Nebraska's groundwater legacy: Nitrate contamination beneath irrigated cropland

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Key Points:
- Nitrate contamination has significantly expanded beneath irrigated cropland
- Increasing groundwater nitrate concentrations are rarely reversed
- Under most management scenarios nitrate inputs exceed aquifer concentrations

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Nebraska's groundwater legacy: Nitrate contamination beneath irrigated cropland

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Abstract A 31 year record of ~44,000 nitrate analyses in ~11,500 irrigation wells was utilized to depict the decadal expansion of groundwater nitrate contamination ($N \geq 10$ mg/L) in the irrigated corn-growing areas of eastern and central Nebraska and analyze long-term nitrate concentration trends in 17 management areas (MAs) subject to N fertilizer and budgeting requirements. The 1.3 M contaminated hectares were characterized by irrigation method, soil drainage, and vadose zone thickness and lithology. The areal extent and growth of contaminated groundwater in two predominately sprinkler-irrigated areas was only ~20% smaller beneath well-drained silt loams with thick clayey-silt unsaturated layers and unsaturated thicknesses >15 m (400,000 ha and 15,000 ha/yr) than beneath well and excessively well-drained soils with very sandy vadose zones (511,000 ha and 18,600 ha/yr). Much slower expansion (3700 ha/yr) occurred in the 220,000 contaminated hectares in the central Platte valley characterized by predominately gravity irrigation on thick, well-drained silt loams above a thin (~5.3 m), sandy unsaturated zone. The only reversals in long-term concentration trends occurred in two MAs (120,500 ha) within this contaminated area. Concentrations declined 0.14 and 0.20 mg N/L/yr ($p < 0.02$) to ~18.3 and 18.8 mg N/L, respectively, during >20 years of management. Average annual concentrations in 10 MAs are increasing ($p < 0.05$) and indicate that average nitrate concentrations in leachates below the root zone and groundwater concentrations have not yet reached steady state. While management practices likely have slowed increases in groundwater nitrate concentrations, irrigation and nutrient applications must be more effectively controlled to retain nitrate in the root zone.

1. Introduction

Nitrate is the most common chemical contaminant in the world's aquifers [*Spalding and Exner*, 1993; *Thorburn et al.*, 2003; *Jalali*, 2005; *Batlle Aguilar et al.*, 2007] and a major drinking water impairment in the United States. As early as the 1940s, *Comly* [1945] linked the ingestion of nitrate-contaminated private well water by infants and children to methemoglobinemia, an acute and potentially fatal condition in which blood hemoglobin is altered and the tissues are deprived of oxygen. The condition was not observed in infants consuming water with less than 10 mg NO_3-N/L [*Walton*, 1951]. The U.S. Public Health Service adopted the 10 mg NO_3-N/L standard in 1962 with the issuance of the first nitrate drinking water standard [*U.S. Public Health Service*, 1962] and 10 mg N/L became the maximum contaminant level (MCL) for nitrate under the 1974 Safe Drinking Water Act. In 1991, a 1 mg/L MCL was promulgated for nitrite-N (NO_2-N) and the 10 mg N/L MCL was revised to include both nitrate and nitrite (Federal Register, 56, 3526 (1 January 1991)). Both standards are based solely on protecting infants from methemoglobinemia [*Fan and Steinberg*, 1996]. The causal role of nitrate in certain cancers [*Freedman et al.*, 2000; *Weyer et al.*, 2001; *Rhoades et al.*, 2013], adverse reproductive outcomes [*Croen et al.*, 2001; *Brender et al.*, 2004], and other chronic health effects is inconclusive [*Ward et al.*, 2005; *U.S. Environmental Protection Agency*, 2007]. The latest review of the National Primary Drinking Water Regulations found the MCLs for nitrate and nitrite remain appropriate (Federal Register, 75, 15519 (29 March 2010)).

A highly soluble and mobile anion, nitrate is readily transported with recharge through oxic soils to groundwater. Nitrate occurs naturally in groundwater at concentrations <2 mg N/L [*Mueller and Helsel*, 1996]. Concentrations above a 3–4 mg N/L threshold reflect anthropogenic contributions [*Nolan et al.*, 2002]. While many nitrogen sources contaminate groundwater, agricultural use of commercial and animal waste fertilizers and septic systems in densely populated areas have had the greatest impact on groundwater quality

[*Nolan et al*., 1997]. Commercial N fertilizer is the major source of groundwater N-contamination nationwide [*Rupert*, 2008; *Burow et al*., 2010] and has long been recognized as the major source of contamination in Nebraska's aquifers [*Exner and Spalding*, 1979; *Gormly and Spalding*, 1979]. National assessments of nitrate's occurrence in groundwater [*Spalding and Exner*, 1993; *Burow et al*., 2010] report that the most wide-spread contamination is beneath densely irrigated areas. The heavier N fertilization requirements of irrigated crops; irrigation of predominately well to excessively well-drained soils; and application of water in excess of crop needs likely exacerbate the N flush to groundwater [*Schepers et al*., 1991a; *Bruce et al*., 2003]. Nonlinear regression models have delineated many of the largest irrigated areas in the United States as highly vulnerable to contamination [*Nolan and Hitt*, 2006]. In the western United States, nitrate loss via denitrification in the vadose zone beneath irrigated fields is minimal. Sprinkler irrigation aerates the already oxic groundwater used for irrigation and the aerated sprinkler return flows oxygenate the soils which are generally low in organic matter [*Burow et al*., 2010].

Long-term nitrate concentration trends have been reported for only a few aquifers contaminated by agricultural leachates. Statistically significant decadal changes occurred in nitrate concentrations at eight of 25 National Water-Quality Assessment Program well networks in predominately agricultural areas. Statistically significant increases in concentrations occurred at six networks. All wells were sampled once during 1988–2000 and once during 2001–2010 [*Lindsey and Rupert*, 2012]. After a decade of implementing voluntary beneficial or best management practices (BMPs), nitrate concentrations in the young groundwater of Canada's Abbotsford-Sumas aquifer increased [*Wassenaar et al*., 2006]. Enhanced N leaching of inorganic fertilizer during fall and winter rains negated the assumed BMP of partially replacing some animal waste, which was the prevalent nitrate source, with inorganic N fertilizer. The authors concluded that voluntary BMPs were ineffectual and that nitrate loading to the vadose zone or the receiving environment should be monitored to timely identify nutrient management practices that do not reduce leaching. Agricultural management in Denmark induced a trend reversal in groundwater nitrate concentrations which had increased between 1950 and 1980 [*Hansen et al*., 2011]. Improved manure and animal waste management between 1970 and 1980 contributed greatly to the early reductions in nitrogen loading. Danish environmental action plans implemented in 1985 regulate nutrient applications and have significantly lowered nitrate application rates on crops and reduced N in leachates an estimated 33%. While government-sponsored controls in the United Kingdom have similarly reduced nitrate in soil, high nitrate concentrations in deep well abstractions have not improved and necessitated long-term resource reductions, decreased operational flexibility, and increased consumer cost for water [*Knapp*, 2005]. In the United States, 16 years (1988–2003) of nutrient and irrigation management in an intensively irrigated corn-growing area of Nebraska's Central Platte Natural Resources District Ground Water Quality Management Area saw a significant ($p < 0.0001$) decrease in groundwater nitrate concentrations albeit at the slow rate of 0.26 mg N/L/yr. Average concentrations peaked at 26.8 mg N/L in 1988 after increasing at rates of 0.8–1 mg N/L since 1974 [*Exner et al*., 2010].

The statutes of most central and western states that rely heavily on groundwater as a potable water source promote its protection for existing and future beneficial uses; have an antidegradation clause; and propose a framework for addressing nonpoint source (NPS) contamination. The states' approaches to reducing NPS nitrate are varied but, in general, each has criteria and procedures for designating areas for management; protocols and guidelines for preparation and implementation of a plan to mitigate the contamination; and a mechanism for evaluation of the effectiveness of the adopted recommendations. In some states, following designation as a groundwater management area (MA) by the appropriate state agency, a local committee together with state agencies may develop an action plan. Usually, it has a strong education and outreach component and encourages adoption of BMPs. Soil and water testing and data analysis are conducted by the appropriate state agency. Voluntary compliance is preferred [*Idaho Groundwater Quality Council*, 1996; *Oregon Department of Environmental Quality*, 2011; *Washington Administrative Code*, 2013] but may be enforced if concentration criteria are not met [*Idaho Ground Water Quality Council*, 1996]. Management areas may also be established by existing state government subdivisions charged with protecting natural resources [*Bishop*, 1996]. Since 1986 Nebraska's Natural Resources Districts (NRDs) have had legislative authority to establish groundwater management areas primarily to protect groundwater quality and, in addition to the existing quantity control measures, could require use of BMPs and attendance at education programs [*Exner and Spalding*, 1987]. Legislation passed in 1991 required NRDs revise their existing groundwater management plans to more adequately address water quality concerns. The Central Platte NRD's

