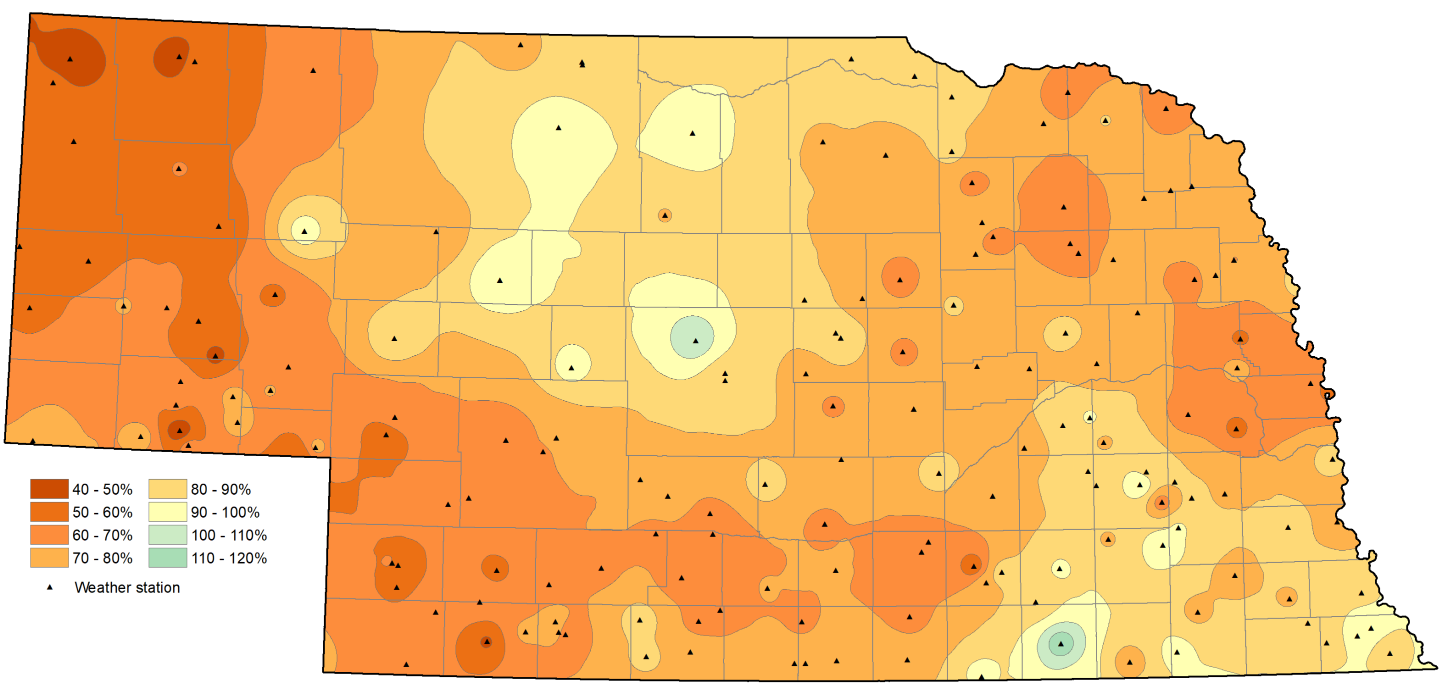
Precipitation levels in Eastern Nebraska, the Panhandle, and Southwest Nebraska were significantly below the 30-year normal, and groundwater levels have generally declined in these areas. Groundwater levels have declined 2 to 5 feet over most of northeastern Nebraska, with significant water-level declines measured in Colfax County, recording a maximum one-year decline of 16.59 feet. Other significant areas of 2 to 5- foot declines occurred in southwest Nebraska, and in more localized areas of the Panhandle. More localized areas of decline also occurred in the Platte River Valley in central Nebraska.

Figure 7. Groundwater-Level Changes in Nebraska - Spring 2020 to Spring 2021



Sources: U.S. Geological Survey, Nebraska Water Science Center; U.S. Bureau of Reclamation, Kansas-Nebraska Area Office; Nebraska Natural Resources Districts; Central Nebraska Public Power and Irrigation District; Conservation and Survey Division, School of Natural Resources, University of Nebraska–Lincoln

Figure 8. Percent of Normal Precipitation - January 2020 to January 2021



Sources: National Climate Data Center, Asheville, North Carolina; High Plains Regional Climate Center, University of Nebraska-Lincoln

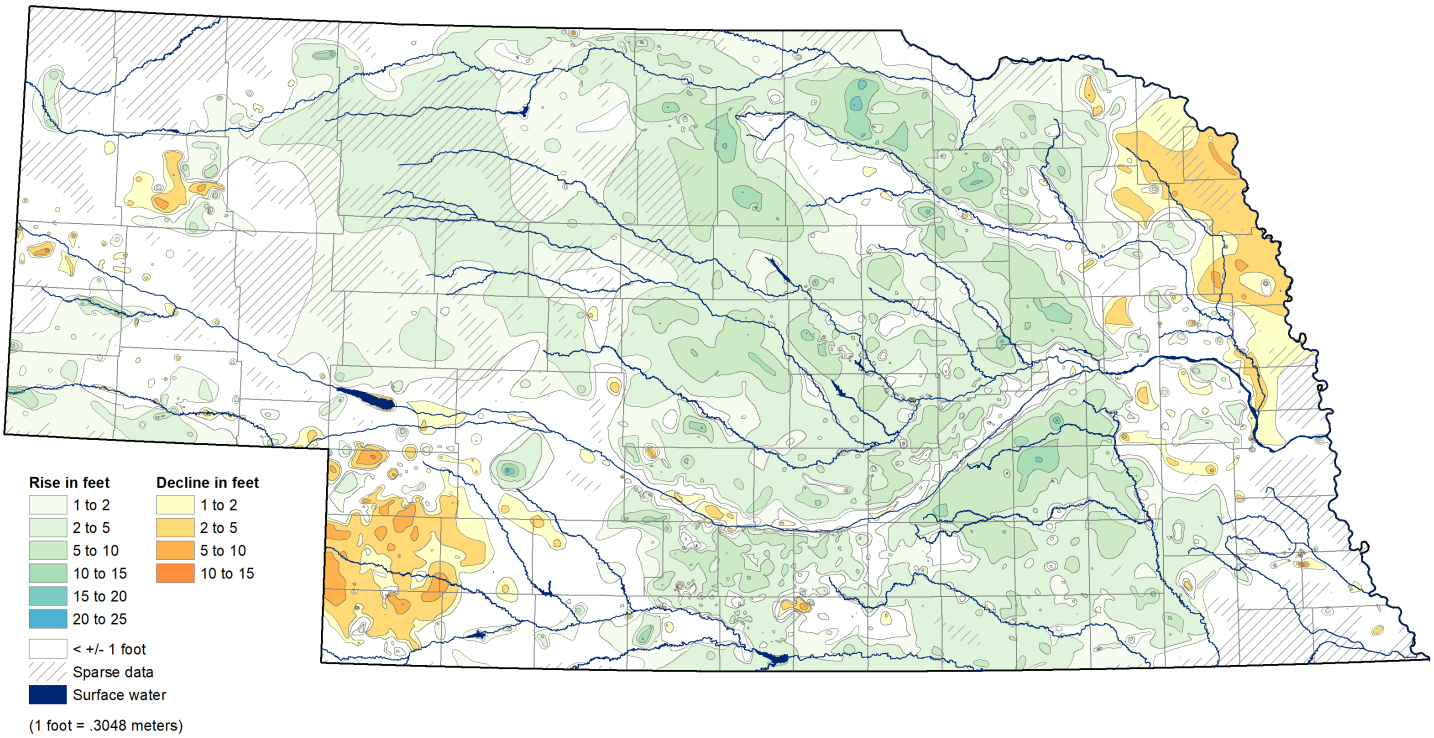
CHANGES IN GROUNDWATER LEVELS, SPRING 2016 TO SPRING 2021

On average, groundwater levels in Nebraska increased by 2.59 feet statewide between the spring of 2016 and the spring of 2021.

The five-year groundwater-level change map was developed on the basis of 4,796 wells which were measured consecutively in spring 2016 and spring 2021. Of these wells, 77% recorded groundwater-level rises, and 49% of wells recording rises greater than one foot. Over the past five years, average groundwater levels have risen by an average of 2.59 feet statewide. The rises depicted in Figure 9 are partly associated with recovery following the record-setting drought of 2012, and partly due to above-average precipitation over much of the last 5 years (Fig. 10).

