3-2020

Recharge Seasonality Based on Stable Isotopes: Nongrowing Season Bias Altered by Irrigation in Nebraska

Mikaela Cherry

Troy E. Gilmore

Aaron R. Mittelstet

Didier Gastmans

Vinicius Santos

See next page for additional authors

Authors
Mikaela Cherry, Troy E. Gilmore, Aaron R. Mittelstet, Didier Gastmans, Vinicius Santos, and John Gates

Cherry Mikaela (Orcid ID: 0000-0003-1081-0296)

Mittelstet Aaron (Orcid ID: 0000-0001-9857-5539)

Gastmans Didier (Orcid ID: 0000-0002-1340-3373)

Mikaela Cherry (Orcid ID: 0000-0003-1081-0296)

Recharge Seasonality Based on Stable Isotopes: Nongrowing Season Bias Altered by Irrigation in Nebraska

Running head: groundwater recharge seasonality

Author's names: Mikaela Cherry[1], Troy Gilmore [1,2], Aaron Mittelstet[2], Didier Gastmans [3], Vinicius Santos[3], John Gates[4]

1. University of Nebraska – Conservation and Survey Division, School of Natural Resources, Lincoln, Nebraska, USA. 101 Hardin Hall, 3310 Holdrege Street, Lincoln, NE 68583-0996
2. University of Nebraska – Department of Biological Systems Engineering, Lincoln, Nebraska, USA. 223 L. W. Chase Hall, Lincoln, NE 68583-0726
3. São Paulo State University (UNESP) - Environmental Studies Center, AV. 24A, 1515 – Bela Vista, Rio Claro, Sao Paulo, BR 13506-900
4. Climate Corporation, San Francisco, CA, USA.

Corresponding Author: Mikaela Cherry, Mikaela.cherry@huskers.unl.edu

Acknowledgements

The authors thank the U.S. Department of Agriculture - National Institute of Food and Agriculture (Hatch project NEB-21-177), the Nebraska Environmental Trust (grant # 18-135), the SPRINT FAPESP (project number: 2017/50038-5), and the FAPESP scholarship (Process number 2016/18735-5) for the support. The authors also thank the Natural Resources Districts for assistance with sample collection. The authors thank Aaron Young and Dana Divine for their discussion of Nebraska aquifers and Colleen Steele and Michele Waszigis for data compilation.

Data Availability Statement: The data that support the findings of this study are available upon reasonable request from the corresponding author. Groundwater isotope data will be made available at http://wateriso.utah.edu/waterisotopes/index.html.

Abstract

The sustainability of groundwater resources for agricultural and domestic use is dependent on both the groundwater recharge rate and groundwater quality. The main purpose of this study was to improve understanding of the timing, or seasonality, of groundwater recharge through the use of stable isotopes. Based on 659 groundwater samples collected from aquifers underlying Natural Resources Districts in Nebraska, the isotopic composition of groundwater (δ^{2}H, δ^{18}O) was compared to that of precipitation by (a) mapping the isotopic composition of groundwater samples and (b) mapping a seasonality index for groundwater. Results suggest that for the majority of the state, groundwater recharge has a nongrowing season signature (October – April). However, the isotopic composition of groundwater suggests that in some intensively irrigated areas, human intervention in the water cycle has shifted the recharge signature toward the growing season. In other areas, a different human intervention (diversion of Platte River water for irrigation) has likely produced an apparent but possibly misleading nongrowing season recharge signal because the Platte River water differs isotopically from local precipitation. These results highlight the need for local information even when interpreting isotopic data over larger regions. Understanding the seasonality of recharge can provide insight into the optimal times to apply fertilizer, specifically in highly conductive soils with high leaching potential. In areas with high groundwater nitrate concentrations this information is valuable for protecting the groundwater from further degradation. While previous studies have framed nongrowing season recharge within the context of future climate change, this study also illustrates the importance of understanding how historical human intervention in the water cycle has affected groundwater recharge seasonality and subsequent implications for groundwater recharge and quality.

Key Words: Groundwater, High Plains Aquifer, Recharge, Stable Isotopes, Isoscapes

1. Introduction

The quantity and timing of groundwater recharge are both important factors for managing groundwater systems. However, many recharge estimates are in terms of annual recharge and lack information on seasonal recharge characteristics and the influence of human activities (e.g., irrigation) on recharge seasonality (Assefa & Woodbury, 2013; Fiedler, 2007; Fortune, 2010). Studies that incorporate future climate projections into their groundwater models (Crosbie et al., 2013; Meixner et al., 2016) illustrate that precipitation quantities and timing will impact the groundwater recharge rate, including in the Northern High Plains aquifer in Nebraska (Lauffenburger, Gurdak, Hobza, Woodward, & Wolf, 2018). Changes in presence and type of vegetation may also impact groundwater recharge rates (Han, Currell, Cao, & Hall, 2017; Keese, Scanlon, & Reedy, 2005; Scanlon et al., 2006; Scanlon, Reedy, Stonestrom, Prudic, & Dennehy, 2005). Approaches to agricultural water management will shift over time to adapt to these new realities, making predictions of climate impacts on groundwater resources more difficult. It is valuable to understand how past agricultural management practices may have altered recharge dynamics in order to inform future predictions.

Alteration of groundwater recharge through land cover change may lead to a substantial increase or decrease in available groundwater resources (Han et al., 2017). In agricultural systems with distinct growing seasons, recharge from irrigation-related sources may alter the timing and magnitude of recharge and therefore the volume of groundwater storage. Irrigation return flows (deep drainage) and canal leakage have led to spatial patterns of groundwater isotopic composition (Joshi et al., 2018). Groundwater systems may show vertical stratification of isotopic composition, indicating the extent to which altered recharge sources have displaced or overlain groundwater that was recharged under natural conditions (Böhlke, O'Connell, & Prestegaard, 2007; Harvey & Sibray, 2001).

Recharge seasonality not only influences the quantity of groundwater, but also has implications for groundwater quality (Matiatos & Wassenaar, 2019). It is important to understand how modern agricultural practices have influenced the timing of groundwater recharge and the implications for future management of water quantity and quality. There is a strong linkage between field-scale agricultural water management and leaching of agro-chemicals (including nitrate) into groundwater (Exner, Hirsh, & Spalding, 2014). Timing of both fertilizer and water application is necessary to reduce leaching (Derby, Casey, & Knighton, 2009). However, the rate of development and adoption of best practices, the unpredictability of natural precipitation, and the complexity and timing of nitrogen cycling (mineralization, nitrification, denitrification, etc.) each have high uncertainty. Increased understanding of both natural and altered recharge processes is critical for identifying where and when groundwater quality is more likely to improve through optimal regulation and best management practices in agricultural regions.

Previous studies have used stable isotope signatures to show a seasonal bias in the timing of groundwater recharge (Jasechko et al., 2014, 2017), and to identify the relative importance of recharge sources such as high-intensity versus low-intensity precipitation (Jasechko et al., 2015) at continental or global scales. In this study, we evaluated the seasonality of groundwater recharge at regional scales, which are highly relevant to local management of groundwater quantity and quality in highly productive agricultural areas over a major recharge area in the northern High Plains Aquifer region. Thus, this study focuses on two topics that have received relatively little attention in previous regional-scale studies of recharge seasonality using stable isotopes: (1) the influence of agricultural water management (i.e., human intervention in the water cycle) on the seasonality of groundwater recharge, and (2) implications of natural and altered recharge seasonality for groundwater quality in agricultural landscapes.

2. Background and Methods

2.1 Site Description

The inner continental location of Nebraska (about 1,500 km from the Gulf of Mexico, Pacific and Atlantic Oceans; Figure 1) contributes to varying climate, from moist sub-humid climate in the east to dry, semi-arid climate in the west. Average annual temperatures show a NW-SE gradient ranging from 6.9ºC to 11.0ºC. Seasonal variation is characterized by hot summers, with July mean daily temperatures of 23.6ºC and cold winters, with mean temperatures of -5.5ºC in January (Owenby & Ezell, 1992, Frankson et al., 2017). Thirty-year normal precipitation (1981-2010) varies from 330 mm/year in the western border with Wyoming and to almost 900 mm/year in the southeastern border along the Missouri River (PRISM, 2019; Figure 1). Most of the precipitation falls during the spring and summer months (Figure 2), with 71% falling during the growing season of May 1 to September 30, but seasonal and annual precipitation is widely variable (Young et al., 2019, Frankson et al., 2017). Precipitation in the year of 2011, when the isotope samples were collected, was on-average higher across most of the western part of Nebraska compared to the 30 year normal (1970-2000 normal; Young et al. 2019), with drier conditions in the east.

Evapotranspiration (ET) tends to follow the same pattern as precipitation, with greater potential ET during the growing season based on statewide estimates for an alfalfa reference crop. Other agronomic crops may have similar seasonal patterns because actual ET is usually calculated using a linear crop coefficient (correction factor) multiplied by reference ET for alfalfa or grass (Irmak, Howell, Allen, Payero, & Martin, 2005). Land surface elevations also contribute to differences in climate, gradually transitioning from 1,655 m above sea level in the west to 256 m above sea level in the east.