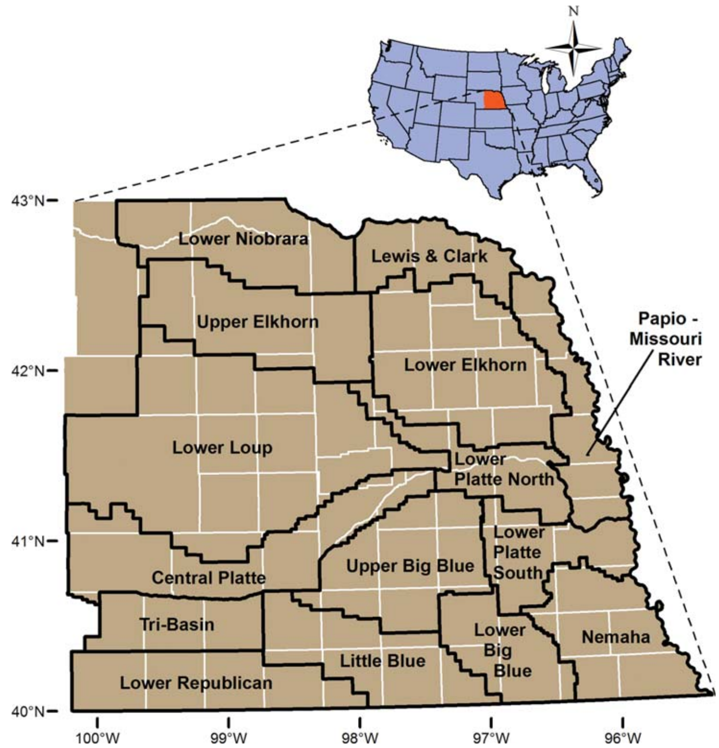

Figure 1. Location of the study area within Nebraska and associated natural resources districts.

management plan, implemented in 1987, became the model for other NRDs. Each NRD has as many as four groundwater quality management tiers based on nitrate concentrations. Specific management and reporting regulations become increasingly stricter in each tier. Usually, entire NRDs are tier 1 MAs and focus only on education and demonstration.

In Nebraska, irrigated corn is the largest consumer of nitrogen fertilizer and receives heavier N fertilizer applications than nonirrigated corn. Corn is grown on ~70% of Nebraska's 3.4 Mha of irrigated row crops [*U.S. Department of Agriculture*, 2009]. Approximately 80% of the irrigated corn hectares are in central and eastern Nebraska [*U.S. Department of Agriculture*, 2009]. Extensive NPS nitrate contamination of groundwater occurs primarily in eastern and central Nebraska while contamination in western Nebraska is limited to groundwater beneath alluvial deposits in narrow river valleys [*Spalding and Exner*, 1993]. Nebraska is one of only a few states with a long-term (>30 years) public record of groundwater nitrate concentrations. The study objectives are to examine decadal changes in the areal expanse of nitrate-contaminated (NO_3-N $\geq$10 mg/L) groundwater beneath irrigated cropland and the relationship between vadose zone characteristics and areas of emerging contamination in central and eastern Nebraska (Figure 1) and, in the contaminated areas, to analyze concentration trends in wells with long-term nitrate records and their response to regulated management.

2. Methods

2.1. Groundwater Nitrate Data

Groundwater nitrate concentrations were obtained from actively pumping irrigation wells during the irrigation season (June, July, and August). Irrigation wells usually tap the more transmissive zones of an aquifer and integrate nitrate concentrations from the more productive vertical horizons of the aquifer. Thus, they are better indicators of nitrate conditions in NPS-contaminated areas than are monitoring or domestic wells [*Zlotnik et al.*, 1993]. The nitrate data were obtained from the Quality-Assessed Agrichemical Contaminant Database for Nebraska Groundwater [*University of Nebraska-Lincoln*, 2000]. These publicly available data from federal, state, and local agencies and University of Nebraska monitoring and research projects have met the minimum criteria for each of seven essential elements (well location, well depth, sample date, sampling procedure and sample preservation, analytical method, and field and laboratory quality assurance practices). About 44,000 nitrate analyses in 11,465 irrigation wells were available for the period (1981–2011) covered by this study. Personnel licensed by the State of Nebraska conducted the irrigation well sampling. The sample usually was obtained from a faucet at the wellhead. Irrigation wells that were not in continuous operation were pumped for at least 2 h [*Schepers et al.*, 1991b]. Samples were collected in polyethylene bottles and immediately put on ice until submitted for laboratory analysis. Occasionally samples were preserved with acid. With the exception of Lower Loup NRD samples prior to 2002, all samples were analyzed by the EPA-approved cadmium reduction method and concentrations reported as NO_2-N plus NO_3-N.

The distribution of nitrate concentrations was mapped using ArcGIS 10.1 conversion and cartography toolsets. The highest nitrate concentration in each well during the decade was averaged across 2 km by 2 km grid cells using the point-to-raster tool. The raster-to-polygon tool was used on grid cells with an average concentration $\geq$10 mg N/L. During conversion, the polygons were left orthogonal and not simplified. A polygon union was performed with no gaps allowed to fill in any open grid cells that were surrounded on all sides by $\geq$10 mg N/L. The data were consolidated into contiguous contaminated areas with the aggregate-polygons tool and major rivers as aggregation barriers. During all decades, the polygon aggregation was not forced to preserve orthogonal shapes. For 1981–1990 and 1991–2000, the aggregation distance was 6 km and the minimum hole size was 3000 ha. The wider geospatial distribution of the data during 2001–2010 necessitated increasing the aggregation distance and minimum hole size to 7.2 km and 4000 ha, respectively. The aggregated polygons for each decade were smoothed using Polynomial Approximation with Exponential Kernel (PAEK) and a smoothing tolerance of 4 km. In no instances were the endpoints for rings preserved during the smooth polygon process. The entire procedure was repeated using the median nitrate concentration in each well during the decade.

For the nitrate trend analyses, individual irrigation wells with nitrate data for at least half the years of the trend interval were selected. Additionally, data were required for the first year and either of the last 2 years of the trend analysis time frame. If more than one concentration was reported in a well in a year, the concentrations were averaged. Average annual nitrate concentrations were calculated for years in which the number of sampled wells was greater or equal to half the maximum number sampled in any year of the trend interval. Concentration trends were determined using linear regression. Statistical significance was described by the p value for a 2-tailed test. p values $<$0.05 were considered statistically significant.

2.2. Depth to Water and Saturated Thickness

The depth to water map was constructed using the ArcGIS 10.0 topo-to-raster tool for 72,620 wells completed after 1989 and with static water levels reported as greater than zero (http://www.dnr.ne.gov/groundwater-data). Flow line and lake layers from the National Hydrography Dataset (http://www.dnr.ne.gov/national-hydrography-dataset) were used to accommodate water level changes in highly sloped areas surrounding surface water bodies. The modeled depth to water was determined for all irrigation wells with a nitrate analysis between 2001 and 2010 using the ArcGIS 10.0 extract values-to-points tool. The difference between the well depth as given in the Agrichemical Contaminant Database and the modeled depth to water is the saturated zone well penetration depth.

3. Results and Discussion

3.1. Areal Distribution of Contamination

During each of the previous three decades, the area underlain by groundwater nitrate concentrations $\geq$10 mg N/L in the 11.2 Mha of central and eastern Nebraska nearly doubled. Using maximum nitrate concentrations the areas increased from 0.41 to 0.85 to 1.3 Mha (Figure 2). While the contaminated area delineated using median concentrations was less expansive in each decade, the decadal trends were similar with the contaminated areas increasing from 0.35 to 0.73 to 1.0 Mha. The contaminated areas are intensively irrigated (Figure 3a) and cropped to continuous corn or, more recently in some areas, corn in rotation with soybeans (Figure 3b). In the last decade, $\sim$30% of the irrigated area was underlain by nitrate-contaminated groundwater. Extensive production of nonirrigated row crops (Figure 3a), largely corn and soybeans in rotation (Figure 3b), also occurs in the study area. Groundwater beneath these areas seldom exceeds the MCL (Figure 3).