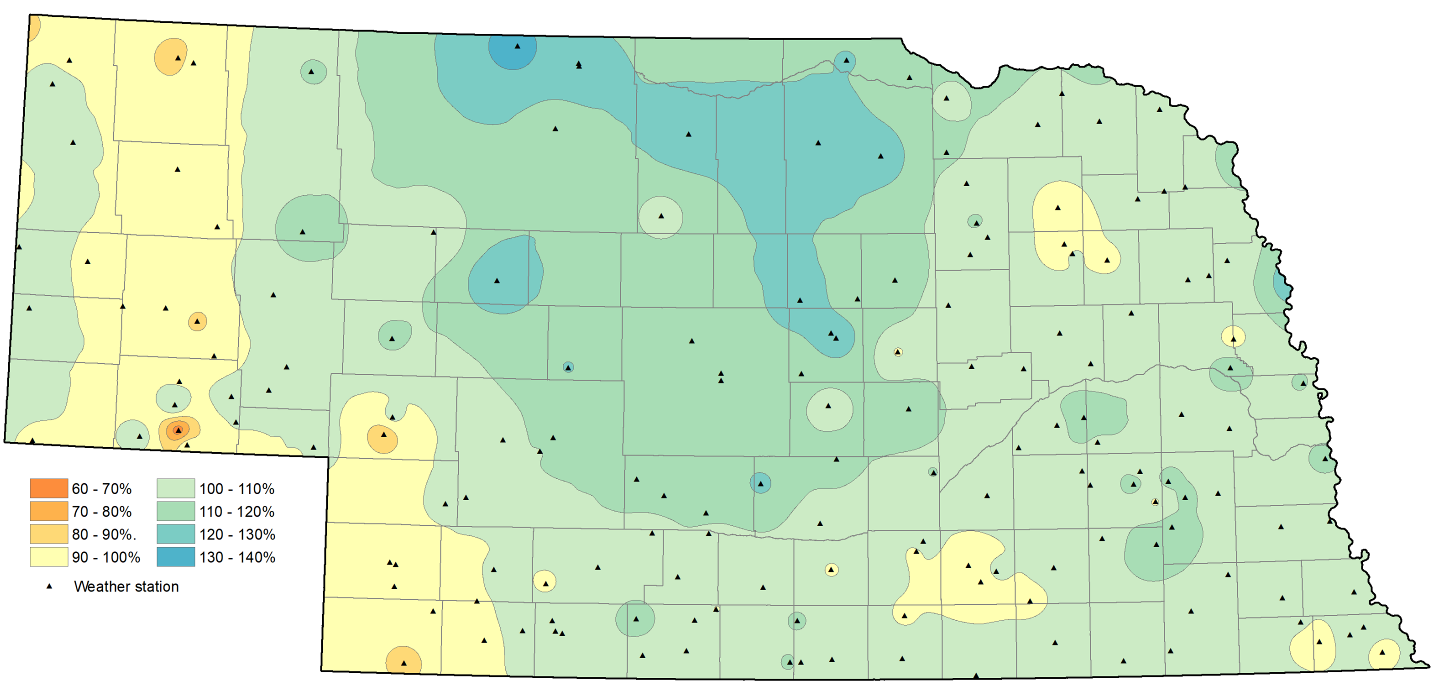
Of the 172 reporting stations in Nebraska, 136 reported 5-year average precipitation values above the 30-year mean. The 5-year average precipitation values were especially high in north central Nebraska which experienced significant flooding in early 2019. Of the 4,796 wells measured in 2021, 23% exhibited declines, and 13% of all measured wells recorded declines of greater than one foot. Spatially significant declines occurred in Box Butte, Chase, Colfax, Dundy and Scotts Bluff counties, as well as counties in northeast Nebraska bordering the Missouri River. Declines in these counties may be the results of: (1) localized precipitation patterns and associated irrigation pumping, (2) patterns of known long-term continued drawdowns, (3) changes to water storage or transport in canal systems, or (4) fluctuations in river flow and recovery from mass flooding events in the Missouri River. Other localized areas of groundwater-level decline appear across the state. Most of these areas are associated with a single well; thus, these declines likely resulted from changes in pumping schedules or recent pumping prior to the measurements of water levels within them.

Figure 9. Groundwater-Level Changes in Nebraska - Spring 2016 to Spring 2021



Sources: U.S. Geological Survey, Nebraska Water Science Center; U.S. Bureau of Reclamation, Kansas-Nebraska Area Office; Nebraska Natural Resources Districts; Central Nebraska Public Power and Irrigation District

Figure 10. Percent of Normal Precipitation - January 2016 to January 2021



Sources: National Climate Data Center, Asheville, North Carolina; High Plains Regional Climate Center, University of Nebraska-Lincoln

CHANGES IN GROUNDWATER LEVELS, SPRING 2011 TO SPRING 2021

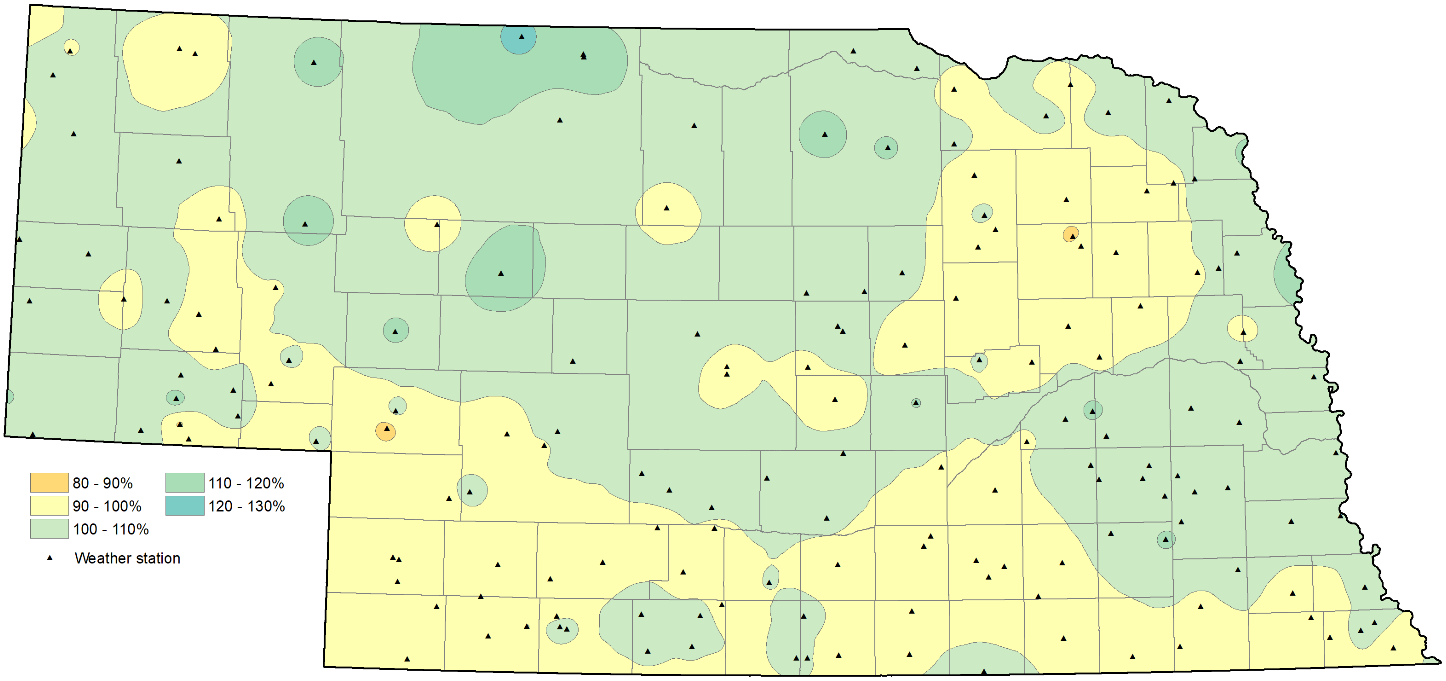
Despite major shifts in weather conditions and record setting drought, modest groundwater-level rises were recorded throughout much of Nebraska over the last 10 years.

Weather conditions from the spring of 2011 to the spring of 2021 ranged from record-setting drought to periods of much above-average precipitation. Water levels in the 2011 to 2021 period were also impacted by weather conditions in the previous decade as much of the Midwest, and all of Nebraska were in a period of drought from 2000 to about 2007. Groundwater-level declines were recorded throughout the state during this period (Burbach, 2007). Precipitation was above normal between 2007 and early 2012, restoring groundwater levels to pre-drought or above pre-drought conditions in much of eastern and central Nebraska. From the spring of 2012 through the spring of 2013, however, Nebraska experienced the driest single year on record, resulting in groundwater-level declines which eliminated many of the groundwater-level rises associated with the high-rainfall years between 2007 and early 2012. Precipitation values over most of Nebraska were near the long-term average in late 2013 and 2014. Between 2014 and 2019, precipitation levels generally remained near or slightly above the 30-year average. Precipitation values in early 2019 were well above the 30-year average for much of central and northern Nebraska, with some stations recording nearly double average annual precipitation amounts (Fig. 8). Despite the major year-to-year fluctuations in precipitation extremes, precipitation values have generally remained near the 30-year average for Nebraska over the last 10 years (Fig. 11).