Harvey (2001) and Harvey and Welker (2000) measured $\delta^{18}O$ and $\delta^{2}H$ in precipitation at two locations, Mead and North Platte, Nebraska (Figure 1). For the two stations, temperature measured during the same period (1989-1994) was quite similar to the 30-year normal values. Harvey (2001) and Harvey and Welker (2000) assumed that the isotopic composition for the period should be representative of normal precipitation with respect to temperature effects. The Mead station $\delta^{18}O$ ranged from -23.6 to -0.7‰ and $\delta^{2}H$ ranged from -172.0 to -0‰. The North Platte station $\delta^{18}O$ ranged from -30.5 to +1.7‰ and $\delta^{2}H$ ranged from -228.0 to +11.0‰. The isotopic composition of precipitation is more depleted during the nongrowing season months compared to the growing season (Figure 2). The majority of the annual precipitation falls during the growing season (Figure 2).

While only available from two stations, the isotope data for precipitation in Nebraska have been incorporated with other observations outside of Nebraska in the development of national and continental-scale isoscape maps (Bowen & Revenaugh, 2003) in ArcGrid format (Bowen, 2018). Given the absence of a spatially detailed, long term precipitation isotope dataset for Nebraska, we used the available gridded maps (Bowen, 2018) to determine monthly (Figure 2) and mean annual isotopic values for precipitation in Nebraska for this study. The maps are based on global precipitation data interpolated by an algorithm created by Bowen and Wilkinson (2002), which uses the relationship of latitude and altitude to predict isotopic composition (Bowen & Revenaugh, 2003; Bowen, Wassenaar, & Hobson, 2005; Bowen & Wilkinson, 2002, Welker, 2000). Below, all references to the gridded dataset are referenced as Bowen (2018).

2.2 Modeling Precipitation Sources

The origin and trajectory of air masses that have resulted in precipitation were evaluated using the HYSPLIT Model (Hybrid-Single Particle Langragian Integrated Trajectory - available at: http://ready.arl.noaa.gov/HYSPLIT_traj.php) (Stein et al., 2015). This model uses a three-dimensional Lagrangian air mass vertical velocity algorithm to determine the position of the air masses and reports these values at an hourly time resolution over the trajectory (Soderberg et al., 2013; Sánchez-Murillo et al., 2017). Air masses back trajectories were estimated for periods of 240 hours, which are in agreement with the estimated residence time of water in the atmosphere (Gimeno, Drumond, Nieto, Trigo, & Stohl, 2010; van der Ent & Tuinenburg, 2017). Trajectories were simulated using NOAA meteorological data (GDAS, global data assimilation system: 2006-present)(Su, Yuan, Fung, & Lau, 2015). The starting time 12:00 p.m. of the sampling day in North Plate. Ending elevations of the trajectories were set to 1,500 m above the surface, considered to be the height of the cloud base, typically between 700-850 hPa. Maps of trajectory frequencies were generated using the ArcGIS software, calculating the sum of the number of times the trajectories pass through one grid cell, of 3°x 3° size.

2.3 Groundwater Data Collection and Analysis

In the summer of 2011, 789 groundwater samples were collected by licensed groundwater technicians at Natural Resource Districts (NRDs) across Nebraska. Well purging was done according to standard procedures suitable for annual groundwater quality sampling (primarily nitrate) adopted by each NRD. Groundwater samples were collected in 30 mL bottles with screw-tight lids, filled to the neck and capped immediately after sampling. Electrical tape was wrapped around the lid before shipping to the University of Nebraska-Lincoln.

Samples collected by NRDs were analyzed for δ^2H and δ^{18}O of water by cavity ring down laser spectroscopy method, using a Picarro analyzer at the University of Nebraska-Lincoln. The equation for d-excess is d-excess= δ^2H-8* δ^{18}O (Dansgaard, 1964), and can be used to understand the source of moisture and evaporative processes. Two groundwater samples with a d-excess lower than -5‰ were removed from the dataset based on the assumption that there was an error in sampling, transport, or analysis.

All 789 samples collected had an NRD identifier. For 679 samples the exact well coordinates were also known. Of these 679 samples, 593 also had documented well depths. For two NRDs where samples were collected, but the well locations were not documented, a single representative data point based on the average isotopic composition was plotted. In the Lower Loup NRD, the data point was plotted at the centroid. For the Central Platte NRD, the data point was placed at the approximate east-west center of the NRD because the centroid was located outside the NRD boundary. One value used to represent groundwater isotopic composition for Twin Platte NRD was taken from and plotted in the approximate location described in Harvey and Welker (2000).

Groundwater nitrate data from the Quality-Assessed Agrichemical Contaminant Database (University of Nebraska-Lincoln, 2014) was used for mapping groundwater nitrate concentrations throughout the state. The database contains groundwater nitrate data from as early as the 1970s, and numerous published maps since the 1990s have shown consistent regional patterns of groundwater nitrate concentrations (e.g., Exner et al., 2014; NDEQ, 2017). For this study, nitrate data from years 2010-2014 were used to give a recent and comprehensive representation of groundwater nitrate in Nebraska. Groundwater nitrate samples recorded in the database were primarily collected by groundwater technicians using standard operating procedures adopted by their respective NRD. Quality assessment for the agrichemical database is described in Exner et al. (2005).

2.4 Seasonality calculation

In ArcGIS, raster files with the average monthly isotopic composition of precipitation were used to calculate a weighted average isotopic composition for the growing season, nongrowing season, and annual average. These values were then extracted from each of the groundwater sampling locations. The seasonality ratio was calculated after Jasechko et al. (2014, 2017) as

$$\frac{(R/P)_{growing}}{(R/P)_{nongrowing}} = \frac{\delta_{GW} - \delta_{P(growing)}}{\delta_{P(annual)} - \delta_{P(growing)}} \Big/ \frac{\delta_{GW} - \delta_{P(nongrowing)}}{\delta_{P(annual)} - \delta_{P(nongrowing)}}$$

where *R* and *P* represent groundwater recharge and precipitation fluxes, respectively. Subscripts *growing* and *nongrowing* indicate the growing season and nongrowing seasons, respectively. δ_{GW} represents the isotopic composition of groundwater and δ_P represents the isotopic composition of rainfall.

Previous studies have calculated a seasonality ratio based on a winter/summer ratio where winter is defined as all months where the average temperatures is below 0 °C (Jasechko et al. 2017). For this study, the seasonality ratios were calculated based on growing season (May 1 through September 30) and nongrowing season given the relevance of these two periods to the timing of crop production and irrigation, although the use of winter/summer time periods had similar results. A seasonality ratio greater than one indicates a nongrowing season bias for groundwater recharge. Locations with a negative recharge ratio were excluded from this study.

3. Results

3.1 Precipitation Source and Isotopic Variation

Based on Hysplit analyses, growing-season precipitation is most likely to originate from the Gulf of Mexico (Figure 3). This corresponds to precipitation that is more enriched in the heavier isotopes (δ^2H, $\delta^{18}O$). During the nongrowing season, precipitation is more likely to originate from the West over the Rocky Mountains. This precipitation is depleted due to the orographic effects of the Rocky Mountains as well as the Northern Pacific Ocean being a less enriched source of moisture than the Gulf of Mexico (Harvey and Welker, 2000). When calculated from available gridded data (Bowen, 2018), the seasonal cycle of $\delta^{18}O$ and δ^2H values yields more positive values in the summer and more negative values in the winter (Figure 2), which is typical of continental areas (Rozanski, Araguás-Araguás, & Gonfiantini, 1993). The seasonal cycle is also very consistent with the “U-shaped” patterns described by Harvey (2001) and Harvey and Welker (2000). The isotopic composition of the precipitation becomes more enriched throughout the year, peaks in July before becoming more depleted again.

The median isotopic signature for the modeled nongrowing season precipitation was more negative (-12.05‰) than for the mean groundwater value (-8.32‰), annual precipitation (-9.80‰) and growing season precipitation (-6.28‰) (Figure 4). Based on a Kruskal-Wallis test (used since the data were not normally distributed) the medians for the isotope signatures for growing season and nongrowing season precipitation were significantly different (*p*-value <<

0.01). Though the assumption of normality was not met, an ANOVA and Tukey's Comparison test were run. Each of the aforementioned means were significantly different from each other.

3.3 Spatial Isotopic Patterns of Precipitation and Groundwater

Mapping the isotopic composition of groundwater suggests a pattern of more depletion in the northwest compared to the southeast part of Nebraska (Figure 5B). This overall pattern of depletion is consistent with the statewide pattern for mean annual isotopic composition for precipitation (Figure 5A), but with a greater range in values and with greater spatial variation (Figure 5). $\delta^{18}O$ for groundwater ranged from -17.9‰ to -6.0‰ (mean = -9.85±2.1‰). Groundwater $\delta^{2}H$ values followed patterns similar to $\delta^{18}O$ and ranged from -134.7 to -30.8‰ (mean = -70.0±19‰). Isotopic precipitation values from Bowen (2018) had a narrower range compared to groundwater (Figure 5) and weighted average composition of precipitation during the growing season was $\delta^{2}H$ = -62.85‰ and $\delta^{18}O$ = -8.63‰. In the North Platte River Valley and south-central portions of the state, d-excess is especially low in the vicinity of groundwater mounds.