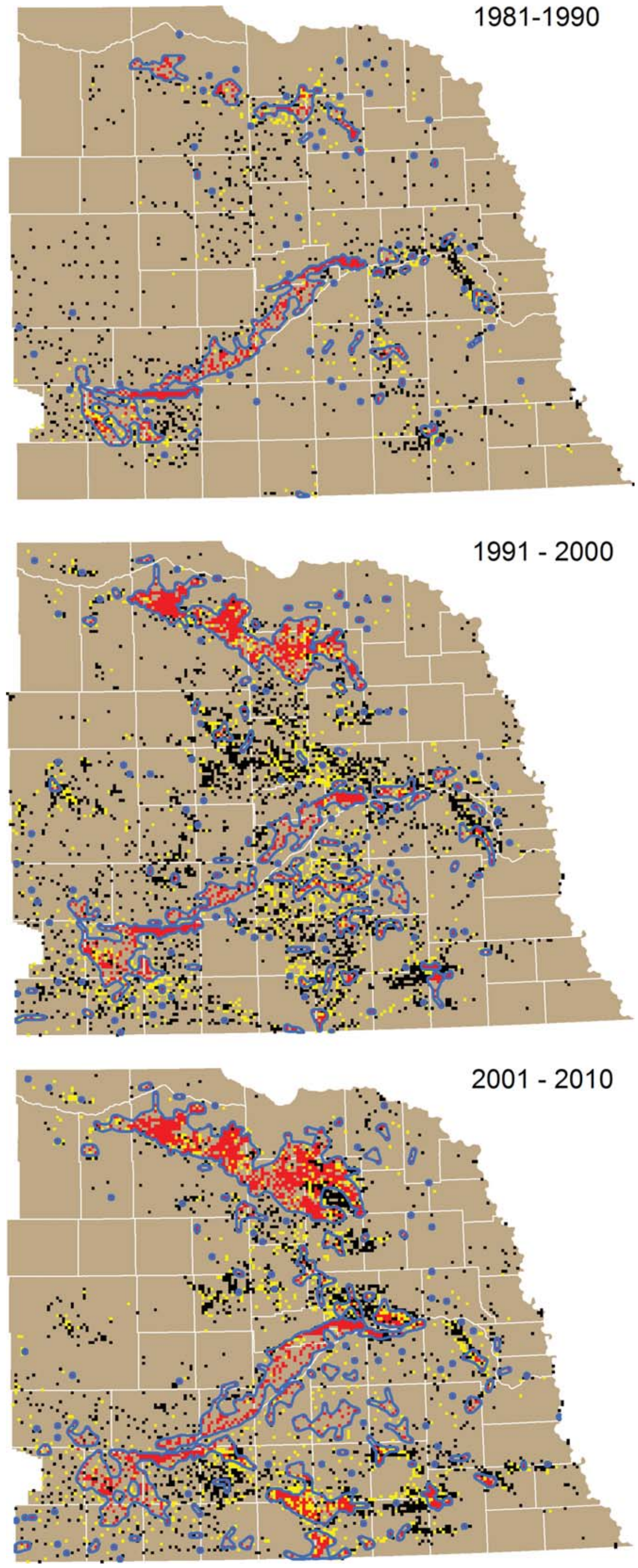

Figure 2. Decadal emergence of contaminated (≥10 mg N/L) groundwater. In each decade, the highest nitrate concentrations in irrigation wells within 2 km by 2 km grid cells were averaged. Black cells depict average concentrations <5 mg N/L, yellow cells 5 to <10 mg N/L, and red cells ≥10 mg N/L. The red grid cells were the basis for modeling the ≥10 mg N/L contaminated areas outlined in blue.

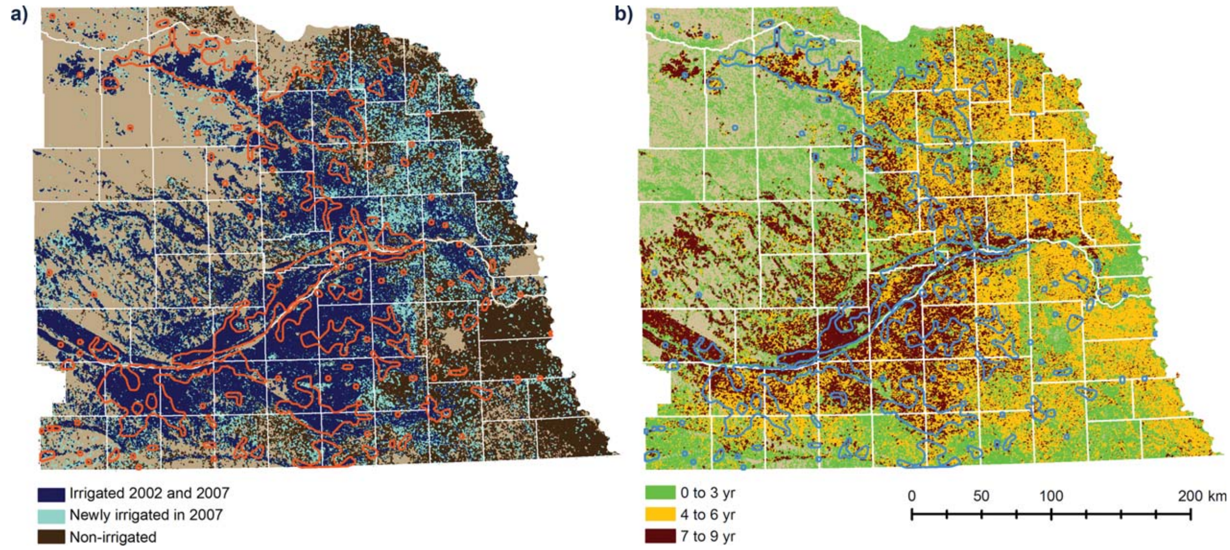

Figure 3. Distribution of (a) irrigated and nonirrigated row crops and (b) years of corn production between 2002 and 2010. Irrigated areas were drafted from the MIrAD-US project under the USGS Early Warning and Environmental Monitoring Program (http://earlywarning.usgs.gov/USirrigation/). Nonirrigated areas are those cropped to dryland corn and dryland soybeans on the 2005 Nebraska Land Use Map (http://www.calmit.unl.edu/2005landuse/statewide.shtml). The number of years in corn production was assessed by stacking raster layers of annual data from the National Agricultural Statistics Service (NASS) Cropland Data Layer (http://nassgeodata.gmu.edu/CropScape/). Groundwater nitrate concentrations in the outlined areas were $\geq$10 mg N/L during 2001–2010.

Contaminated groundwater in the predominantly nonirrigated southeastern, southwestern, and extreme northern parts of the study area occurs in small pockets of irrigated cropland (Figure 3a).

3.2. Characterization of Contaminated Areas

Major differences in agricultural practices and hydrology necessitated grouping the larger contaminated groundwater areas with intensive irrigation according to irrigation method (Figure 4a), soil drainage characteristics (Figure 4b), vadose zone thickness (Figure 5), and sediment lithology. The large, contiguous contaminated area north of the Elkhorn River (444,000 ha) and the two contiguous areas south of the

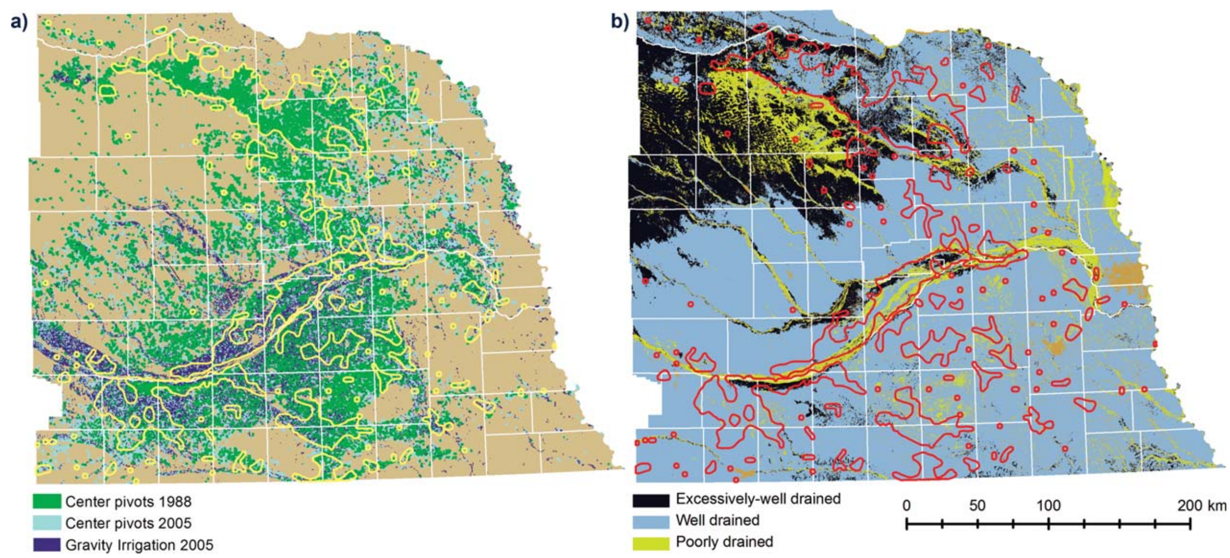

Figure 4. (a) Irrigation application methods and (b) soil drainage capacities. The irrigation methods are from the University of Nebraska-Lincoln Conservation and Survey Division 1988 Center Pivot Inventory (http://snr.unl.edu/data/geographygis/NebrGISwater.asp#pivot) and the Center for Advanced Land Management Information Technologies 2005 Nebraska Land Use map (http://www.calmit.unl.edu/2005landuse/statewide.php). The seven drainage classifications of the Soil Survey Geographic Database (http://www.dnr.state.ne.us/databank/ssurgo2.html) were consolidated into three groups. Groundwater nitrate concentrations in the outlined areas were $\geq$10 mg N/L during 2001–2010.