Of 4,042 wells measured in both spring of 2011 and spring of 2021, 58% recorded groundwater-level rises, with 49% rising more than one foot (Fig. 12). Groundwater-level declines were recorded in 41% of wells measured in Nebraska from the spring of 2011 to spring 2021, and 27% of measured wells experienced declines of greater than one foot. Groundwater levels in wells have risen by an average of 0.49 feet statewide over the last 10 years.

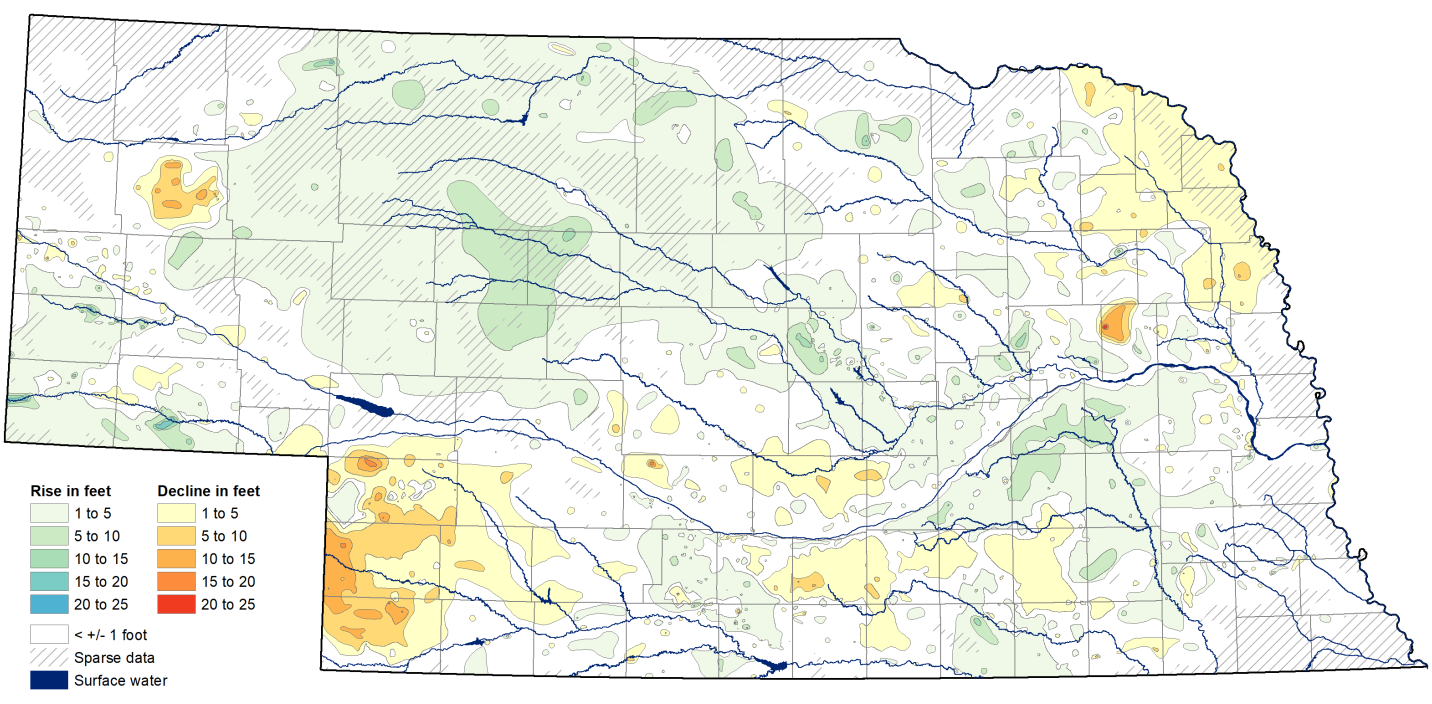
From the spring of 2011 to the spring of 2021, groundwater levels have fluctuated regionally, despite near-average precipitation statewide. The regional patterns of groundwater-level changes may have resulted from: (1) extreme regional variability in year-to-year precipitation and associated irrigation pumping rates, (2) delayed reaction time of aquifers to climate trends, (3) and increased runoff during brief, high-intensity rainfall events. Although some long-term trends can be observed at this scale, such as steadily increasing levels in the central Sand Hills, steadily rising levels in Butler, Polk and York counties, and steadily decreasing levels in known problem areas, groundwater levels have fluctuated from year to year due to extreme variations in yearly rainfall, recharge, and evapotranspiration over the past 10 years. Groundwater-level changes mapped in Figure 12, therefore, may exhibit the effects of short-term extremes rather than long-term trends.

Figure 11. Percent of Normal Precipitation - January 2011 to January 2021



Sources: National Climate Data Center, Asheville, North Carolina; High Plains Regional Climate Center, University of Nebraska-Lincoln

Figure 12. Groundwater-Level Changes in Nebraska - Spring 2011 to Spring 2021



Sources: U.S. Geological Survey, Nebraska Water Science Center; U.S. Bureau of Reclamation, Kansas-Nebraska Area Office; Nebraska Natural Resources Districts; Central Nebraska Public Power and Irrigation District

CHANGES IN GROUNDWATER LEVELS, PREDEVELOPMENT TO SPRING 2021

Long-term groundwater-level changes in Nebraska primarily reflect aquifer depletion in areas of dense irrigation development and increases in storage due to seepage from canals and reservoirs.

Spring 2021 groundwater levels indicate both long-term declines and long-term rises from predevelopment in certain areas of Nebraska (Fig. 13). Almost all of the areas of significant groundwater-level declines correspond to high irrigation-well densities in aquifers that are deep and have little direct connection to surface water (Fig. 14). The greatest decline from predevelopment to 2021 is approximately 126 feet, in Box Butte County just north of the city of Alliance. Notable groundwater-level declines from predevelopment to spring 2021 have occurred in Box Butte County, the southwestern part of the state near Chase, Perkins, and Dundy counties, and in the Panhandle. A large area of smaller declines in southeast to south-central Nebraska reflects slight depletion of the High Plains Aquifer. The largest groundwater-level rises occurred in Gosper, Phelps, and Kearney counties, where there are extensive canals and surface-water-irrigation systems.

The predevelopment groundwater levels used in Chase, Perkins, and Dundy counties are representative of the approximate average groundwater levels prior to 1953. A general trend of declining groundwater levels that began around 1966 correlates temporally with the intensive use of groundwater for irrigation. The approximate average groundwater levels prior to 1938 were utilized as predevelopment values for the groundwater-level change map in Box Butte County. Intensive groundwater development for irrigation since 1950 has caused groundwater levels to decline by 5 feet to more than 125 feet from predevelopment levels (Fig. 13). Records from wells in both the southwestern counties and in Box Butte County indicate that rates of decline have been essentially steady, despite subsequent changes in groundwater management practices, water use allocations, and fluctuations in the amount of annual precipitation (Korus and Burbach, 2009b).

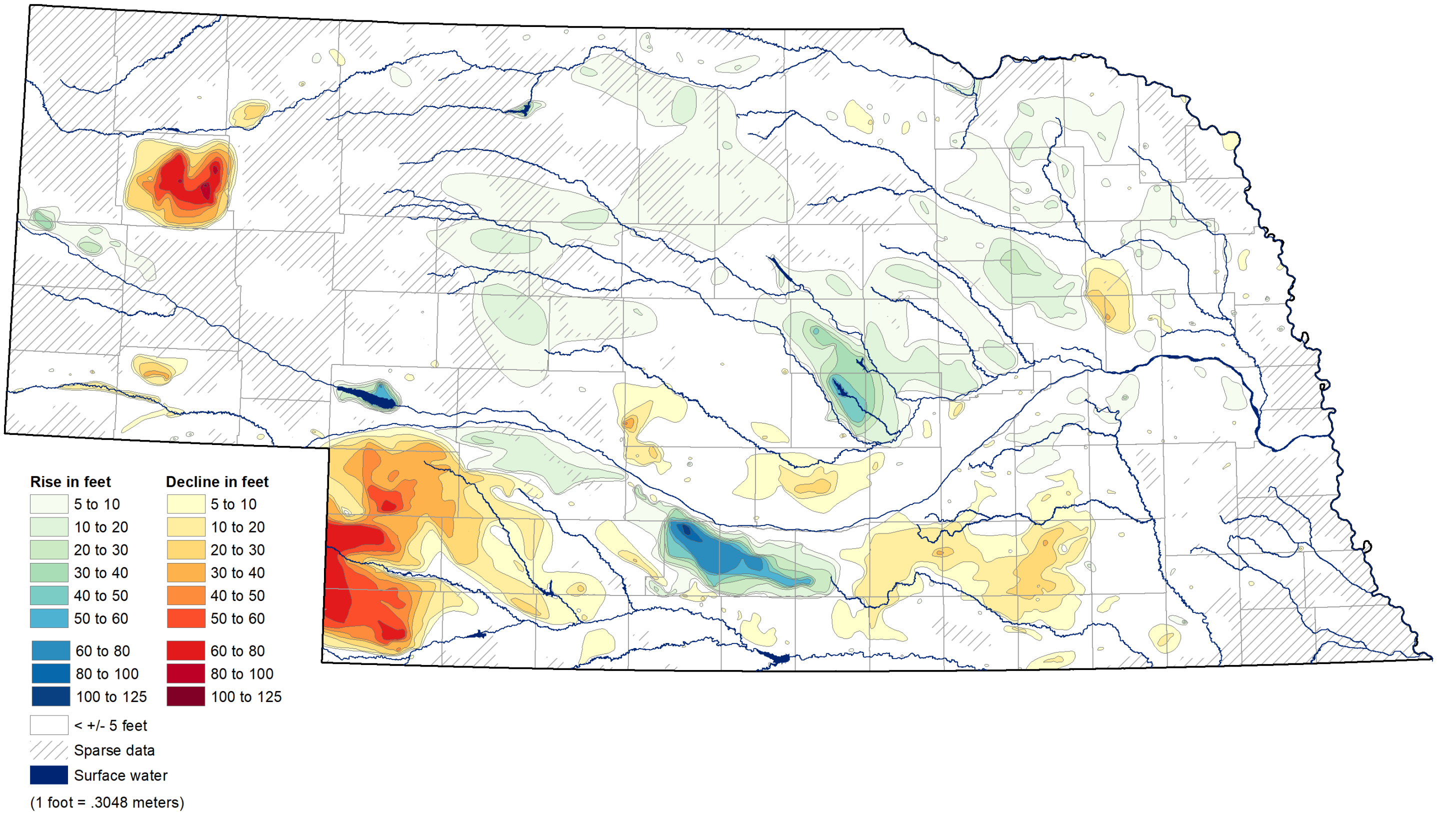
Much of southeastern to south-central Nebraska has experienced long-term groundwater-level declines since predevelopment times (Fig. 13). Predevelopment water levels in this area are generally representative of the approximate average water levels prior to 1950. Groundwater levels in large parts of this region have declined more than 10 feet, and in some areas by more than 30 feet, since predevelopment.