3.4 Spatial Seasonality Patterns

Based on groundwater seasonality ratios greater than one, there appears to be a modest winter recharge bias throughout much of the state (Figure 6A). This is similar to other temperate climates throughout the world where there is a high amount of evapotranspiration during the growing season and therefore less water available for recharge (Jasechko et al. 2014). The northwest part of the state shows the strongest nongrowing seasonality ratio, while wells in the southeast and southwest part of the state tended to exhibit a bias toward growing season recharge. Some areas with a growing season seasonality ratio coincided with a high-density of irrigation wells (Figure 6B), while areas with groundwater mounds from flood irrigation coincided with a nongrowing seasonality ratio. (Figure 6C). With regard to groundwater quality, a comparison of seasonality ratios with groundwater nitrate concentrations in nearby wells did not reveal a strong spatial correlation (Figure 6D).

3.5 Data Quality

In this study, samples were collected from a range of well types and depths, which reduces the possibility of widespread systematic bias that might occur if, for example, wells of only one type or depth were sampled across the state. To assess for a systematic bias we used well depth as the primary variable, given that depth is a strong control on groundwater and vadose zone water lag times. For the 593 samples where well depth information was available, well depth (ground elevation minus the elevation at the bottom of the screen) ranged from 2.7 to 210 m with most well depths ranging from 15 to 75 m (Figure 7). Due to the nonnormal distribution of the data, a Kruskal-Wallis test was applied to determine if there was a difference between the median $\delta^{18}O$ at the various depths (well depths were divided into 15 m increments up to 90 m, with 30 m increments for depths greater than 90 m). There was not a significant difference between the groups (p-value = 0.083), thus the average isotopic values for co-located wells (e.g., well nests) were used for the interpolation of the groundwater isotopes (Figure 7). It was assumed that few samples collected would fall in the category of fossil water, which could have a different isotopic signature than modern water.

4. Discussion

4.1 Anthropogenic Influences on Isotopic Composition and Seasonality

Given that precipitation is greatest during the growing season and assuming that precipitation is the primary source of recharge, it is intuitive that groundwater signatures across much of Nebraska should be similar to the precipitation during the growing season. However, ET is also greatest in the summer (Figure 2), which could lead to less precipitation available for recharge compared to the nongrowing season. This appears to be the case for much of Nebraska. However, there are areas in the southwest and the southeast Nebraska where irrigation during the summer is likely causing more recharge during the growing season (Figure 6A), given the correlation between high-density irrigation and seasonality ratio less than one. In western Nebraska irrigation allotments for several NRDs exceed the total summer precipitation (NRDnet.org, 2017). While central Nebraska receives more precipitation during the summer, the irrigation allotments still exceed the precipitation. In these cases, summer precipitation that might otherwise be removed by ET may instead recharge the groundwater. That is, because irrigation provides antecedent soil moisture that leads to greater recharge during precipitation events.

Near the groundwater mound in south-central Nebraska there is high-density irrigation, but unlike other intensively irrigated areas to the east and southwest, the south-central mound area has an apparent nongrowing season recharge bias. Irrigation water in South-Central Nebraska is diverted from the Platte River, which is partially sourced from snowmelt in the Rocky Mountains and has a more depleted isotopic signature (Kendall & Coplen, 2001). Long-term canal leakage and irrigation in this area has led to the long-term persistence of a large groundwater mound (Korus et al. 2013). Thus, the seasonality index in this area may be strongly influenced by the Platte River isotopic signal and has the appearance of a nongrowing season recharge signal even if recharge predominantly occurs in the summer. This interpretation is also supported by the d-excess map (Figure 5C) where the evaporated signal of Platte River water is evident. The impacts of canal leakage and surface water irrigation can also be seen in western Nebraska, where the d-excess indicates that recharge is occurring from the irrigation water sourced from the North Platte River, which has a lower d-excess than precipitation (Kendall and Coplen, 2001).

The furthest southeast part of the state also shows a growing season recharge signal. This is the warmest and wettest part of the state and summer precipitation may be more available for recharge. However, aquifers in this area are discontinuous and the spatial extent of the limited irrigation coincides with most of the wells sampled in this study (Figure 1B). Thus it is possible that irrigation is inducing a summer seasonality ratio, but the complexity of the local aquifers limit the appropriateness of extrapolating results outside the densely sampled areas.

Although not apparent for most samples in this study (Figure 4), the isotopic composition of groundwater may reflect additional evaporative losses if it is recycled repeatedly (i.e., groundwater is pumped for irrigation, then serves as recharge, and is pumped again, and so on). In terms of the seasonality index, a more evaporative isotopic signature will suggest a stronger growing season signal for recharge. The most likely location for this bias is in southeastern Nebraska, along the Platte River valley, where groundwater is particularly shallow and lag times between irrigation application and recirculation are relatively short. In southwest Nebraska, recharge rates are lower and vadose zone thickness is greater (often >30 m), leading to greater lag times between the time of recharge and lower potential for recirculating (pumping and re-applying) groundwater.

4.2 Groundwater Quality Implications

In areas with intense irrigation and crop production, the timing of fertilizer and irrigation (or precipitation) are closely linked with nutrient leaching (Derby et al., 2009; Exner et al., 2014). Understanding both natural and human-influenced recharge processes is important for identifying where and when groundwater quality is more likely to improve through optimal regulation and best management practices. Improvements are most likely when both water and agro-chemical (fertilizers, pesticides, etc.; we will focus on nitrate from fertilizers as an example) application are managed together (Di & Cameron, 2002; Kranz et al., 2009).

Differences in irrigation allotments, combined with precipitation patterns, type of crop, timing and amount of fertilizer application, local soils, and geology all influence the extent of nutrient leaching. In Nebraska, irrigation allotments are determined locally by NRDs and vary throughout the state. Some areas in the western districts allow for 178 cm of irrigation spread over 5 years. In the eastern part of the state, which receives more precipitation, irrigation is limited to 53 cm in 3 years (NRDnet.org, 2017). Other districts in the central and eastern parts of the state do not currently limit irrigation (Middle Niobrara, Upper Loup, Twin Platte, Central Platte, Lower Loup, Lower Niobrara, Lewis and Clark, Upper Elkhorn, Papio-Missouri, Nemaha, Lower Big Blue, Upper Big Blue) (NRDnet.org, 2017). However, irrigation allotments are only one potential driver for water use and therefore potential for leaching. Past studies have also found that the highest precipitation throughout the state occurs in May and June before the water demand from corn has peaked (Kranz et al., 2009). Along with irrigation allotments, NRDs have a wide range of requirements for fertilizer application, in some cases requiring applicator training (e.g., https://water.unl.edu/waternmgt), and/or limiting the timing of application and/or the amount of fertilizer that can be applied at one time (NRDnet.org, 2017).

Despite the complexities described above, a qualitative evaluation of recharge seasonality and groundwater quality (Figure 6) is valuable for supporting and understanding the effects of (1) existing regulations (Exner, Perea-Estrada, & Spalding, 2010; Sixt, Klerkx, Aiken, & Griffin, 2019) and (2) potential new regulations for areas with severely degraded groundwater quality (Little Blue NRD, 2012; NDEQ, 2016). We emphasize that the results of this study may serve as a useful regional perspective; regulatory decisions must be made using a range of information, including local knowledge of watershed and hydrogeologic characteristics and agronomic legacies (past practices, regulations, and economic drivers). As an example of a regional observation, areas where recharge appears biased toward the growing season (i.e., southeast, south-central, and part of southwest Nebraska), it is intuitive to consider growing season fertilizer and water management as a top priority. In areas with a nongrowing season recharge signal and high groundwater nitrate concentrations (e.g., northeast Nebraska) it is possible that ending the growing season with little or no nitrogen in the soil and limiting fall fertilizer application would give the greatest initial improvements in groundwater quality, especially in sandy soils with high hydraulic conductivity and poor water and nutrient retention. But it is imperative to use a systems approach to management and regulation; our results are one line of evidence, highlighting how surface and ground water should be viewed as one hydrological system. The management practices and watershed characteristics (i.e. soil type, land use, agronomic practices) will not only impact the groundwater quality but also surface water quality(Gilmore et al., 2016; Mittelstet, Gilmore, Messer, Rudnick, & Heatherly, 2019).

Of course, groundwater flow patterns, biogeochemistry, and actual nitrate recharge fluxes (if available) must also be considered in local groundwater management plans. Additional work is needed to test relationships between the observed seasonality patterns and best management practices that have the greatest potential for reducing groundwater nitrate concentrations. Comparison of observed seasonality from isotopes with local and regional models and/or field observations that provide seasonal recharge rates and seasonal nutrient fluxes would be especially valuable. Seasonality of modern recharge may also inform climate models, which predict an increase in both rainfall and recharge rates across Nebraska (Crosbie et al., 2013) but may not fully capture future groundwater recharge trends due to a lack of information on seasonality and on human intervention in the water cycle.