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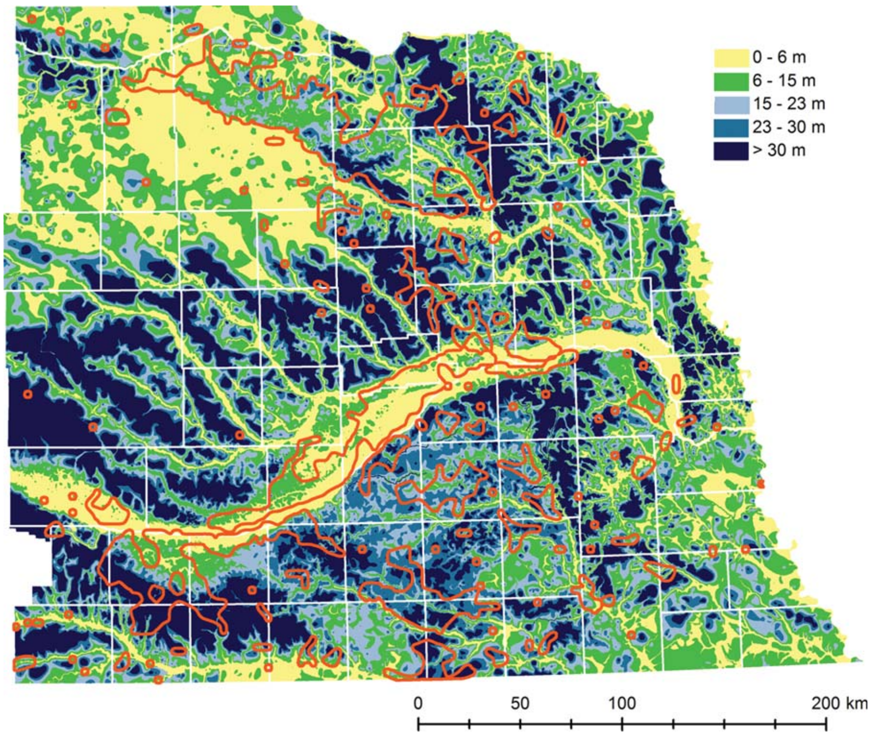

Figure 5. Depth to water. Groundwater nitrate concentrations in the outlined areas were $\geq$10 mg N/L during 2001–2010.

Platte (43,800 ha) and Loup Rivers (23,600 ha) comprise Group A (Figure 6). Group B occupies 220,000 ha along and north of the Platte River. Many discontinuous contaminated areas between the Platte, Republican, and Big Blue Rivers comprise the 400,000 ha of Group C. About 13% of the 1.3 million contaminated hectares were not classified. They are small emerging areas and are primarily south of the Platte River (Figure 2).

3.2.1. Group A

Well and excessively well-drained soils (Figure 4b), very sandy vadose zones, and spray application of irrigation water via center-pivot systems (Figure 4a), characterize the three Group A areas depicted in red in Figure 6. The unsaturated zone is >15 m thick in 46% of the 444,000 contiguous hectares contaminated north of the Elkhorn River and in 14% of the area is >30 m thick (Figure 5). Test hole drilling in Antelope County, located in the center of the contiguous area, showed a high level of sediment heterogeneity with layers of eolian sands, sandy silts, and silty sands [*Souders and Shaffer*, 1969]. The presence of continuous, confining clay lenses was not reported and suggests that

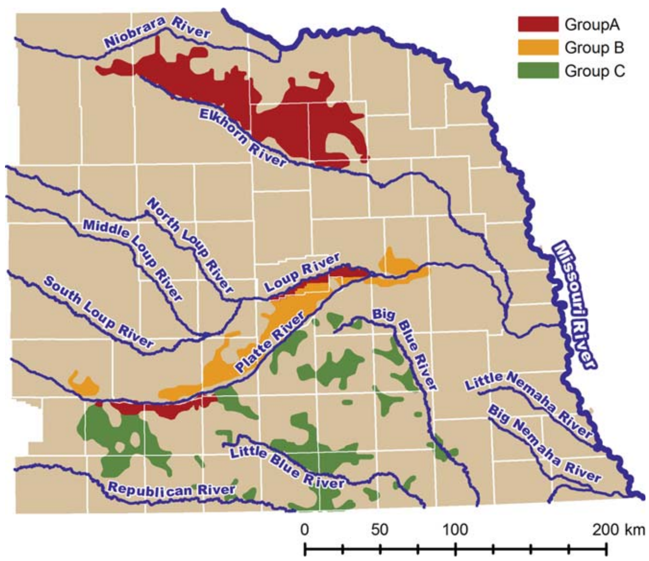

Figure 6. Contaminated groundwater during 2001–2010 classified according to soil drainage, vadose zone lithology and thickness, and irrigation practice. Major rivers are depicted.

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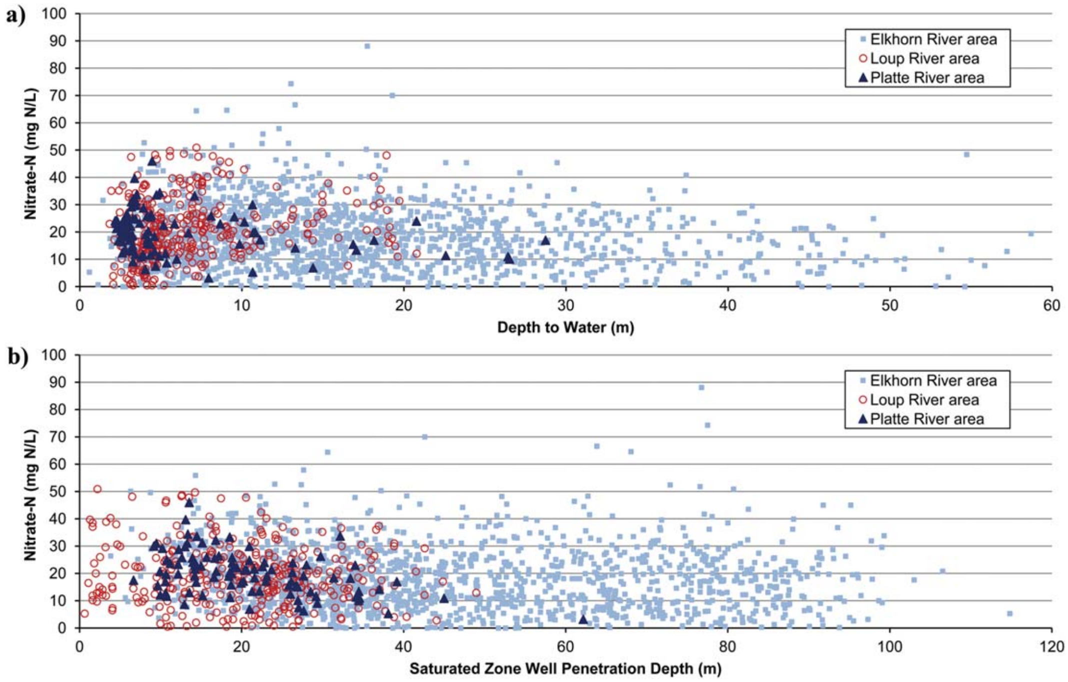

Figure 7. Nitrate-N concentration distribution in Group A contaminated groundwater with (a) depth to water and (b) saturated zone well penetration depth. Nitrate concentrations were the highest value in each irrigation well between 2001 and 2010.

vertical flow through the unsaturated zone is relatively uninhibited. Shallower and less variable depths to water occur in the smaller contaminated area south of the Loup River (Figures 5 and 6). The unsaturated thickness averages 6 m and in 95% of the sampled irrigation wells ranges from 1.8 to 15 m (Figure 7a). Similar depths to water occur in the contaminated area south of the Platte River where the unsaturated thickness averages 6 m and ranges from 2 to 22 m in 95% of the sampled wells (Figure 7a). These thin ($<$6 m), sandy, unsaturated zones cause both areas to be extremely vulnerable to nitrate leaching. Both small Group A areas are remnants of The Sandhills, a north-central Nebraska landmark occupying about one third of the state. Low organic matter soils and sandy vadose zones in the three Group A areas combined with oxygen-enriched irrigation return flows from spray applications strongly suggest that nitrate loss via denitrification is highly unlikely during downward transport.