Groundwater-level declines also occurred in large areas between the Platte and Loup or South Loup rivers and in the Republican River Valley and the Panhandle. Irrigation-well densities are high in some, but not all, of the aforementioned areas. Aquifer characteristics, rates of recharge, and irrigation scheduling may have contributed to these declines as well.

Groundwater-level rises from predevelopment generally occurred in areas of surface-water irrigation systems. Storage of water in Lake C. W. McConaughy began in 1941, and seepage losses caused groundwater-level rises of as much as 60 feet in nearby observation wells (Ellis and Dreeszen, 1987). Groundwater levels around the lake generally stabilized by about 1950 and since then have fluctuated in response to changes in reservoir levels and precipitation (Johnson and Pederson, 1984). Water released from storage in Lake C. W. McConaughy is subsequently diverted from the Platte River near Sutherland west of North Platte, and then flows through the Tri-County Canal and a series of reservoirs toward Dawson, Gosper, Phelps, and Kearney counties, where it has been used for irrigation since 1941. The deep percolation of water from these irrigation-distribution systems and from excess water applied to crops has gradually increased groundwater levels by more than 100 feet (Fig. 13). Groundwater levels have also risen in response to seepage from Sutherland Reservoir, Lake Maloney, and their associated canals in eastern Keith and central Lincoln counties. Similarly, there are groundwater-level rises of as much as 60 feet associated with irrigation canals in southern Sioux, Scotts Bluff, and western Morrill counties.

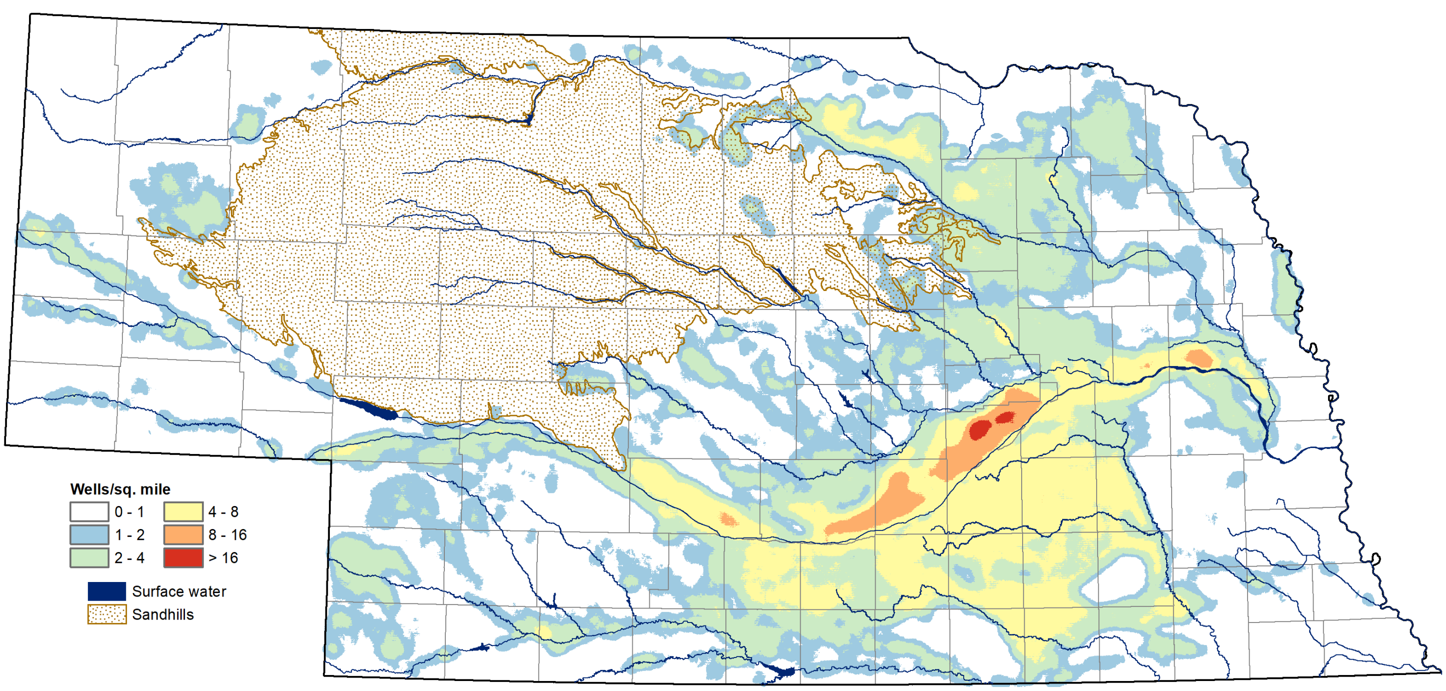
Groundwater-level rises of 10 to more than 50 feet occurred in portions of central Nebraska (Fig. 13). The highest groundwater-level rises occurred in Valley, Sherman, and Howard counties in response to sustained seepage from irrigation canals, Sherman and Davis Creek reservoirs, and the deep percolation of irrigation water applied to crops.

Figure 13. Groundwater-Level Changes in Nebraska - Predevelopment to Spring 2021



Sources: U.S. Geological Survey, Nebraska Water Science Center; U.S. Bureau of Reclamation, Kansas-Nebraska Area Office; Nebraska Natural Resources Districts; Central Nebraska Public Power and Irrigation District

Figure 14. Density of Active Registered Irrigation Wells - December 2021



Source: Nebraska Department of Natural Resources

CHANGES IN GROUNDWATER LEVELS, PREDEVELOPMENT TO SPRING 1981 AND SPRING 1981 TO SPRING 2020

Prior to 1981, groundwater levels were declining in nearly all areas of the state. After 1981, however, markedly different changes occurred in the east compared to the west.