4.3 Limitations and Wider Implications

As with any regional study of groundwater isotopes or quality, this study relies on the substantial simplification of mapping groundwater data in one dimension when the sampled wells are drawn from a three-dimensional space. There are inherent challenges associated with lag times between precipitation events and groundwater sampling, driven by watershed characteristics (e.g., soils), recharge rates, hydrogeology, and well construction. These challenges include the potential persistence of major hydrologic events (Boutt, Mabee, & Yu, 2019), which could have a pronounced effect on shallow groundwater wells, or wells with short screened intervals. On the other hand, shallow and/or wells with short screened intervals can provide discrete information (e.g., they are ideal for analyzing stratification of groundwater quality and age (e.g., Böhlke 2002)). Irrigation wells or other wells with long screened intervals may yield water with a wide range of groundwater and vadose zone transit times and therefore a mixture of many different recharge years (Böhlke, 2002). Despite the tendency toward groundwater mixing, long-screened wells have been effective for long-term monitoring of groundwater quality (Zlotnik, Burbach, Exner, & Spalding, 1995).

This study focused on precipitation as the primary source of recharge, but there are other sources of recharge including deep drainage from irrigation water, which may be sourced from local groundwater, surface water, or a mixture of precipitation and irrigation sources. The confounding effect of diverted river water on recharge seasonality is an important feature of this study. The visual impact on the map of seasonality index (Figure 6) is substantial, particularly in south-central Nebraska. It is important in future studies to consider localized differences in water management to avoid misconceptions regarding recharge seasonality and/or groundwater vulnerability.

The potential impact on groundwater quality in areas with substantial irrigation return flows is a balance between the direct leakage of low-nitrate canal water versus leaching of nitrate below crop fields that were historically watered with less efficient irrigation methods. Direct canal leakage has been shown to dilute groundwater nitrate concentrations in in the vicinity of irrigation canals in western Nebraska, while excessive deep drainage may cause higher groundwater nitrate concentrations in diffuse recharge (Bohlke et al. 2007). These conflicting impacts are currently being studied in the vicinity of the groundwater mound in south-central Nebraska. These scenarios are not unique to Nebraska, however, and relevant to other irrigated areas (Han et al. 2017).

Understanding seasonality in terms of climate and anthropogenic changes is important for Nebraska and similar scenarios worldwide to better manage water quality and water quantity. The results of this and future studies should be considered in tandem with predicted changes in climate. For example, Nebraska is predicted to become warmer and wetter over the next 100 years (Bathke, Oglesby, Rowe, & Wilhite, 2014). This could lead to a lengthening of the growing season, which could in turn shorten the amount of precipitation that is recharged during the (shorter) nongrowing season. Changes in storm intensity may also alter when recharge occurs (Bathke et al., 2014).

5. Conclusions

Understanding the timing of groundwater recharge is important for both groundwater quantity and quality management. Climate change impacts on precipitation may alter the amount or timing of groundwater recharge, but it is not the only factor to consider. Human alterations to the water cycle may influence the seasonality of groundwater recharge. In particular, irrigated agriculture continues to increase worldwide (The World Bank, 2003). Changes in the amount and type of irrigation used on cropland in heavily cultivated regions around the world have and will impact recharge seasonality.

In this study, the majority of Nebraska shows a modest bias toward nongrowing season seasonality ratio. This is consistent with studies that have found that evapotranspiration during the growing season is greater than precipitation, leading to a small percentage of groundwater recharge during this time (Jasechko et al., 2014). Areas around the Platte River with a large number of irrigation canals show isotopic composition similar to that of the river, while areas with a high percentage of pivot irrigation show more of a growing season recharge signal. The growing season recharge signal in these areas indicates that an excess of irrigation water has been applied or that the isotopic composition has been altered from continuous irrigation. In either case, groundwater and precipitation isotope data reveal how human intervention in the water cycle has altered the seasonality of groundwater recharge in Nebraska. Other areas in Nebraska with intensive irrigation retain a nongrowing season recharge signature but also exhibit high groundwater nitrate concentrations.

Further modeling and field studies quantifying the amount of recharge occurring during each season would be useful for future water planning needs in the face of an altered climate and for evaluating agricultural best management practices most likely to contribute to improved groundwater quality.

Citations

Assefa, K. A., & Woodbury, A. D. (2013). Transient, spatially varied groundwater recharge modeling. *Water Resources Research*, *49*(8), 4593–4606. https://doi.org/10.1002/wrcr.20332

Bathke, D. J., Oglesby, R. J., Rowe, C. M., & Wilhite, D. A. (2014). *Understanding and Assessing Climate Change: Implications for Nebraska*.

Böhlke, J. K., O'Connell, M. E., & Prestegaard, K. L. (2007). Ground Water Stratification and Delivery of Nitrate to an Incised Stream under Varying Flow Conditions. *Journal of Environment Quality*, *36*(3), 664. https://doi.org/10.2134/jeq2006.0084

Böhlke, John Karl. (2002). Groundwater recharge and agricultural contamination. *Hydrogeology Journal*, *10*(1), 153–179. https://doi.org/10.1007/s10040-001-0183-3

Boutt, D. F., Mabee, S. B., & Yu, Q. (2019). Multiyear Increase in the Stable Isotopic Composition of Stream Water From Groundwater Recharge Due to Extreme Precipitation. *Geophysical Research Letters*, *46*(10), 5323–5330. https://doi.org/10.1029/2019GL082828

Bowen, G. J. (2018) Gridded maps of the isotopic composition of meteoric waters. http://www.waterisotopes.org.

Bowen, G. J., Putman, A., Brooks, J. R., Bowling, D. R., Oerter, E. J., & Good, S. P. (2018). Inferring the source of evaporated waters using stable H and O isotopes. *Oecologia*, *187*(4), 1025–1039. https://doi.org/10.1007/s00442-018-4192-5

Bowen, G. J., & Revenaugh, J. (2003). Interpolating the isotopic composition of modern meteoric precipitation. *Water Resources Research*, *39*(10), 1–13. https://doi.org/10.1029/2003WR002086

Bowen, G. J., Wassenaar, L. I., & Hobson, K. A. (2005). Global application of stable hydrogen and oxygen isotopes to wildlife forensics. *Oecologia*, *143*(3), 337–348. https://doi.org/10.1007/s00442-004-1813-y

Bowen, G. J., & Wilkinson, B. (2002). Spatial distribution of δ18O in meteoric precipitation. *Geology*, *30*(4), 315–318. https://doi.org/10.1130/0091-7613(2002)030<0315:SDOOIM>2.0.CO;2

Crosbie, R. S., Scanlon, B. R., Mpelasoka, F. S., Reedy, R. C., Gates, J. B., & Zhang, L. (2013). *Potential climate change effects on groundwater recharge in the High Plains Aquifer , USA*.

49, 3936–3951. https://doi.org/10.1002/wrcr.20292

Dansgaard, W. (1964). Stable isotopes in precipitation. *Tellus*, *16*(4), 436–468. https://doi.org/10.3402/tellusa.v16i4.8993

Derby, N. E., Casey, F. X. M., & Knighton, R. E. (2009). Long-Term Observations of Vadose Zone and Groundwater Nitrate Concentrations under Irrigated Agriculture. *Vadose Zone Journal*, *8*(2), 290. https://doi.org/10.2136/vzj2007.0162

Di, H. J., & Cameron, K. C. (2002). Nitrate leaching in temperate agroecosystems: Sources, factors and mitigating strategies. *Nutrient Cycling in Agroecosystems*, *64*(3), 237–256. https://doi.org/10.1023/A:1021471531188

Exner, M. E., Hirsh, A. J., & Spalding, R. F. (2014). Nebraska's groundwater legacy: Nitrate contamination beneath irrigated cropland. *Water Resources Research*, 4474–4489. https://doi.org/10.1002/2013WR015073

Exner, M. E., Perea-Estrada, H., & Spalding, R. F. (2010). Long-term response of groundwater nitrate concentrations to management regulations in Nebraska's Central Platte valley. *TheScientificWorldJournal*, *10*, 286–297. https://doi.org/10.1100/tsw.2010.25

Exner, M. E., Spalding, R. F., & Harrell, D. M. (2005). Development of a quality-assessed agrichemical database for monitoring anthropogenic impacts on ground-water quality. *Environmental Monitoring and Assessment*, *107*(1–3), 249–257. https://doi.org/10.1007/s10661-005-3108-0

Fiedler, P. D. and K. (2007). Global-scale modeling of groundwater recharge. *Hydrology and Earth System Sciences Discussions, European Geosciences Union*, *4*(6), 4069–4124.

Fortune, D. (2010). *Groundwater Recharge Project*. Retrieved from papers2://publication/uuid/519B5C26-A286-4C28-8896-B32254F1D8C6

Gilmore, T. E., Genereux, D. P., Solomon, D. K., Solder, J. E., Kimball, B. A., Mitasova, H., & Birgand, F. (2016). Quantifying the fate of agricultural nitrogen in an unconfined aquifer: Stream-based observations at three measurement scales. *Water Resources Research*, *52*(3), 1961–1983. https://doi.org/10.1002/2015WR017599

Gimeno, L., Drumond, A., Nieto, R., Trigo, R. M., & Stohl, A. (2010). On the origin of continental precipitation. *Geophysical Research Letters*, *37*(13), 1–7. https://doi.org/10.1029/2010GL043712

Han, D., Currell, M. J., Cao, G., & Hall, B. (2017). Alterations to groundwater recharge due to anthropogenic landscape change. *Journal of Hydrology*, *554*, 545–557. https://doi.org/10.1016/j.jhydrol.2017.09.018

Harvey, F. E., & Welker, J. M. (2000). Stable isotopic composition of precipitation in the semi-arid north-central portion of the US Great Plains. *Journal of Hydrology*, *238*(1–2), 90–109. https://doi.org/10.1016/S0022-1694(00)00316-4

Harvey, F. Edwin, & Sibray, S. S. (2001). Delineating Ground Water Recharge from Leaking Irrigation Canals Using Water Chemistry and Isotopes. *Ground Water*, *39*(3), 408–421.