The Ogallala aquifer is beneath the contiguous, four-county Group A contaminated area north of the Elkhorn River. It is relatively heterogeneous although predominantly sandstone with saturated thicknesses reaching 150 m [*Souders and Shaffer*, 1969]. The saturated zone penetration depth averages 45 m in the sampled wells and ranges from 4 to 91 m in 95% of the wells (Figure 7b) while in the Loup and Platte River areas the penetration depths average 20 and 21 m, respectively (Figure 7b). High nitrate concentrations occur at all depths (Figure 7b). Densely spaced, high-capacity irrigation wells likely increase vertical mixing of groundwater [*Spalding et al*., 2001]. Gravel-packing the $\sim$1 m diameter well bores below the water table creates vertical conduits for water to circulate within the aquifer and could partially account for nitrate in the deeper screened wells. Sealing the boreholes between highly transmissive zones would reduce vertical movement. The occurrence of nitrate in deep wells beneath densely irrigated areas also has been reported in Washington [*Wassenaar et al*., 2006] and the southern Great Plains [*Bruce et al*., 2003]. In the last two decades, the areal growth of the Group A contaminated area was 18,600 ha/yr. Median nitrate concentrations yielded a substantial but slower growth rate of 14,800 ha/yr.

The management areas shown in Figure 8 encompass $\sim$50% (228,000 ha) of the contiguous contaminated area. Those with sufficient data for trend analysis are located in Antelope and south central Holt counties in the Upper Elkhorn NRD (UENRD), in Knox County in the Lewis and Clark NRD (LCNRD), and in western and north-central Holt County in the Lower Niobrara NRD (LNNRD). In 1998, average concentrations ranged from slightly above the MCL (11.3 mg N/L) in the Antelope MA to more than twice the MCL (25.7 mg N/L) in

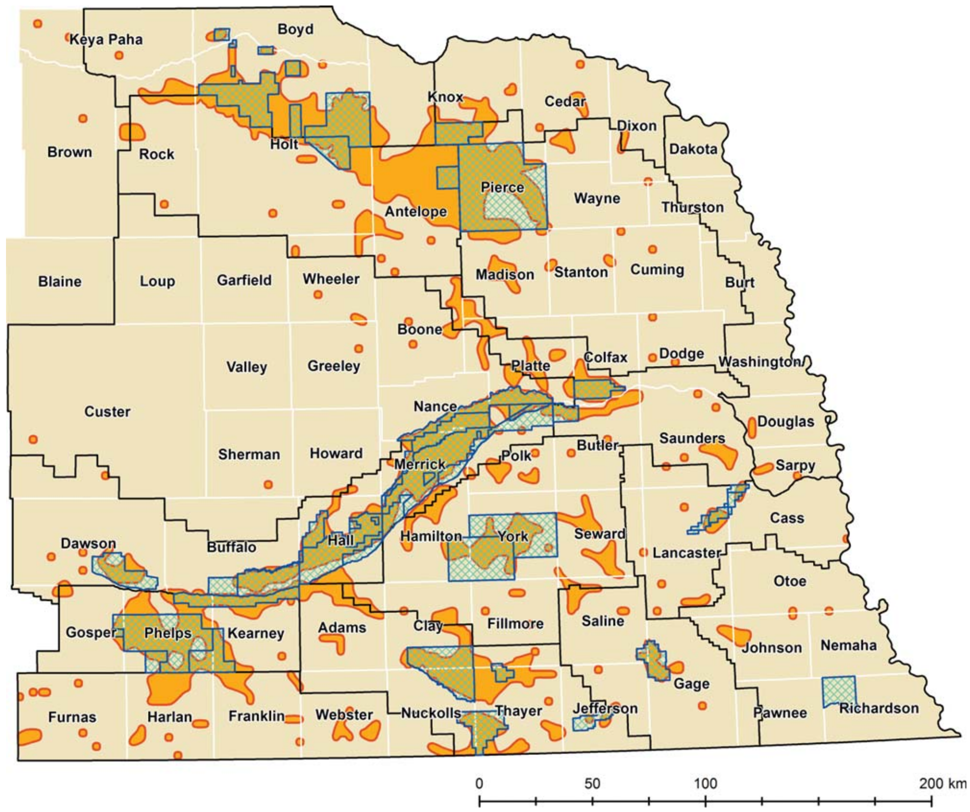

Figure 8. Tier 2 and 3 management areas and contaminated (≥10 mg N/L) groundwater. Management areas as of 31 December 2011 are shown as hatched pattern. Concentrations in orange areas were ≥10 mg N/L during 2001–2010.

the western Holt MA (Figure 9a). Average concentrations >20 mg N/L were reported in the latter area as early as 1976 and coincided with heavy irrigation development [*Exner and Spalding*, 1979]. Average annual N concentrations in the Antelope and Knox MAs increased ~0.20 mg N/L/yr ($p = 0.0017$ and $p = 0.025$, respectively) during the 14 year period. Significant concentration trends were not evident in the other three MAs.

For approximately 25 years, similar average nitrate concentrations in the Group A contaminated groundwater in the Lower Loup NRD (LLNRD) and Tri-Basin NRD (TBNRD) MAs south of the Loup and Platte rivers, respectively, have increased at almost identical rates (Figure 9b). Average annual nitrate concentrations in the MAs south of the Loup and Platte rivers increased from 14.5 to 20.3 mg N/L and from 13.6 to 20.7 mg N/L, respectively, at average rates of 0.26 mg N/L/yr ($p < 0.0001$) and 0.23 mg N/L/yr ($p < 0.0001$), respectively. The rate of increase in the Lower Loup MA calculated from the database records is identical (0.26 mg N/L/yr, $p < 0.0001$) to that calculated using the LLNRD's 27 year record of average annual concentrations for a much larger number of wells [*Lower Loup Natural Resources District*, 2012].

3.2.2. Group B

Gravity irrigation (Figure 4a) of corn and soybeans (Figure 3b) grown on ~1.5 m thick, well-drained, silt loam soils (Figure 4b) positioned above a thin, sandy unsaturated layer (Figure 5) characterizes the 220,000 ha of Group B contaminated groundwater (Figure 6). A 200,000 ha contaminated area was delineated using median nitrate concentrations. The small difference between the maximum and median nitrate concentration delineated areas is likely related to long-term (>35 years) [*Gormly and Spalding*, 1979] localization of the majority of the contamination by the lack of infiltration through bordering poorly drained bottomland soils (Figure 4b), low (<1 mg N/L) nitrate inflow from the Platte River, and reduced aquifer loading as a result of adoption of better management practices [*Spalding et al.*, 1978; *Exner et al.*, 2010]. Soil drainage heterogeneity is greater in the eastern Central Platte NRD (CPNRD) than in the other contaminated areas of the NRD. The very short (<1 m) distance to groundwater in many areas of the eastern CPNRD coupled with