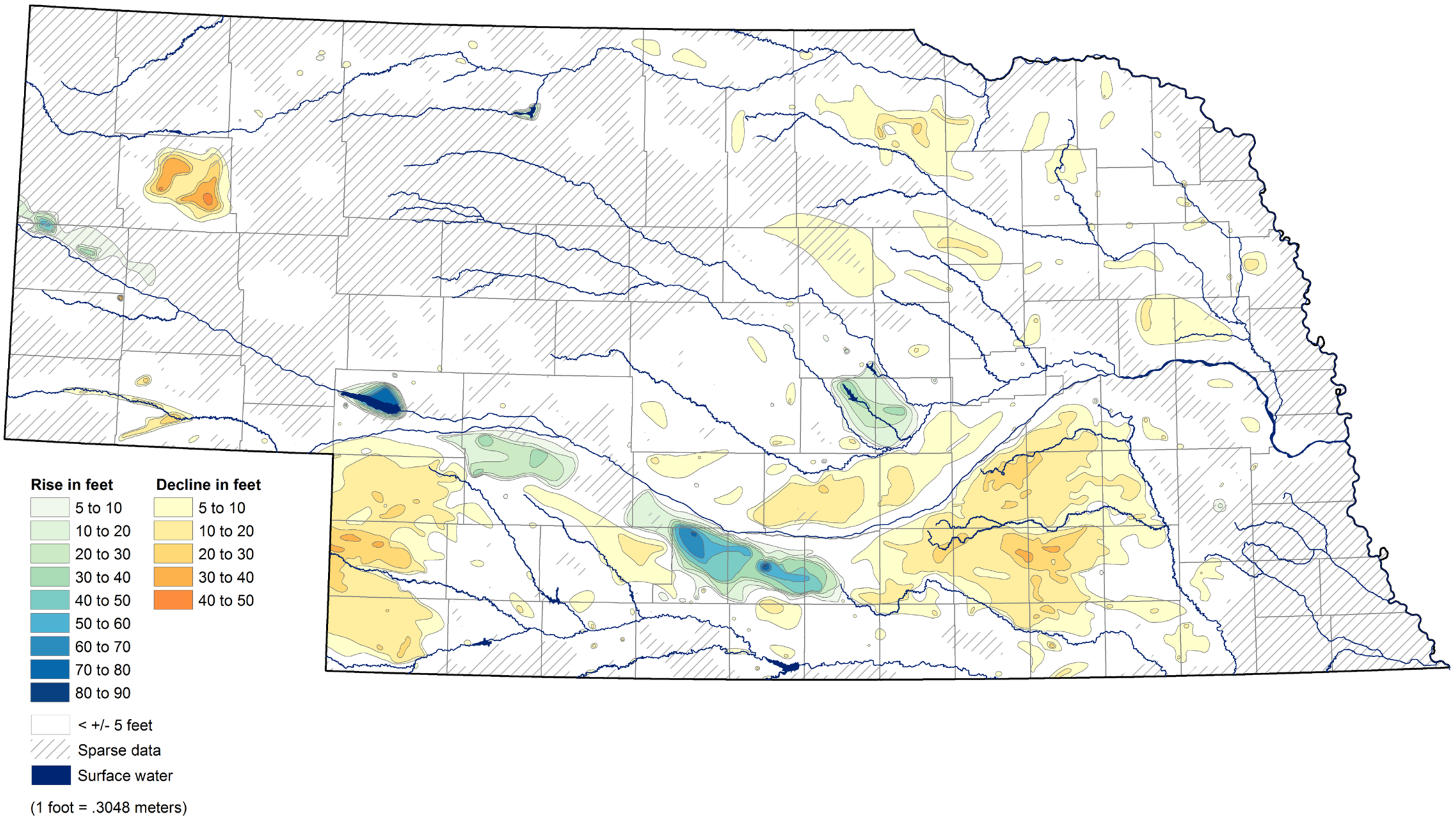
Groundwater-level changes from predevelopment to spring 1981 reflect the responses of aquifers to the spread of groundwater and surface-water-irrigation systems in Nebraska. Areas of significant groundwater-level declines exhibit a general correspondence with dense irrigation wells (cf. Johnson and Pederson, 1981). Declines were generally equal in magnitude in both the eastern and western areas (Fig. 15). The largest areas in which declines occurred were in Box Butte County in the Panhandle, Chase, Perkins, and Dundy counties in southwestern, south-central and southeastern Nebraska, Platte River Valley, central Nebraska, and northeast portion of the Sand Hills. Declines exceeded 40 feet in Box Butte County in the Panhandle, 30 feet in Chase County in the southwest, and as much as 10 feet in Clay and Fillmore counties in the south central. Declines occurred in smaller areas of the Republican River drainage as well as the northeast. Almost all groundwater-irrigated areas in Nebraska experienced declines of some magnitude. Such declines are the unavoidable responses of aquifers to development, according to laws of hydrologic mass balance (Korus and Burbach, 2009a).

Groundwater-level rises from predevelopment to spring 1981 were associated with irrigation canal systems and reservoirs (Fig. 15). The rise in southern Sioux and northern Scotts Bluff counties can be related to seepage from the Interstate Canal System, among numerous smaller systems, and excess water applied to crops beginning in the early 20th century. The rise in this area locally exceeds 50 feet. The groundwater-level rise in Cherry County is associated with seepage from Merritt Reservoir since the mid-1960s. It exceeds 20 feet immediately adjacent to the reservoir. Seepage from Lake C. W. McConaughy since 1941 caused groundwater levels to rise more than 100 feet by 1981. Reservoirs and canals south of the Platte River, which are used for hydroelectric power production and irrigation, provided seepage that caused groundwater levels to rise from eastern Keith County to western Kearney County (see discussion in previous section). Groundwater levels began rising in this area after 1941 and had nearly reached their maximum by 1981. In Howard and Sherman counties, groundwater levels began rising in 1963 due to seepage from Sherman Reservoir, its irrigation-distribution system, and deep percolation of irrigation water applied to crops. Rises of 10 to more than 30 feet occurred in this two-county area by 1981.

A much different pattern of groundwater-level changes has emerged in Nebraska since 1981 (Fig. 16). In central and eastern Nebraska, areas in which declines had occurred from predevelopment times until 1981 subsequently experienced rises of 5 feet to more than 20 feet from 1981 to 2021. This pattern of pre-1981 decline and post-1981 recovery is evident in many wells, including the Hastings recorder well, which has a continuous record dating to the mid-1930s. Although water levels in Polk, Hamilton and York Counties continue to rise from 1981 levels, rising levels have slowed or begun to decline in other counties in south-central and southeastern Nebraska since the drought of 2012, thereafter, water levels in this region have fluctuated yearly.

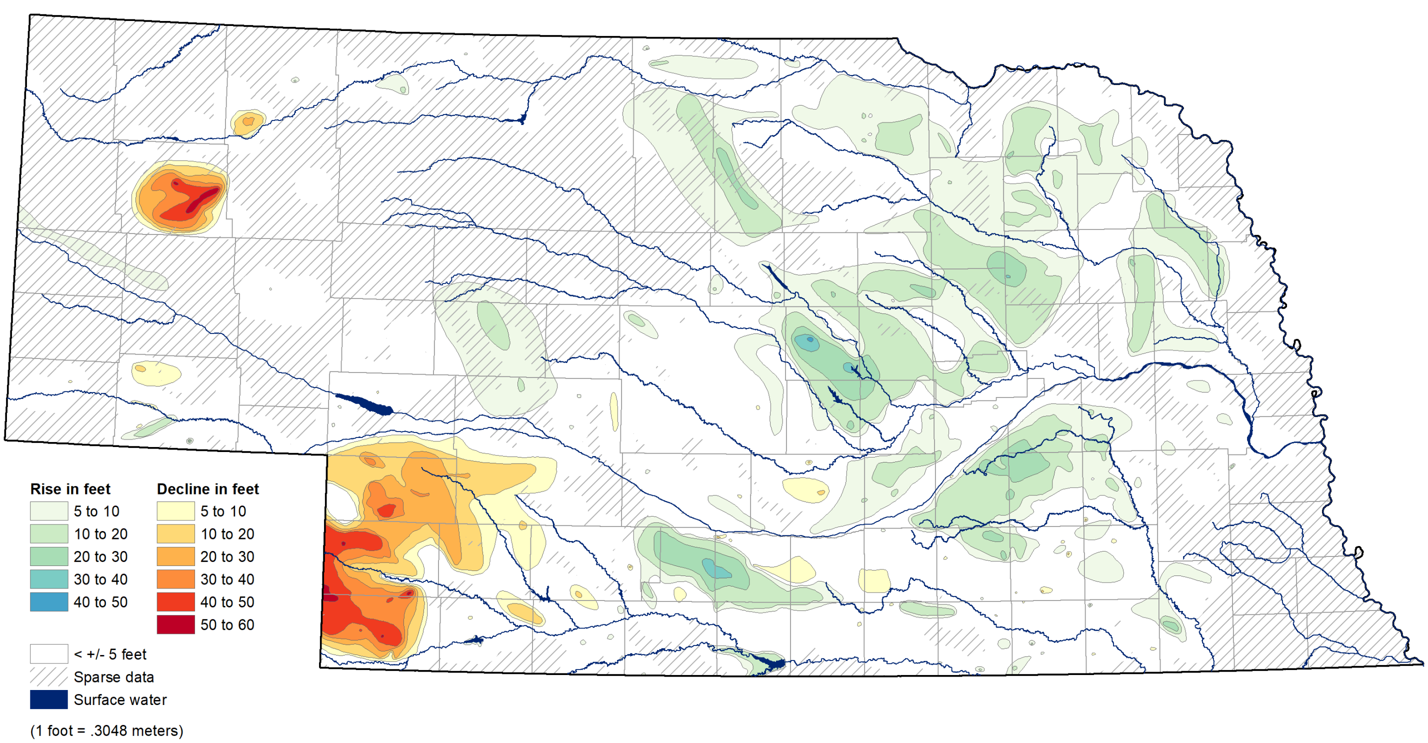
Declines in south-central and southeastern Nebraska reached a maximum in 1981 and then recovered. Declines in some parts of these two regions of the state are now less than 5 to 10 feet relative to predevelopment levels (Figs 13, 15, 16). Groundwater levels in most of south-central and southeastern Nebraska combined, however, remain below predevelopment levels by 5 feet to more than 30 feet. The post-1981 recovery of groundwater levels in south-central and southeastern Nebraska probably resulted from a combination: (1) reduced groundwater withdrawals during several long periods of above-average precipitation, (2) increased irrigation efficiencies that resulted in reduced pumping rates and volumes, and (3) stabilization of groundwater levels as the aquifer equilibrated to the new hydrological conditions imposed on it by irrigation development decades earlier (Korus and Burbach, 2009a). These rises may also be related to increasing rates of recharge. In some areas, a shallow water table aquifer is separated from the primary aquifer by a confining layer. Irrigation during the first several decades after development was primarily by means of flooding