Irmak, S., Howell, T. A., Allen, R. G., Payero, J. O., & Martin, D. L. (2005). STANDARDIZED ASCE PENMAN-MONTEITH: IMPACT OF SUM-OF-HOURLY VS. 24-HOUR TIMESTEP COMPUTATIONS AT REFERENCE WEATHER STATION SITES. *Transactions of the ASAE 2005*, *48*(3), 1–16.

Jasechko, S., Lechler, A., Pausata, F. S. R., Fawcett, P. J., Gleeson, T., Cendon, D. I., … Yoshimura, K. (2015). Late-glacial to late-Holocene shifts in global precipitation δ18O. *Climate of the Past*, *11*(10), 1375–1393. https://doi.org/10.5194/cp-11-1375-2015

Jasechko, Scott, Birks, S. J., Gleeson, T., Wada, Y., Fawcett, P. J., Sharp, Z. D., … Welker, J. M. (2014). The pronounced seasonlity of global groundwater recharge. *Water Resources Research*, *50*, 8845–8867. https://doi.org/10.1002/2014WR015809.Received

Jasechko, Scott, Wassenaar, L. I., & Mayer, B. (2017). Isotopic evidence for widespread cold-season-biased groundwater recharge and young streamflow across central Canada. *Hydrological Processes*, *31*(12), 2196–2209. https://doi.org/10.1002/hyp.11175

Joshi, S. K., Rai, S. P., Sinha, R., Gupta, S., Densmore, A. L., Rawat, Y. S., & Shekhar, S. (2018). Tracing groundwater recharge sources in the northwestern Indian alluvial aquifer using water isotopes (δ18O, δ2H and 3H). *Journal of Hydrology*, *559*, 835–847. https://doi.org/10.1016/j.jhydrol.2018.02.056

Keese, K. E., Scanlon, B. R., & Reedy, R. C. (2005). Assessing controls on diffuse groundwater recharge using unsaturated flow modeling. *Water Resources Research*, *41*(6), 1–12. https://doi.org/10.1029/2004WR003841

Kendall, C., & Coplen, T. B. (2001). Distribution of oxygen-18 and deuteriun in river waters across the United States. *Hydrological Processes*, *15*(7), 1363–1393. https://doi.org/10.1002/hyp.217

Korus, J., Howard, L., Young, A., Divine, D., Burbach, M., Jess, J., and Hallum, D. (2013). The Groundwater Atlas of Nebraska, Conservation and Survey Division, University of

Nebraska, Resource Atlas 4b.

Kranz, W. L., Farmaha, B. S., Grassini, P., Hergert, G. W., Shaver, T., & Shapiro, C. A. (2009). *Irrigation and Nitrogen Management*. Retrieved from http://extensionpublications.unl.edu/assets/pdf/ec2008.pdf

Lauffenburger, Z. H., Gurdak, J. J., Hobza, C., Woodward, D., & Wolf, C. (2018). Irrigated agriculture and future climate change effects on groundwater recharge, northern High Plains aquifer, USA. *Agricultural Water Management*, *204*(March), 69–80. https://doi.org/10.1016/j.agwat.2018.03.022

Little Blue NRD, Upper Big Blue NRD, & City of Hastings. (2012). *Hastings wellhead protection groundwater managment area action Plan*. Retrieved from http://www.littlebluenrd.org/pdf%27s/groundwater/hastings_mgmt_area_rules.pdf

Matiatos, I., & Wassenaar, L. I. (2019). Stable isotope patterns reveal widespread rainy-period-biased recharge in phreatic aquifers across Greece. *Journal of Hydrology*, *568*, 1081–1092. https://doi.org/10.1016/j.jhydrol.2018.11.053

Meixner, T., Manning, A. H., Stonestrom, D. A., Allen, D. M., Ajami, H., Blasch, K. W., … Walvoord, M. A. (2016). Implications of projected climate change for groundwater recharge in the western United States. *JOURNAL OF HYDROLOGY*, *534*, 124–138. https://doi.org/10.1016/j.jhydrol.2015.12.027

Mittelstet, A. R., Gilmore, T. E., Messer, T., Rudnick, D. R., & Heatherly, T. (2019). Evaluation of selected watershed characteristics to identify best management practices to reduce Nebraskan nitrate loads from Nebraska to the Mississippi/Atchafalaya River basin. *Agriculture, Ecosystems and Environment*, *277*(February), 1–10. https://doi.org/10.1016/j.agee.2019.02.018

NDEQ. (2017). *2017 Nebraska Groundwater Quality Monitoring Report* (Vol. 1304). Retrieved from http://deq.ne.gov/Publica.nsf/Pubs_GW.xsp

NDEQ, District, L. and C. N. R., District, L. E. N. R., District, L. N. N. R., & District, U. E. N. R. (2016). *Bazile Groundwater Management Area plan*. Retrieved from http://www.lcnrd.org/news/Final October Approval BGMA PLan All Parties.pdf

NRDnet.org. (2017). *601 s. 12*. Retrieved from https://www.nrdnet.org/sites/default/files/groundwater_management_summary_2017__0.pdf

Owenby, J. R., & Ezell, D. S. (1992). Monthly station normals of temperature, precipitation, and heating and cooling degree days, 1961–90. In *Climatography of the United States. No. 81, National Climatic Data Center*. Admin., Asheville, N.C.

Rozanski, K., Araguás-Araguás, L., & Gonfiantini, R. (1993). Isotopic Patterns in Modern Global Precipitation. *Geophysical Monograph*, *78*, 1–36. https://doi.org/10.1029/gm078p0001

Sánchez-Murillo, R., Durán-Quesada, A. M., Birkel, C., Esquivel-Hernández, G., & Boll, J. (2017). Tropical precipitation anomalies and d-excess evolution during El Niño 2014-16. *Hydrological Processes*, *31*(4), 956–967. https://doi.org/10.1002/hyp.11088

Scanlon, B. R., Keese, K. E., Flint, A. L., Flint, L. E., Gaye, C. B., Edmunds, W. M., & Simmers, I. (2006). *Global synthesis of groundwater recharge in semiarid and arid regions*. *3370*(March), 3335–3370. https://doi.org/10.1002/hyp

Scanlon, B. R., Reedy, R. C., Stonestrom, D. A., Prudic, D. E., & Dennehy, K. F. (2005). Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. *Global Change Biology*, *11*(10), 1577–1593. https://doi.org/10.1111/j.1365-2486.2005.01026.x

Sixt, G. N., Klerkx, L., Aiken, J. D., & Griffin, T. S. (2019). Nebraska's Natural Resource District system: synergistic approaches to groundwater quality management. *Water Alternatives*, *12*(2), 725–747.

Soderberg, K., Good, S. P., O'connor, M., Wang, L., Ryan, K., & Caylor, K. K. (2013). Using atmospheric trajectories to model the isotopic composition of rainfall in central Kenya. *Ecosphere*, *4*(3), 1–18. https://doi.org/10.1890/ES12-00160.1

Stein, A. F., Draxler, R. R., Rolph, G. D., Stunder, B. J. B., Cohen, M. D., & Ngan, F. (2015). NOAA's HYSPLIT Atmospheric Transport and Dispersion Modeling System. *Bulletin of the American Meteorological Society*, *96*(12), 2059–2077. https://doi.org/10.1175/BAMS-D-14-00110.1

Su, L., Yuan, Z., Fung, J. C. H., & Lau, A. K. H. (2015). A comparison of HYSPLIT backward trajectories generated from two GDAS datasets. *Science of the Total Environment*, *506–507*, 527–537. https://doi.org/10.1016/j.scitotenv.2014.11.072