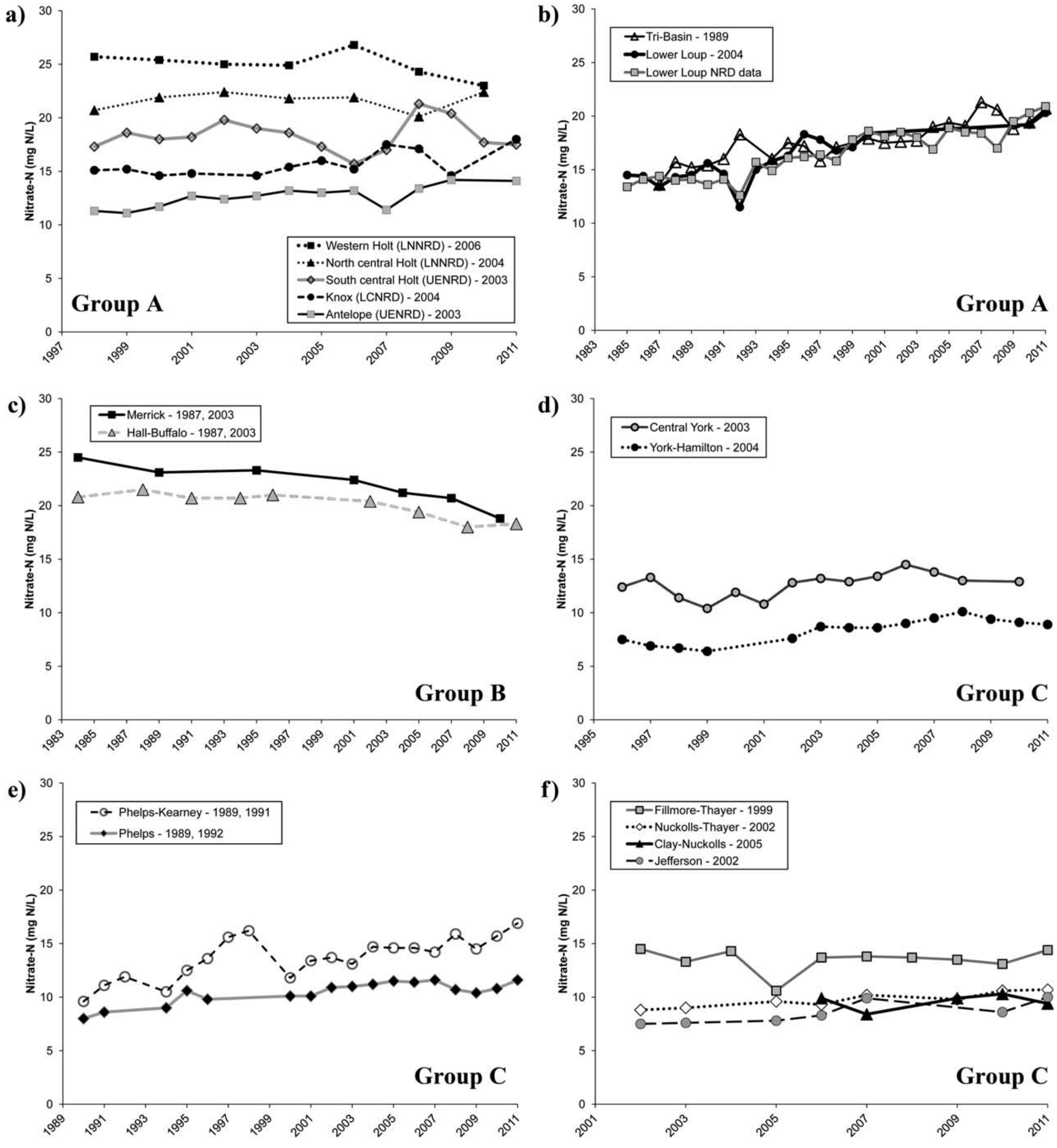

Figure 9. Nitrate-N concentration trends in management areas within Groups A, B, and C. Group A trends (a) north of the Elkhorn River and (b) south of the Platte and Loup rivers; Group B trends in the (c) two largest contiguous MAs in the Central Platte NRD; and Group C trends in (d) the Upper Big Blue NRD, (e) the Tri-Basin NRD, and (f) the Little Blue NRD. Regulations were implemented in the year in the legend. Small areas were annexed in the second year shown.

the application of anhydrous N fertilizer using knives that can intercept the water table likely affect vulnerability more than transport through the well to poorly drained soils. Within this area of the NRD, however, the incidence of very high nitrate concentrations (30–60 mg N/L) was greatest beneath excessively well-drained, intensely irrigated soils [*Spalding et al.*, 1978]. Depth to groundwater is <6 m in 77% of the contaminated area which has an average unsaturated thickness of 5.3 m (Figure 10a).

The primary aquifer is composed of relatively homogeneous sands and gravels. The average saturated thickness penetrated by the sampled irrigation wells is 19 m (Figure 10b). The Ogallala, a deep secondary aquifer,

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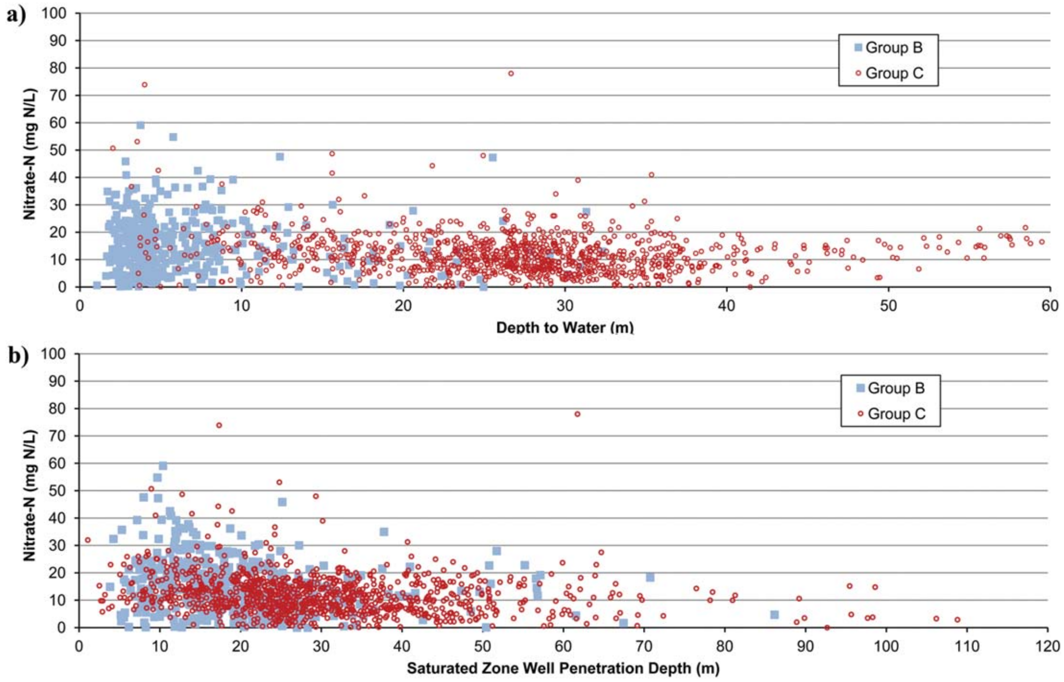

Figure 10. Nitrate-N concentration distribution in Groups B and C contaminated groundwater with (a) depth to water and (b) saturated zone well penetration depth. Nitrate concentrations were the highest value in each irrigation well between 2001 and 2010.

underlies the westernmost part of the contaminated area. A relatively thick aquitard protects the Ogallala from downward transport of the nitrate in the primary aquifer. During the last two decades, the rate of growth in the Group B area averaged 3700 ha/yr using the maximum nitrate concentration method and 3300 ha/yr with the median nitrate concentration method.

The contaminated groundwater is almost entirely contained within the 266,000 ha under management (Figure 8). Average nitrate concentrations in the two largest contiguous MAs—a 63,500 ha band stretching from central Buffalo County through Hall County and a 57,000 ha band through the center of Merrick County—were more than double the MCL in 1984 (Figure 9c). In the Merrick MA average concentrations decreased from 23.1 mg N/L in 1989 to 18.8 mg N/L in 2010 at an annual rate of 0.20 mg N/L ($p = 0.015$) and in the Hall-Buffalo MA concentrations declined from 21.5 mg N/L in 1988 to 18.3 mg N/L in 2011 at a rate of 0.14 mg N/L/yr ($p = 0.0012$).

3.2.3. Group C

Group C is characterized by well-drained silt loams (Figure 4b) positioned on a thick eolian clayey-silt unsaturated zone. Depths to groundwater >15 and >30 m (Figure 5) comprise 82% and 31%, respectively, of the 400,000 contaminated hectares (Figure 6). All the contaminated areas are located south of the Platte River and mostly in relatively flat uplands. With the exception of stream valleys where the unsaturated zone has thinned as a result of erosion, the clayey silts in the upper vadose zone are 15–21 m thick [*Spalding and Kitchen*, 1988]. Depth to water in the Group C irrigation wells averaged 23.7 m and in 95% of the wells ranged from 3.8 to 45.3 m (Figure 10a). N profiles in cores taken from the upper vadose zone of irrigated, N-fertilized research plots in the southwestern Upper Big Blue NRD showed nitrate had leached 20 m [*Spalding and Kitchen*, 1988]. Vadose zones beneath excessively fertilized plots had the greatest quantities of nitrate. Matching the high nitrate peaks with those in cores taken at the same locations 5 years later indicated that the nitrate moved ~0.75 m/yr [*Bobier et al*., 1993]. Additional coring in the Upper Big Blue, Little Blue, and Central Platte NRDs has shown that excess nitrate commonly occurs in thick vadose zones beneath N-fertilized, irrigated corn and corn/soybean fields (R. F. Spalding, unpublished data, 2004, 2010–2013). Thus, nitrate can leach though fine-textured eolian sediments and threaten groundwater quality. The saturated thickness penetrated by the wells in this study averaged 27.7 m and in 95% of the wells ranged from 3.1 to 62 m (Figure 10b). The Group C contaminated areas emerged in the last two decades and are increasing at an average rate of 15,000 ha/yr. The average expansion rate of 10,600 ha/yr calculated using median nitrate concentrations is considerably lower. More variability is expected as concentrations in these small emerging areas increase. As many of the numerous small emerging areas (Figure 2) merge and form large areas, nitrate concentrations likely will become more homogeneous as has occurred in Group B and is occurring in Group A contaminated areas.

Group C contaminated groundwater occurs as several discontinuous areas with average annual nitrate concentrations that are generally lower than in Groups A and B. Eight MAs encompass most of the larger areas of contamination and have sufficient data for trend analysis (Figures 8 and 9d–9f). Average nitrate concentrations increased at rates between 0.13 and 0.25 mg N/L/yr in six of the eight MAs and in five of the six average concentrations met or exceeded the MCL in 2011. In the central York and York-Hamilton MAs (Figure 8) average annual concentrations rose 0.14 ($p = 0.043$) and 0.20 ($p < 0.001$) mg N/L/yr, respectively, since 1996 (Figure 9d). Average groundwater nitrate concentrations are increasing in the two largest MAs that include most of the Group C contaminated groundwater in the Tri-Basin NRD. In the Phelps MA and the Phelps-Kearney MA that abuts it on the east and southeast (Figure 8), average concentrations rose to 11.6 and 16.9 mg N/L in 2011, respectively, at rates of 0.13 mg N/L/yr ($p = 0.0001$) and 0.23 ($p = 0.0001$), respectively (Figure 9e). The groundwater nitrate records in the Little Blue NRD MAs are relatively short (Figure 9f). Average annual concentrations in the Nuckolls-Thayer and Jefferson MAs increased 0.20 and 0.25 mg N/L/yr ($p = 0.0009$ and 0.034), respectively, to concentrations that met or exceeded the MCL. Only the Fillmore-Thayer MA concentrations averaged considerably above the MCL ($\sim$14 mg N/L) and, with the exception of 2005, were quite stable during the 10 year record. Average N concentrations in the Clay-Nuckolls MA remained at or below the MCL during the 6 year record.