Figure 15. Groundwater-Level Changes in Nebraska - Predevelopment to Spring 1981



Sources: U.S. Geological Survey, Nebraska Water Science Center; U.S. Bureau of Reclamation, Kansas-Nebraska Area Office; Nebraska Natural Resources Districts; Central Nebraska Public Power and Irrigation District

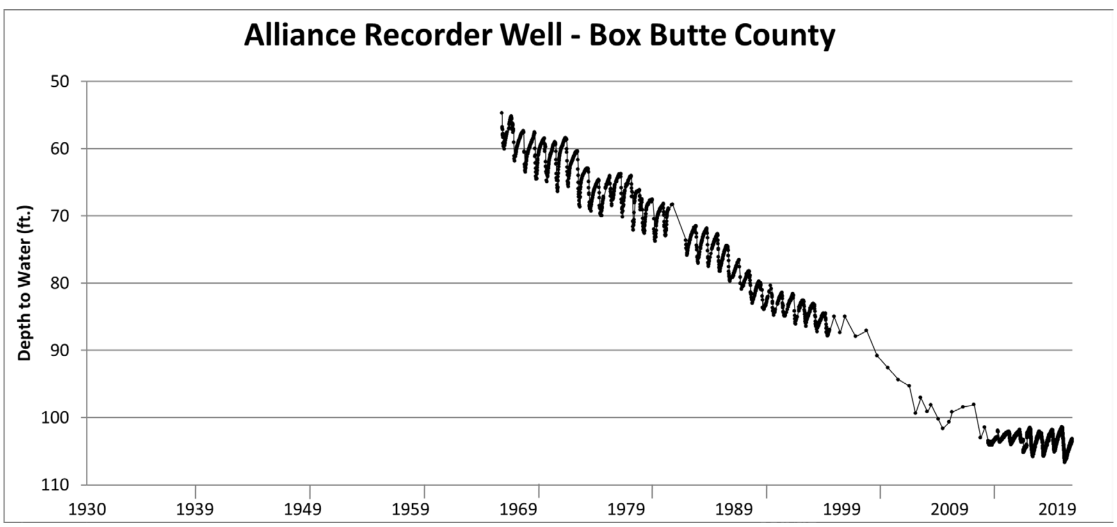
Figure 16. Groundwater-Level Changes in Nebraska - Spring 1981 to Spring 2021

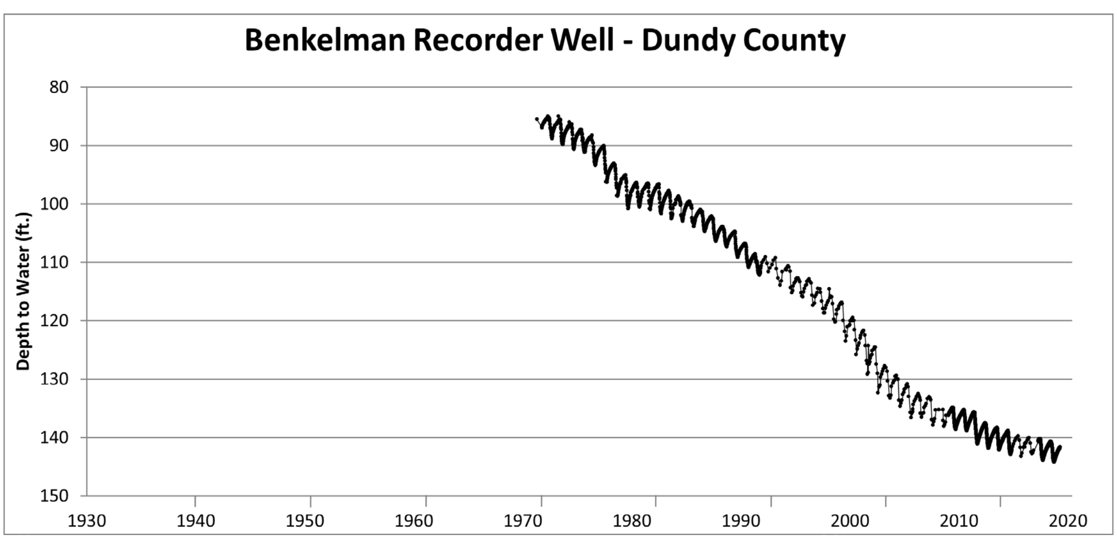


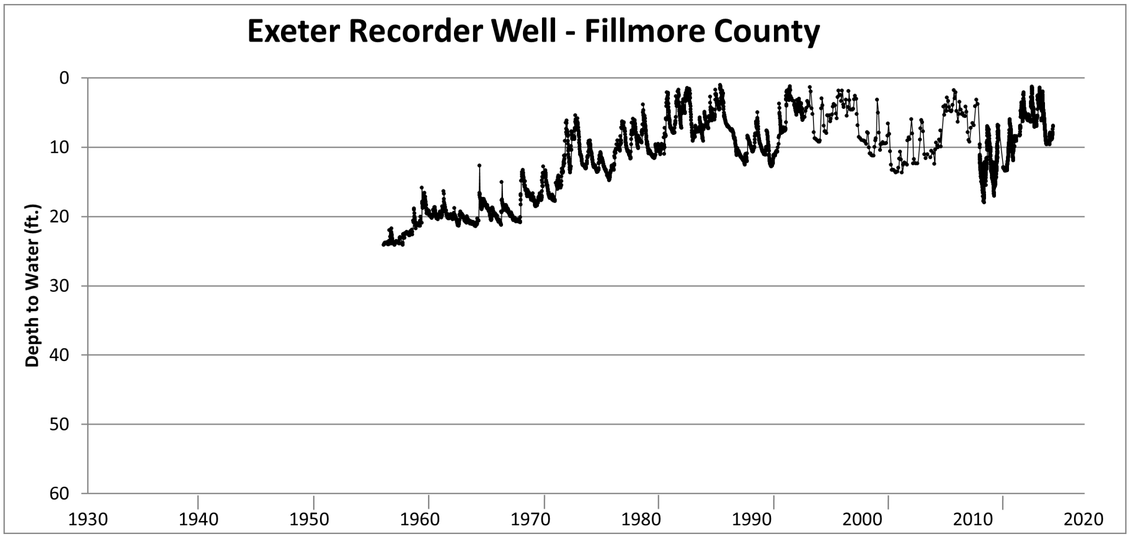
Sources: U.S. Geological Survey, Nebraska Water Science Center; U.S. Bureau of Reclamation, Kansas-Nebraska Area Office; Nebraska Natural Resources Districts; Central Nebraska Public Power and Irrigation District along rows of crops. This method resulted in the over application of water and deep percolation, which artificially recharged the shallow aquifer. The hydrograph for the Exeter recorder well, which is screened in the shallow aquifer, exemplifies this phenomenon (Fig. 17). The steady groundwater-level rise in this well between 1956 and 1981 temporally corresponds to the steady decline observed in nearby wells that are screened in the deep aquifer. Excess irrigation water pumped from the deep aquifer probably recharged the primary aquifer wherever the confining layer is discontinuous or semipermeable. Under these circumstances, surface water would percolate slowly down to the primary aquifer over a long period of time.

In contrast to the groundwater-level rises in the east, levels continued to decline in parts of western Nebraska from 1981 to 2021 (Fig. 16). The Alliance, Benkelman, and Imperial recorder wells show declines of 50 to 60 feet in just 50 years, an average decline of about 1 foot per year (Fig. 17). Brief periods of unchanging or rising groundwater levels occurred, but the rates of decline were steady overall despite changes in groundwater management practices, water use allocations, and fluctuations in the amount of annual precipitation over the past 30 years. The pattern of long-term groundwater-level decline over a large region, such as southwestern Nebraska or Box Butte County, is a normal response of an aquifer to irrigation development. Such declines reflect the release of water from storage in the aquifer and the adjustment of the water table to new hydrological stresses (Korus and Burbach, 2009a). These declines will stabilize only if groundwater withdrawals do not exceed the total yield of the aquifer, which is a function of its hydrogeological characteristics, as well as its sources and rates of recharge.