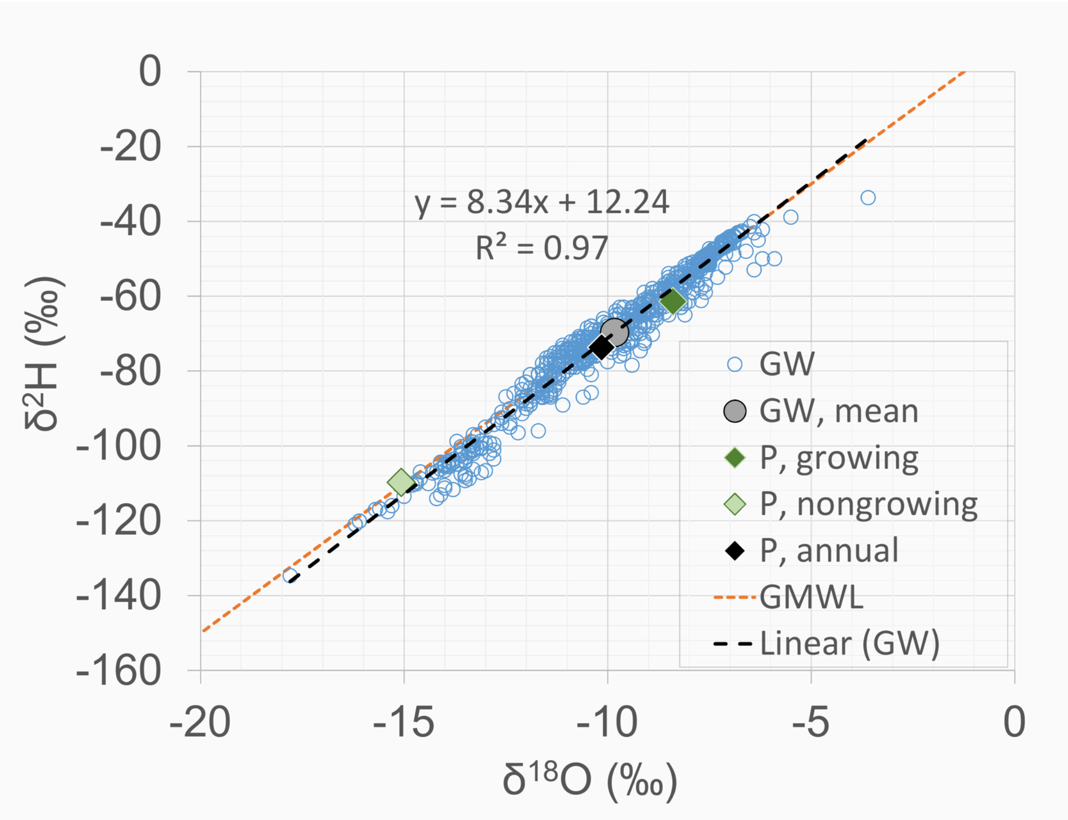
The World Bank. (2003). *Prospects for Irrigated Agriculture*. Washington DC.

van der Ent, R. J., & Tuinenburg, O. A. (2017). The residence time of water in the atmosphere revisited. *Hydrology and Earth System Sciences*, *21*(2), 779–790. https://doi.org/10.5194/hess-21-779-2017

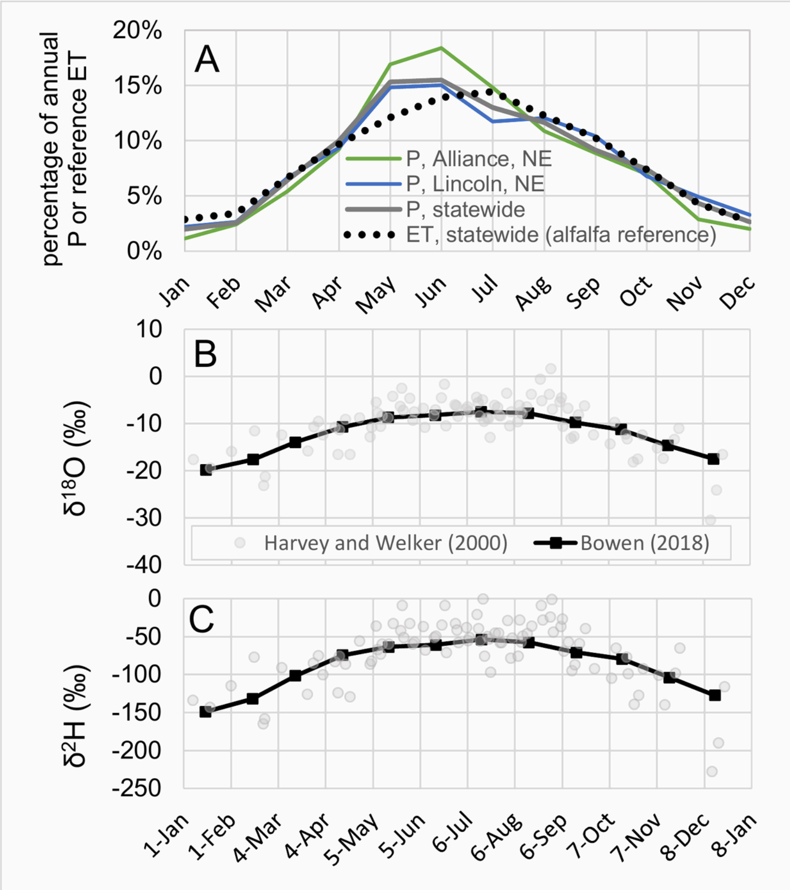
Welker J.M., 2000. Isotopic (d18O) characteristics of weekly precipitation collected across the USA: An initial analysis with application to water source studies. *Hydrological Processes* **14**, 1449-1464

Young, A. R., Burbach, M. E., Howard, L. M., Waszig, M. M., Lackey, S. O., & Joeckel, R. M. (2019). *Nebraska statewide groundwater-level monitoring report 2018*. Retrieved from https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1664&context=conservationsurvey

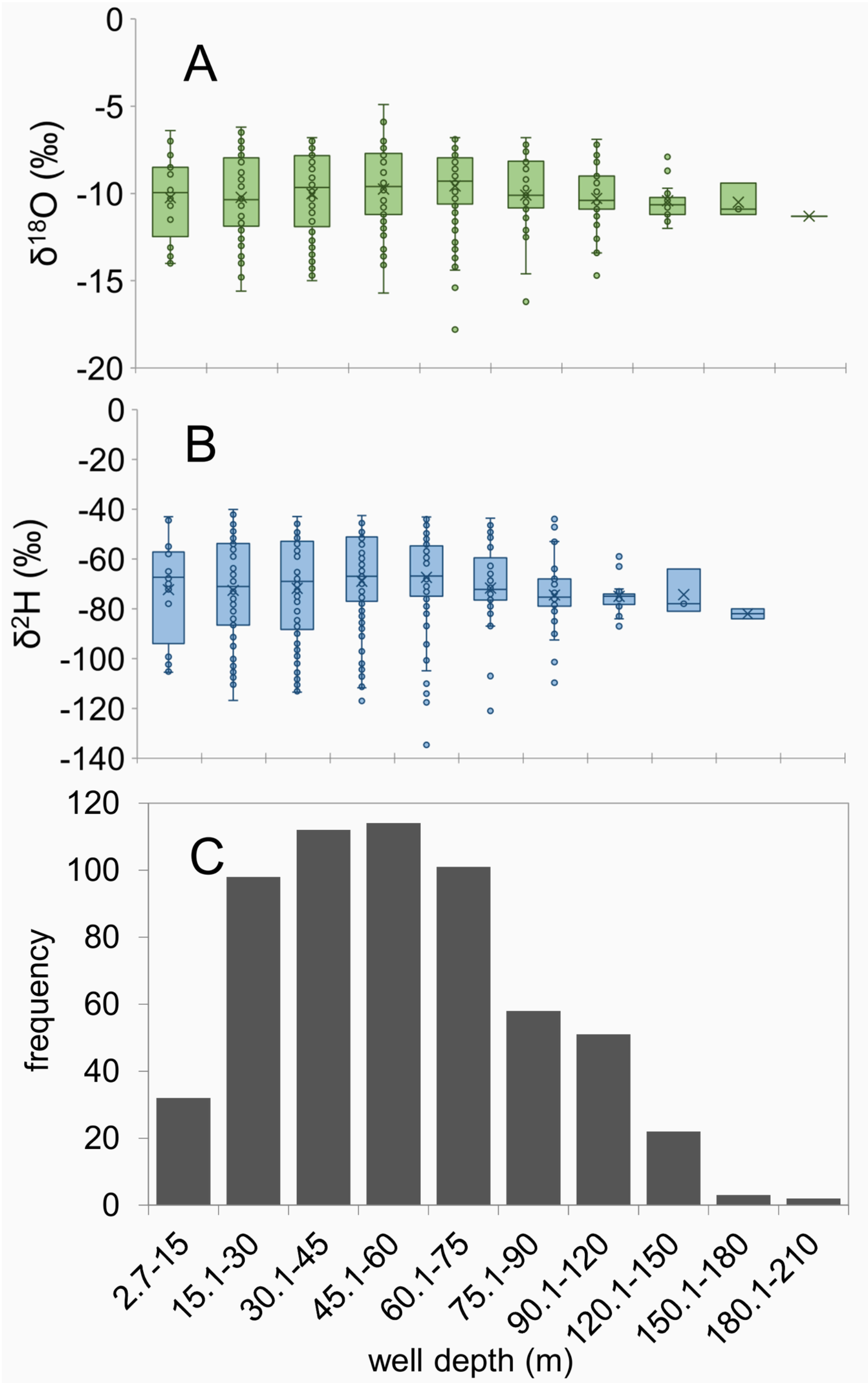
Zlotnik, V. A., Burbach, M. E., Exner, M. E., & Spalding, R. F. (1995). Well sampling for agrichemicals in high capacity systems. *Journal of Soil and Water Conservation*, *50*(1), 95–101.