3.3. Management Area Regulations and the Impact on Concentrations

The 17 MAs in the nine NRDs with relatively large Group A, B, or C groundwater areas (Figure 8) have similar requirements. Producers in all MAs must attend education programs and be certified to apply commercial N fertilizer, adopt N budgeting on regulated fields, and complete an annual report that details the N budget for each regulated field. Budgeting begins with a N fertilizer recommendation. Most districts use a University of Nebraska formula that is based on residual soil N and organic matter and a yield goal which is usually 105% of several previous years' production. Requirements for crediting N inputs from irrigation water, each manure source (e.g., hogs, cattle), and previous legume crops in the budget as well as the density and depth of soil samples varies with the NRD. Scheduling of irrigation water applications is required only in the Upper Big Blue and Little Blue NRDs' MAs. Typically scheduling is encouraged as is monitoring the amount of irrigation water applied. While all management plans address practices on irrigated corn, NRDs may regulate other irrigated row crops and some regulate nonirrigated row crops. Table 1 summarizes the management practices for irrigated corn producers in the tier 2 and 3 MAs whose nitrate concentration trends are depicted in Figure 9.

Increasing or decreasing groundwater nitrate concentrations in the MAs reflect the impact of BMPs on vadose zone N leachates. Higher nitrate concentrations in leachates below the root zone than in the aquifer cause groundwater concentrations to increase. Conversely, lower N concentrations in the leachate reduce groundwater nitrate levels. A trend of decreasing groundwater nitrate concentrations reflects the impact of reduced N loads in the leachate. Increasing groundwater concentrations indicate that a steady state concentration between vadose zone pore water and groundwater has not been attained. Age-dating has shown that groundwater beneath thin, permeable vadose zones is rapidly impacted by changes in vadose zone pore water concentrations [*Spalding et al.*, 2001].

3.3.1. Group A

Tier 2 and 3 MA regulations in the seven Group A MAs have not effected a significant ($p < 0.05$) trend reversal in average nitrate concentrations (Figures 9a and 9b). The seven MAs have the similar budgeting requirements and all require submission of an annual report (Table 1). Differences lie in the timing and application of commercial N fertilizer. The Tri-Basin NRD MA south of the Platte River is the oldest Group A MA. It moved to tier 3 after N concentrations did not decline during the first 15 years in tier 2. In tier 3 commercial N fertilizer applications are banned in fall and winter. Commercial N fertilization is banned until spring in the Lower Loup MA at which time the application must be split between pre-emergence and

Table 1. Prescribed Management Practices for Irrigated Corn as of 31 December 2011[a]

MA	Tier	Year	NRD	Commercial N Fertilizer Application Restrictions (kg N/ha)			N Budget Credits				Annual Report
				Fall (9/1 to 11/1)	Winter	Spring (After 3/1)	Analyses				
							Soil Composite (Depth / Frequency) m/ha	Irrigation Water (Frequency) Years	Manure	Previous Legume Crop	
Group A											
Western Holt	2	2006	Lower Niobrara[b]	0			0.6/16	4	R		R
North-central Holt	2	2004	Lower Niobrara[b]	0			0.6/16	4	R		R
South-central Holt	2	2003	Upper Elkhorn[c]	0			0.6/16	4			R
Antelope	2	2003	Upper Elkhorn[c]	0			0.6/16	4			R
Knox	3	2004	Lewis & Clark[d]	0	0		0.9/16	2		R	R
South of Loup River	3	2004	Lower Loup[e]	0	0	split or use N inhibitor	0.9/32	1	R		R
South of Platte River	2	1989	Tri-Basin[f]	0	0[g]		0.8/32	1			R
South of Platte River	3	2006	Tri-Basin[f]	0	0		0.8/32	1			R
Group B											
Merrick	3	1987	Central Platte[h]	0	0	split or use N inhibitor	0.9/32	1	R	R	R
Hall-Buffalo	3	1987	Central Platte[h]	0	0	split or use N inhibitor	0.9/32	1	R	R	R
Group C											
Central York	2	2003	Upper Big Blue[i]	0 (1996)	0[j] (1996)		0.6/16	0[k,m]	R[l]	R	R
York-Hamilton	2	2004	Upper Big Blue[i]	0 (1996)	0[j] (1996)		0.6/16	0[k,m]	R[l]	R	R
Phelps-Kearney	2	1989	Tri-Basin[f]	0	0[g]		0.8/32	1			R
Phelps	2	1989	Tri-Basin[f]	0	0[g]		0.8/32	1			R
Phelps	3	2006	Tri-Basin[f]	0	0		0.8/32	1			R
Fillmore-Thayer	3	1999	Little Blue[n]	0			0.9/16	0[k]	R		R
Nuckolls-Thayer	2	2002	Little Blue[n]	0			0.9/16[m]	0[k,m]	R[m]		R
Jefferson	2	2002	Little Blue[n]	0			0.9/16[m]	0[k,m]	R[m]		R
Clay-Nuckolls	2	2005	Little Blue[n]	0			0.9/16[m]	0[k,m]	R[m]		R

[a]MA, management area; NRD, natural resources district; R, required.
[b]*Lower Niobrara Natural Resources District* [2003].
[c]*Upper Elkhorn Natural Resources District* [1997].
[d]www.lcnrd.org/groundwater/bgma.
[e]*Lower Loup Natural Resources District* [2002].
[f]*Tri-Basin Natural Resources District* [1992].
[g]On sandy soils.
[h]*Central Platte Natural Resources District* [2003].
[i]*Upper Big Blue Natural Resources District* [1995].
[j]Liquid and dry N forms.
[k]Require irrigation scheduling.
[l]NRD specifies credit amount for each manure source.
[m]Demonstration field only.
[n]www.littlebluenrd.org/Water/management_areas.html.

postemergence and a nitrification inhibitor which prevents rapid conversion of ammonium-N to nitrate-N used if more than half (>90 kg N/ha) of the application is applied before the crop emerges. Fall fertilization is prohibited in all the MAs along the Elkhorn River while the Knox MA also prohibits winter applications. Spring preplant and pre-emergent fertilizer applications are not restricted in this highly contaminated area.

Average annual concentrations in the western Holt MA, which averaged ~25 mg N/L for almost a decade, appear to be trending downward toward a steady state concentration while the relatively recently developed areas in the Antelope and Knox MAs have a significant upward trend ($p < 0.05$) and concentrations in the leachate and groundwater have not yet attained a steady state. Concentrations in the south central Holt MA have fluctuated about a steady state concentration during the period of record. The large unsaturated and saturated thicknesses penetrated by the irrigation wells and the high levels of aquifer heterogeneity in the five MAs likely retard the observable effects of management practices on groundwater nitrate concentrations.

Trend reversals anticipated in MAs with short distances to groundwater (~6 m) and thin saturated thicknesses (20–21 m) have not occurred in the MAs south of the Platte and Loup rivers (Figure 9b). Average concentrations in both MAs increased to ~21 mg N/L in 2011 and will continue to increase until N concentrations in the leachate and groundwater establish steady state concentrations.

3.3.2. Group B

The two large contiguous MAs in the Central Platte NRD (Figure 8) are the only MAs where nitrate concentrations are declining (Figure 9c). Tier 3 prohibitions against fall and winter N fertilization of all soils, preplant and pre-emergent fertilization restrictions including the use of a nitrification inhibitor if >90 kg N/ha is applied before emergence, and very detailed N budgeting have effected a decrease in leachate N concentrations and reversed the ~0.4–1 mg N/L/yr increase in groundwater concentrations that occurred between 1974 and 1984 [*Spalding and Exner*, 1993]. The rate of decrease has been greater in the Merrick MA where concentrations peaked at 24.5 mg N/L, about 4 mg N/L higher than in the Hall-Buffalo MA, in 1984. Concentrations in both MAs average 18–19 mg N/L.

The high density of irrigation wells pumping from a relatively thin (<20 m) and homogeneous saturated thickness promote vertical mixing of the reduced nitrate load in the leachates [*Spalding et al*., 2001]. Unlike most MAs in this study, irrigation water has been applied largely via furrows rather through a sprinkler system (Figure 4a). Even water distribution is much more difficult with furrow irrigation. Since N cannot be applied to the corn crop at the time of maximum uptake as is possible with sprinkler irrigation, the crop's N needs during the entire growing season must be anticipated and applied early in the growing season.