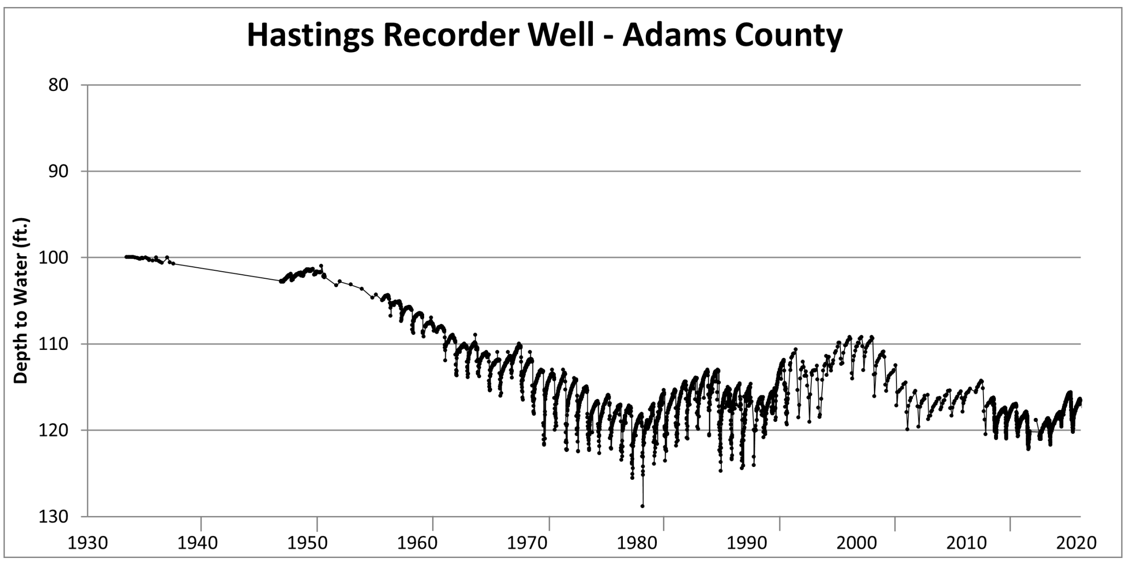
Figure 17. Groundwater-Level Hydrographs Typical of Southwestern and Southeastern Nebraska

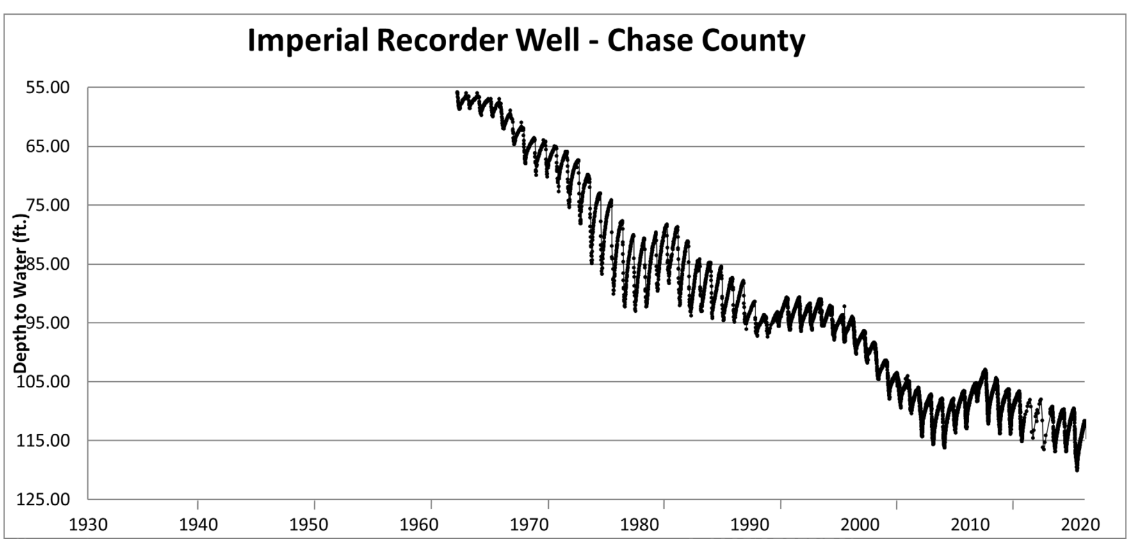






Groundwater level measurements for the Exeter recorder well were discontinued in July 2018





REFERENCES

6 News Staff, 2021. “Drought Conditions Affect Missouri River.” WOWT 6 News, 5 August, 2021 [https://www.wowt.com/2021/08/05/drought-conditions-affect-missouri-river/]. Accessed February 8, 2022.

10/11 NOW, 2021. “Northeast Lincoln Residents Asked to Flush Water Lines.” 10/11 NOW Koln/KGIN, 2 November, 2021 [https://www.1011now.com/2021/11/02/northeast-lincoln-residents-asked-flush-water-lines/]. Accessed February 8, 2022.

Alley, W.M., and Leake S.A., 2004. “The Journey from Safe Yield to Sustainability.” Ground Water, v. 42, p. 12-16.

Bredehoeft, J.D., 1997. “Safe Yield and the Water Budget Myth.” Ground Water, v. 35, p. 929.

Burbach, M.E., 2007, “Groundwater-Level Changes in Nebraska, Spring 2000 to Spring 2007”. University of Nebraska-Lincoln Conservation and Survey Division, Water Survey Map 74.

Anonymous, 2021. “Gov. Ricketts Slams Biden-Harris Administration’s WOTUS Overreach.” Office of Governor Pete Ricketts, 19 November, 2021 [https://governor.nebraska.gov/press/gov-ricketts-slams-biden-harris-administration%E2%80%99s-wotus-overreach]. Accessed February 8, 2022.

Associated Press, 2021. “Missouri River Winter Water Release Expected to be Near Minimum.” KSDK News (St. Louis, MO), 3 June, 2021 [https://www.ksdk.com/article/news/local/missouri-river-winter-water-release-expected-to-be-minimum-this-year-says-army-corps-engineers/63-2bbfd24b-8058-4fbe-a41c-10bc5512aefb]. Accessed February 8, 2021.

Bonderson, A., 2021. “Small Nebraska Town Experiencing Water Filtering Issues.” Nebraska Public Media, 1 December, 2021 [https://nebraskapublicmedia.org/en/news/news-articles/small-nebraska-town-experiencing-water-filtering-issues/]. Accessed February 7, 2022.

Campbell, T., 2021. “Major Ice Jam Along Platte River Begins Breaking Free.” WOWT 6 News, 28 February, 2021 [https://www.wowt.com/2021/03/01/major-ice-jam-along-platte-river-begins-breaking-free/]. Accessed February 8, 2022.

Cole, K., Cordes, H.J., and Gaarder, N., 2021. “Fast, Heavy Rains Cause Street Flooding, Property Damage in Omaha.” Omaha World-Herald, 8 August, 2021 (updated 15 September, 2021) [https://omaha.com/weather/fast-heavy-rains-cause-street-flooding-property-damage-in-omaha/article_6c1e212c-f847-11eb-b0f3-53a41d093359.html]. Accessed February 7, 2022.

Dunker, C., 2021a. “Spill From Troubled Mead Ethanol Plant Traveled 4 Miles in Waterways, State Says.” Lincoln Journal-Star, 17 February, 2021 (updated 2 November, 2021) [https://journalstar.com/news/state-and-regional/nebraska/spill-from-troubled-mead-ethanol-plant-traveled-4-miles-in-waterways-state-says/article_b2cd27a1-643d-5c99-befe-fe8cffeff80e.html]. Accessed February 7, 2022.

Dunker, C., 2021b. “After 25 Years and Millions of Dollars, Superfund Cleanup Continues in Mead Area.” Lincoln Journal-Star, 28 March, 2021 (updated 3 May, 2021) [https://journalstar.com/news/state-and-regional/govt-and-politics/after-25-years-and-millions-of-dollars-superfund-cleanup-continues-in-mead-area/article_dce36eca-6e0e-5cf9-83cd-a2c10f0955f3.html]. Accessed February 7, 2022.

Dunker, C., 2021c. “Small Amounts of Pesticides Detected in Groundwater 6 Miles from AltEn Site.” Lincoln Journal-Star, 9 September, 2021 (updated 15 October, 2021) [https://journalstar.com/news/state-and-regional/nebraska/small-amounts-of-pesticides-detected-in-groundwater-6-miles-from-alten-site/article_fb95662a-d31d-5b5e-9dad-96b635c03459.html]. Accessed February 7, 2022.

Ellis, M.J., and Dreeszen, V.H., 1987. Groundwater Levels in Nebraska, 1986. University of Nebraska-Lincoln, Conservation and Survey Division, Nebraska Water Survey Paper 62, 68 p.