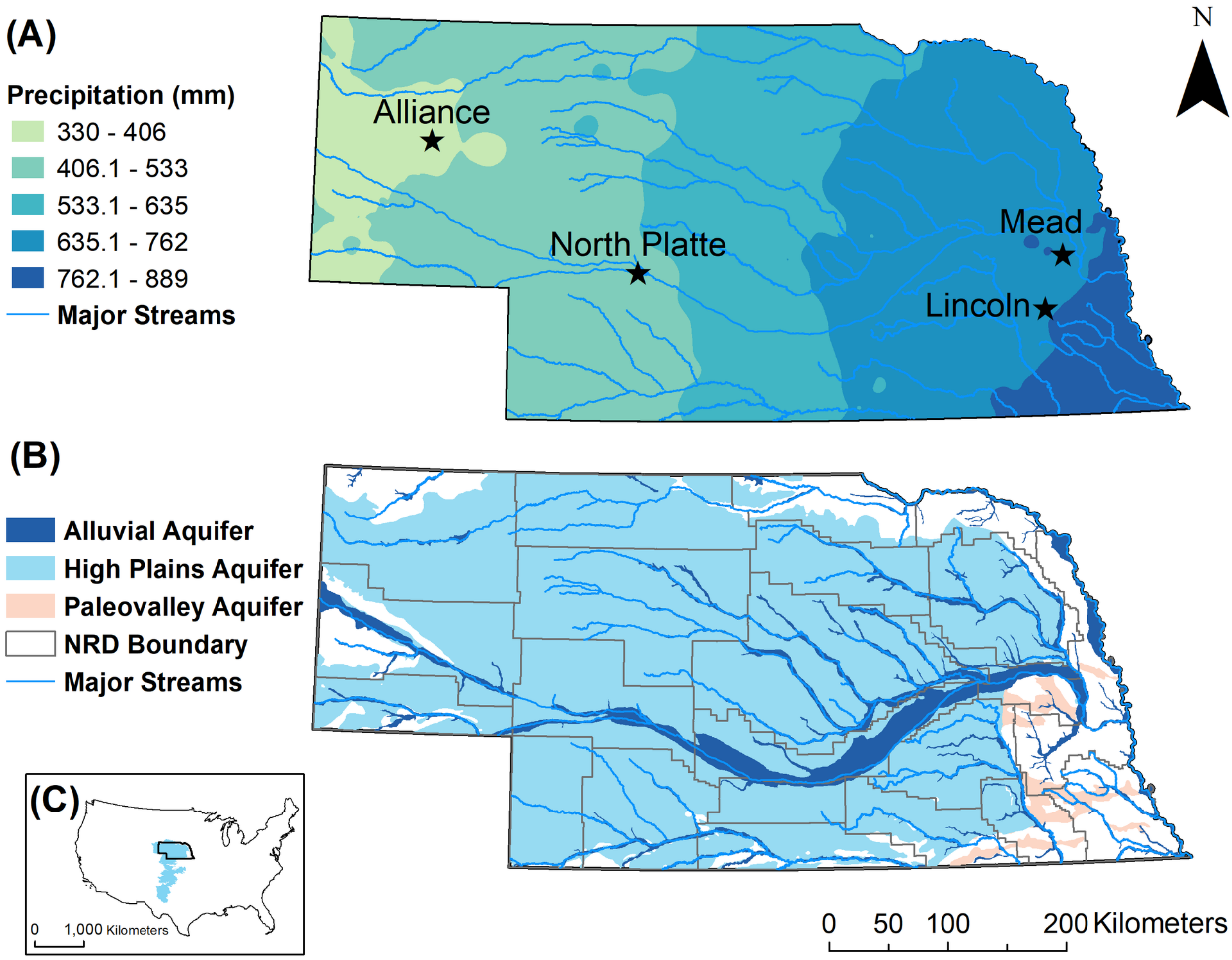
HYP_13683_fig4_GMWL.tif



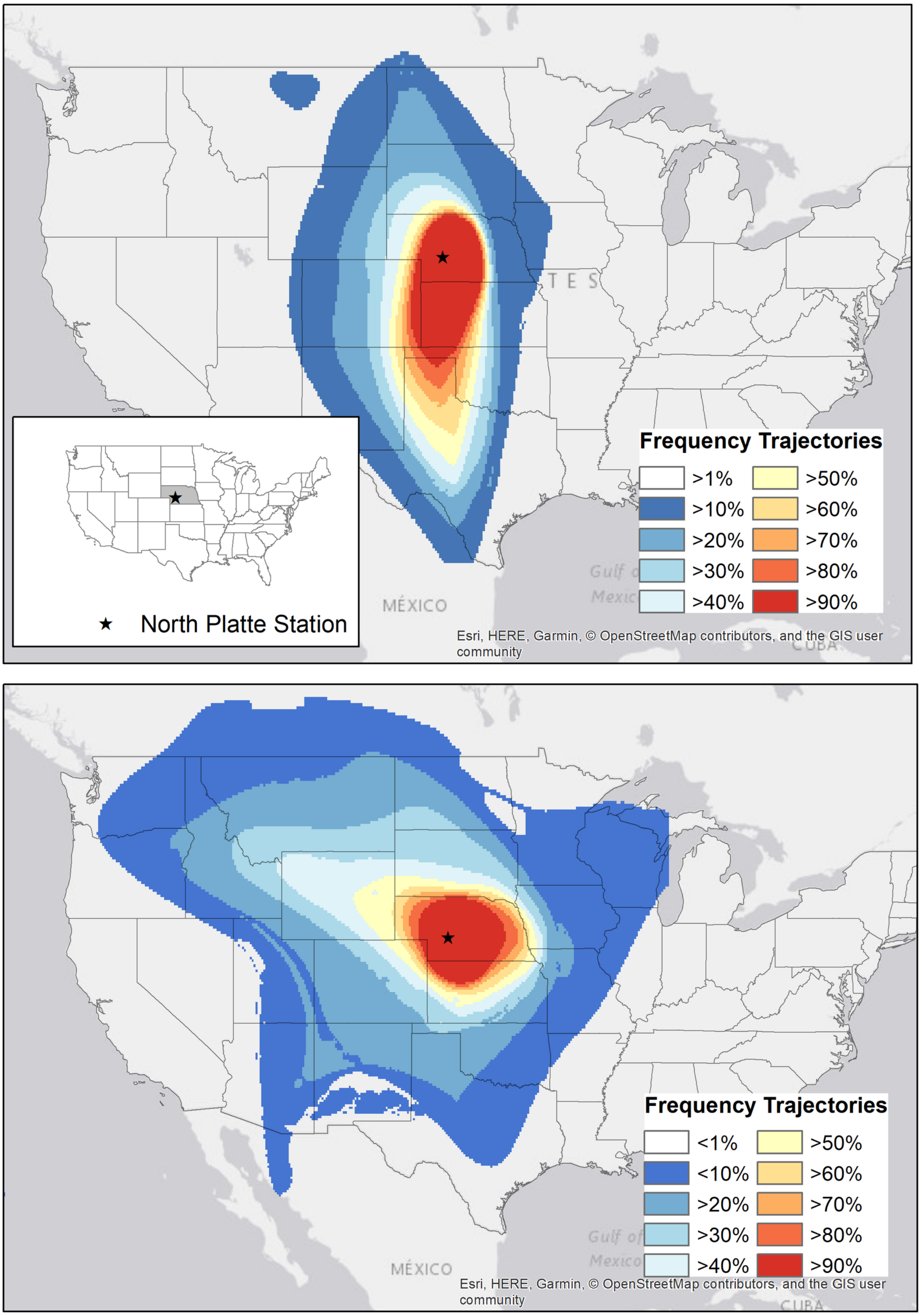
HYP_13683_Fig2_precip.tif



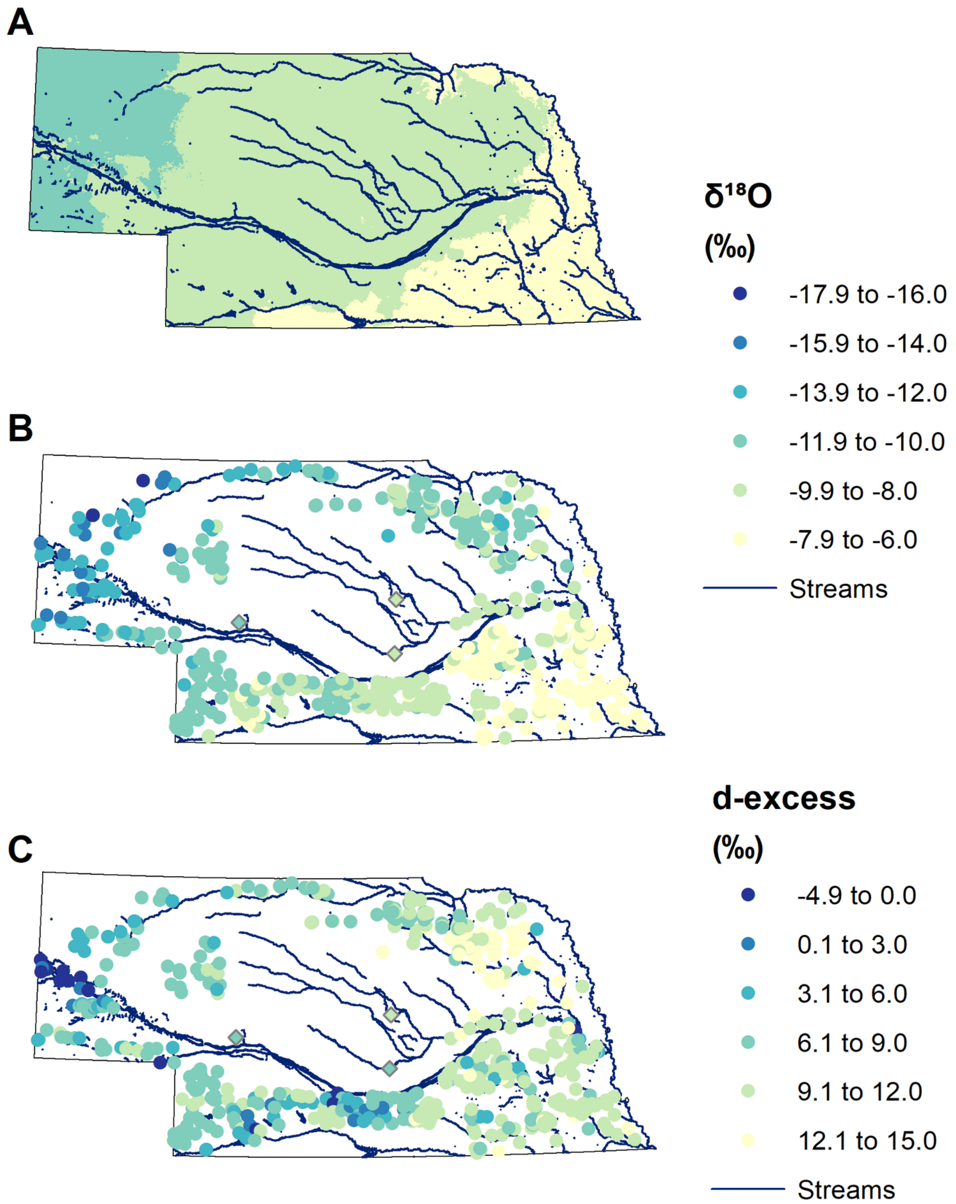
HYP_13683_Fig7_welldepth.tif



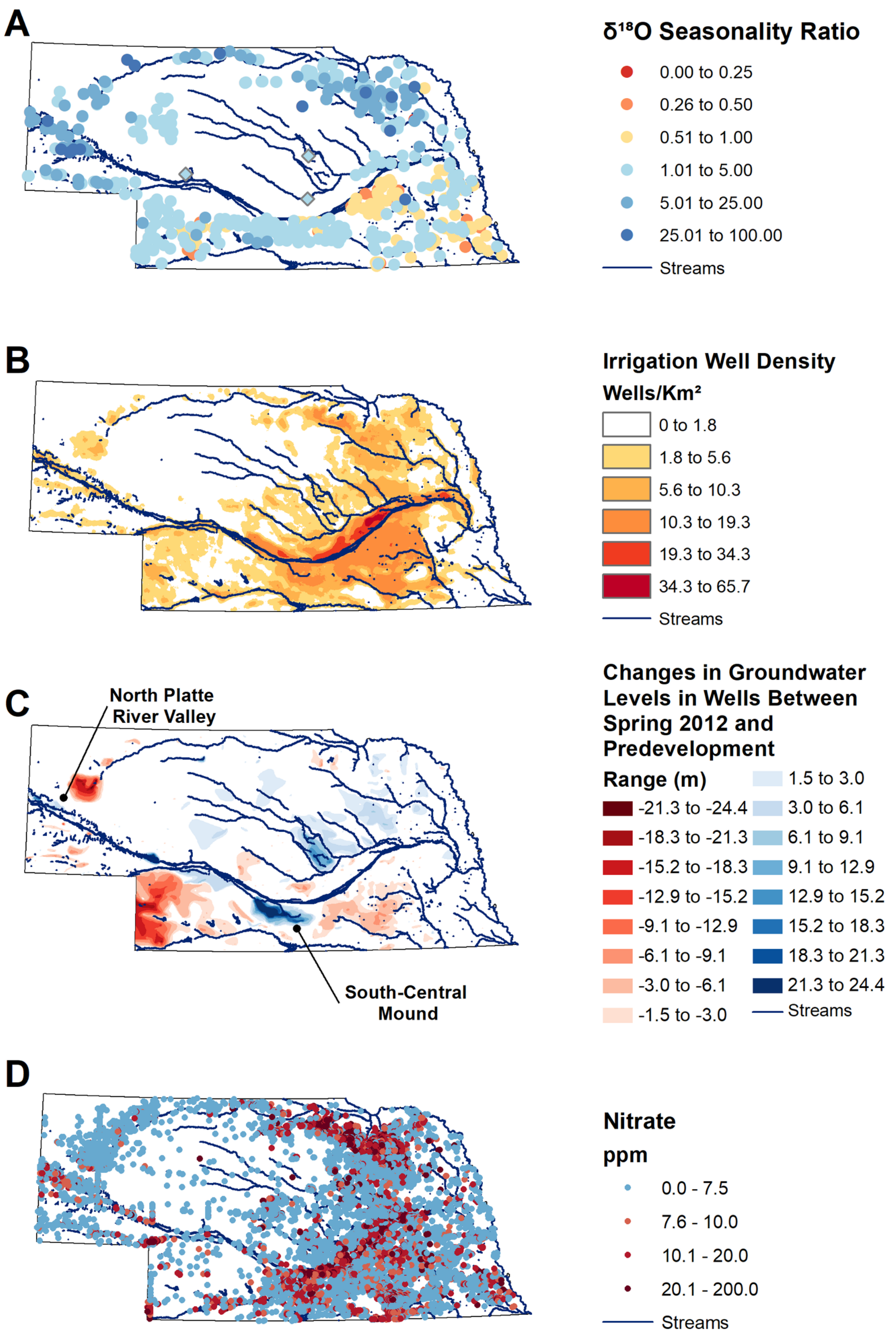
HYP_13683_Fig 1_SiteMap (1).tif



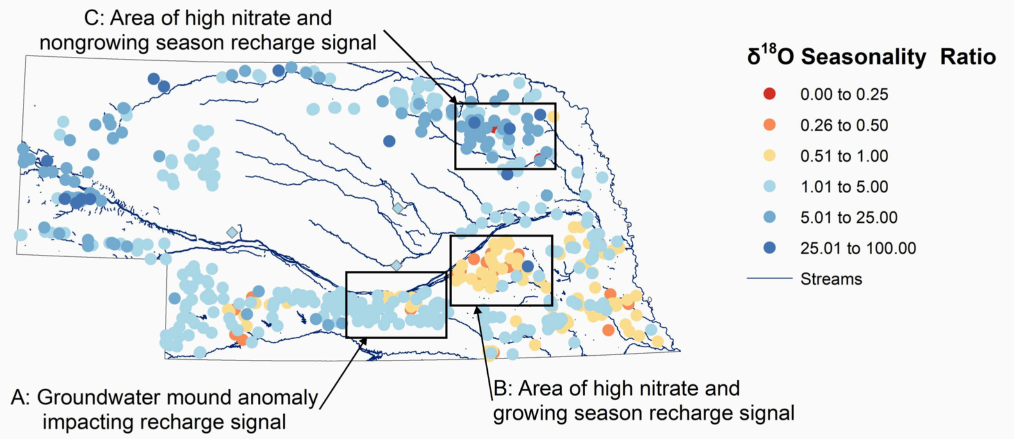
HYP_13683_Fig_3_Precip_Trajectory .tif



HYP_13683_Fig_5_Groundwater_Iso.tif



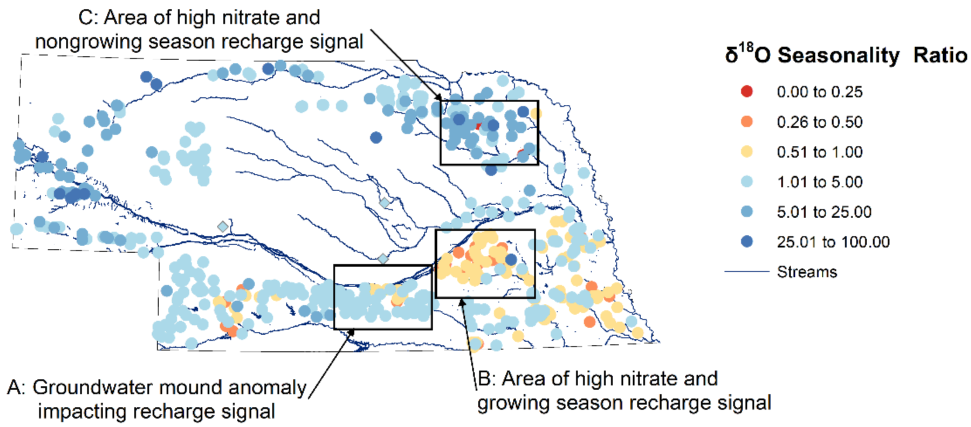
HYP_13683_Fig_6_Recharge_seasonality.tif



HYP_13683_G_A.tif

Recharge Seasonality Based on Stable Isotopes: Nongrowing Season Bias Altered by Irrigation in Nebraska

Author's names: Mikaela Cherry*, Troy Gilmore, Aaron Mittelstet, Didier Gastmans , Vinicius Santos, John Gates



Based on groundwater recharge ratios the majority of Nebraska shows a modest bias toward nongrowing season recharge (ratio >1). Human activities such as irrigation can alter recharge seasonality (A and B). Areas with high nitrate but different recharge seasonality may respond differently to groundwater quality management strategies (B and C).