Hopkins, G., 2021. “City Remains Under Water Conservation Order.” Fairbury Journal-News 3 September, 2021 [https://fairburyjournalnews.com/city-remains-under-water-conservation-order/]. Accessed February 7, 2022.

Johnson, M.S., and Pederson, D.T., 1981. Groundwater Levels in Nebraska, 1980. University of Nebraska-Lincoln, Conservation and Survey Division, Nebraska Water Survey Paper 51, 65 p.

Johnson, M.S., and Pederson, D.T., 1984. Groundwater Levels in Nebraska, 1983. University of Nebraska-Lincoln, Conservation and Survey Division, Nebraska Water Survey Paper 57, 67 p.

Jones, D., 2021. "Heavy Rains Lead to Flash Flooding in Eastern Nebraska." NPR News, 8 August, 2021 [https://www.npr.org/2021/08/08/1025941135/heavy-rains-lead-to-flash-flooding-in-eastern-nebraska]. Accessed February 7, 2022.

KMTV Staff, 2021. "Wastewater Treatment Plant Back Online Following Overnight Storm." KMTV 3 News Now Omaha, 10 July, 2021 [https://www.3newsnow.com/news/local-news/wastewater-treatment-plant-heavily-damaged-by-storm]. Accessed February 7, 2022.

Korus, J.T., and Burbach, M.E., 2009a. Analysis of Aquifer Depletion Criteria with Implications for Groundwater Management. Great Plains Research, v. 19, p. 187-200.

Korus, J.T., and Burbach, M.E., 2009b. Nebraska Statewide Groundwater-Level Monitoring Report 2009. University of Nebraska-Lincoln, Conservation and Survey Division, Nebraska Water Survey Paper 76, 38 p.

Korus, J.T., Howard, L.M., Young, A.R., Divine, D.P., Burbach, M. E., Jess, J.M., and Hallum, D. H., 2013. The Groundwater Atlas of Nebraska. Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln. Resource Atlas 4b/2013. 64 p.

Korus, J.T., and Joeckel, R.M., 2011. Generalized Geologic and Hydrostratigraphic Framework of Nebraska 2011, ver. 2. Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln. Geologic Maps and Charts (GMC) 38.

Lundgren, H., 2021a. "Platte River Ice Jams Continue to Cause Flooding in Eastern Nebraska." WOWT 6 News, 3 March, 2021 [https://www.wowt.com/2021/03/03/flood-watch-continues-in-eastern-nebraska-due-to-ice-jams-along-platte-river/]. Accessed February 8, 2022.

Lundgren, H., 2021b. "Flood Warning Canceled for Dodge County, Ice Jam Breaks Through." WOWT 6 News, 5 March, 2021 [https://www.wowt.com/2021/03/05/flood-warning-canceled-for-dodge-county-ice-jam-breaks-through/]. Accessed February 8, 2022.

Maimone, M., 2004. Defining and Managing Sustainable Yield. Ground Water, v. 42, p. 809-814.

McGuire, V.L., Lund, K.D., and Densmore, B.K., 2012. Saturated Thickness and Water in Storage in the High Plains Aquifer, 2009, and Water-Level Changes and Changes in Water in Storage in the High Plains Aquifer, 1980 to 1995, 1995 to 2000, 2000 to 2005, and 2005 to 2009. U.S. Geological Survey Scientific Investigations Report 2012–5177, 28 p.

National Climatic Data Center, National Oceanic and Atmospheric Administration, 2020. Online Climate Data. [https://www.ncdc.noaa.gov/cdo-web/datasets]. Data Retrieved September 22, 2020.

Nebraska Department of Environment and Energy, 2021. "Mead Facility Completes Shutdown Following NDEE Order." Nebraska Department of Environment and Energy [http://www.deq.state.ne.us/NDEQProg.nsf/Page_1.xsp?databaseName=CN=DEQSER6/O=NDEQ!!Press.nsf&documentId=A5B62790A52C383B8625867700754717&action=openDocument]. Accessed February 7, 2022.

Nebraska Department of Environment and Energy, 2022. "Information and Updates for AltEn Near Mead, Nebraska." Nebraska Department of Environment and Energy [http://dee.ne.gov/Press.nsf/pages/AltEn]. Accessed February 7, 2022.

Nebraska Legislature, 2021a. LB507, "Change provisions relating to hunting permits, electors under the Irrigation District Act, and the Water Sustainability Fund and prohibit the use of treated seed in the production of agricultural ethyl alcohol." [https://nebraskalegislature.gov/bills/intro.php]. Accessed February 7, 2022.

Nebraska Legislature, 2021b. LB650, "Adopt the Nebraska Geologic Storage of Carbon Dioxide Act." [https://nebraskalegislature.gov/bills/view_bill.php?DocumentID=43955]. Accessed February 7, 2022.

NTV News, 2021-1. “Mead Community Rocked by Second AltEn Spill Amid Cleanup and Heavy Rains.” NTV News, 3 September, 2021 [https://nebraska.tv/news/local/mead-community-rocked-by-second-alten-spill-amid-clean-up-and-heavy-rains]. Accessed February 7, 2022.

Salter, P., 2021. “Feds Pledge $50 Million to Help Remove Failed Spencer Dam.” Lincoln Journal-Star, 30 April, 2021 (updated 8 June, 2021) [https://journalstar.com/news/state-and-regional/nebraska/feds-pledge-50-million-to-help-remove-failed-spencer-dam/article_d7beea9a-725c-5286-a272-882b22f088ae.html]. Accessed February 7, 2022.

Schnell, M., 2021. “FIRST ALERT: Spring Flood Outlook 2021.” WOWT 6 News, 17 February, 2021 (updated 18 February, 2021) [https://www.wowt.com/2021/02/17/first-alert-spring-flood-outlook-2021/]. Accessed February 8, 2022.

Sophocleous, M.A., 1997. Managing Water Resources Systems: Why “Safe Yield” is not Sustainable. Ground Water, v. 35, p. 561.

Sophocleous, M.A., 1998. On the Elusive Concept of Safe Yield and the Response of Interconnected Stream-Aquifer Systems to Development. In Perspectives on Sustainable Development of Water Resources in Kansas, ed. M.A. Sophocleous, p. 6-85. Kansas Geological Survey Bulletin 239. KGS, Lawrence, KS.

Sophocleous, M.A., 2000. From Safe Yield to Sustainable Development of Water Resources–the Kansas Experience. Journal of Hydrology, v. 235, p. 27-43.

United States Department of Agriculture, 2017. Census of Agriculture. [URL Https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf/]. Accessed January 20, 2021.

United States Environmental Protection Agency, 2021a. “EPA Announces $263,000 Grant for Nebraska to Improve Drinking Water for Underserved, Disadvantaged Communities.” News Releases: Region 07, 27 August, 2021 [https://www.epa.gov/newsreleases/epa-announces-263000-grant-nebraska-improve-drinking-water-underserved-disadvantaged]. Accessed February 7, 2022.

United States Environmental Protection Agency, 2021b. “EPA Announces Over $63 Million in 2022 Water Infrastructure Funding for Nebraska.” News Releases: Region 07, 2 December, 2021 [ww.epa.gov/newsreleases/epa-announces-over-63-million-2022-water-infrastructure-funding-nebraska]. Accessed February 7, 2022.

Walton, D., 2021. “Nebraska Will Get $65 Million More in Federal Flooding Aid.” Lincoln Journal-Star, 2 June, 2021 (updated 8 July, 2021) [https://journalstar.com/news/state-and-regional/govt-and-politics/nebraska-will-get-65-million-more-in-federal-flooding-aid/article_16f42372-94d5-54ff-8c28-1aa71833c0ee.html]. Accessed February 8, 2022.

Wiltsey, E., 2021a. “Water Shortage Sparks Sprinkler Ban in Rural Lancaster County.” KOLN/KGIN 10 11 Now, 10 June, 2021 [https://www.1011now.com/2021/06/11/water-shortage-sparks-sprinkler-ban-rural-lancaster-county/]. Accessed February 7, 2022.

Wiltsey, E., 2021b. “What’s Next: Keystone XL Pipeline Canceled, Lawsuits Remain.” KOLN/KGIN 10 11 Now, 9 June, 2021 [https://www.1011now.com/2021/06/10/whats-next-keystone-xl-pipeline-canceled-lawsuits-remain/]. Accessed February 8, 2022.

Groundwater-Level Changes in Nebraska Map Series
Available online at http://snr.unl.edu/data/water/groundwatermaps.asp

Year	Publication and Number	Author(s) and year published
pre 1954	U.S.G.S. Open-File Rpt. 54-138	Keech, C.F.; Case, R.L., 1954
1954	U.S.G.S. Open-File Rpt. 55-80	Keech, C.F.; Case, R.L., 1955
1955	U.S.G.S. Open-File Rpt. 56-70	Keech, C.F., 1956
1956	U.S.G.S. Open-File Rpt. 57-61	Keech, C.F., 1957
1957	Nebraska Water Survey Paper 4*	Keech, C.F., 1958
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