3.3.3. Group C

Average nitrate concentrations in the eight Group C MAs have not undergone a trend reversal and in 6 MAs concentrations have increased at rates of 0.13–0.25 mg N/L/yr ($p < 0.05$; Figures 9d–9f). Each of the three NRDs encompassing the Group C MAs has different N fertilizer regulations (Table 1). Fall N fertilization is prohibited in all the MAs. It has been banned in the central York and York-Hamilton MAs as part of a district-wide regulation since 1996. Winter application of liquid and dry N fertilizers, but not anhydrous N, requires the use of a nitrification inhibitor in the central York and York-Hamilton MAs while winter commercial N fertilizer applications are banned on sandy soils in the Phelps-Kearney MA and on all soil types in the Phelps MA. None of the MAs restrict spring fertilizer applications. The Little Blue and Upper Big Blue NRDs are unique in that they require irrigation scheduling in existing MAs. Concentration triggers for the Little Blue NRD MAs are the lowest of the Group C MAs.

Despite more than 20 years of N fertilizer restrictions, nitrate concentrations in the aquifer beneath the Phelps-Kearney and Phelps MAs are at their highest levels and will continue to increase until N input concentrations decrease and begin to dilute the existing high concentrations. N inputs have been regulated for a shorter time (<15 years) in the Upper Big Blue and Little Blue NRDs' MAs and the impacted leachates likely have not yet reached the aquifer.

Presently, nitrate concentrations in leachate below the root zone of irrigated corn grown using recommended BMPs exceed the MCL [*Klocke et al*., 1999; *Spalding et al*., 2001] and can be attained only by serious concessions to yield goals and by the elimination of overly optimistic yield goals [*Schepers et al*., 1991b]. Even with decreased inputs of both water and nitrogen, leaching beneath high N demand row crops is subject to weather-related phenomena. Nitrate leaching increased after spring rains leached preplant N below undeveloped corn root systems [*Spalding et al*., 2001; *Helmers et al*., 2007]. Hail-damaged corn or persistent cloudy conditions during the growing season can result in higher soil N concentrations available for leaching [*Spalding et al*., 2001]. Lysimeter data indicate that leachate nitrate concentrations were not reduced when corn and soybeans were rotated [*Klocke et al*., 1999; *Tarkalson et al*., 2006]. As *Twomey et al*. [2010] report the possibility of small towns and municipalities obtaining groundwater with concentrations at or below the MCL is shrinking while the likelihood of costly treatment options is growing.

4. Conclusion

Known areas of groundwater nitrate contamination with average concentrations above the MCL are expanding and new areas continue to emerge beneath Nebraska's irrigated cropland. Increasing concentration trends have been reversed only in two MAs in the Central Platte NRD where after more than two decades of commercial N fertilizer application restrictions and adoption of N budgeting, concentrations average 18–19 mg N/L. While fertilizer BMPs in the MAs likely have slowed the increases in groundwater concentrations, irrigation has obviously exacerbated leaching and water use must be effectively managed and monitored to limit nitrate leaching below the root zone. Whether N and water management will decrease N fertilizer and water application rates to sufficiently lower groundwater nitrate concentrations is doubtful. Groundwater nitrate contamination likely will expand as marginal cropland is developed for irrigated corn production as a consequence of the United States's reliance on ethanol as a gasoline additive and alternative fuel.

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References

Batlle Aguilar, J. B., P. Orban, A. Dassargues, and S. Brouyère (2007), Identification of groundwater quality trends in a chalk aquifer threatened by intensive agriculture in Belgium, *Hydrogeol. J.*, *15*, 1615–1627, doi:10.1007/s10040-007-0204-y.

Bishop, R. (1996), A local agency's approach to solving the difficult problem of nitrate in the groundwater, *J. Soil Water Conserv.*, *49*, 82–84.

Bobier, M. W., K. D. Frank, and R. F. Spalding (1993), Nitrate-N movement in a fine-textured vadose zone, *J. Soil Water Conserv.*, *48*, 350–354.

Brender, J. D., J. M. Olive, M. Felkner, L. Suarez, W. Marckwardt, and K. A. Hendricks (2004), Dietary nitrites and nitrates, nitrosatable drugs, and neural tube defects, *Epidemiology*, *15*, 330–336, doi:10.1097/01.ede.0000121381.79831.7b.

Bruce, B. W., M. F. Becker, L. M. Pope, and J. J. Gurdak (2003), Ground-water quality beneath irrigated agriculture in the central High Plains aquifer, 1999–2000, *U.S. Geol. Surv. Water Resour. Invest. Rep. 03–4219*, U.S. Geol. Surv., 39 pp., Reston, Va.

Burow, K. R., B. T. Nolan, M. G. Rupert, and N. M. Dubrovsky (2010), Nitrate in groundwater of the United States, 1991–2003, *Environ. Sci. Technol.*, *44*, 4988–4997, doi:10.1021/es100546y.

Central Platte Natural Resources District (2003), *Groundwater Management Plan*, Grand Island, Nebr.

Comly, H. H. (1945), Cyanosis in infants caused by nitrate in well water, *JAMA*, *129*, 112–116.

Croen, L. A., K. Todoroff, and G. M. Shaw (2001), Maternal exposure to nitrate from drinking water and diet and risk for neural tube defects, *Am. J. Epidemiol.*, *153*, 325–331, doi:10.1093/aje/153.4.325.

Exner, M. E., and R. F. Spalding (1979), Evolution of contaminated groundwater in Holt County, Nebraska, *Water Resour. Res.*, *15*, 139–147, doi:10.1029/WR015i001p00139.

Exner, M. E., and R. F. Spalding (1987), Groundwater quality and policy options in Nebraska, in *Nebraska Policy Choices*, edited by R. L. Smith, pp. 187–234, Cent. for Appl. Urban Res., Univ. of Nebr. at Omaha, Omaha, Nebr. [Available at http://digitalcommons.unl.edu/cpar/9/.]

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

Fan, A. M., and V. E. Steinberg (1996), Health implications of nitrate and nitrite in drinking water: An update on methemoglobinemia occurrence and reproductive and developmental toxicity, *Regul. Toxicol. Pharmacol.*, *23*, 35–43.

Freedman, D. F., K. P. Cantor, M. H. Ward, and K. J. Helzlsouer (2000), A case-control study of nitrate in drinking water and non-Hodgkin's lymphoma in Minnesota, *Arch. Environ. Health*, *55*, 326–329, doi:10.1080/00039890009604024.

Gormly, J. R., and R. F. Spalding (1979), Sources and concentrations of nitrate-nitrogen in ground water of the central Platte region, Nebraska, *Ground Water*, *17*, 291–301, doi:10.1111/j.1745-6584.1979.tb03323.x.

Hansen, B., L. Thorling, T. Dalgaard, and M. Erlandsen (2011), Trend reversal of nitrate in Danish groundwater – a reflection of agricultural practices and nitrogen surpluses since 1950, *Environ. Sci. Technol.*, *45*, 228–234, doi:10.1021/es102334u.

Helmers, M. J., T. M. Isenhart, C. L. Kling, T. B. Moorman, W. W. Simpkins, and M. Tomer (2007), Theme overview: Agriculture and water quality in the Cornbelt: Overview of issues and approaches, *Choices*, *22*, 79–85.

Idaho Ground Water Quality Council (1996), *Idaho Ground Water Quality Plan*, 176 pp., Idaho Dep. Health and Welfare, Div. Environ. Qual., Dep. Water Resour., Dep. Agric., Boise, Idaho. [Available at http://www.deq.idaho.gov/media/462972-idaho_gw_quality_plan_final_entire.pdf.]

Jalali, M. (2005), Nitrates leaching from agricultural land in Hamadan, western Iran, *Agric. Ecosyst. Environ.*, *110*, 210–218.

Klocke, N. L., D. G. Watts, J. P. Schneekloth, D. R. Davison, R. W. Todd, and A. M. Parkhurst (1999), Nitrate leaching in irrigated corn and soybean in a semi-arid climate, *Trans. Am. Soc. Agric. Eng.*, *42*, 1621–1630, doi:10.13031/2013.13328.

Knapp, M. F. (2005), Diffuse pollution threats to groundwater: A UK water company perspective, *Q. J. Eng. Geol. Hydrol.*, *38*, 29–51, doi:10.1144/1470-9236/04-015.

Lindsey, B. D., and M. G. Rupert (2012), Methods for evaluating temporal groundwater quality data and results of decadal-scale changes in chloride, dissolved solids, and nitrate concentrations in groundwater in the United States, 1988–2010, *U.S. Geol. Surv. Sci. Invest. Rep.* U.S. Geol. Surv., 2012–5049, 56 pp., Reston, Va.

Lower Loup Natural Resources District (2002), *Groundwater Management Area Rules and Regulations*, Ord, Nebr.

Lower Loup Natural Resources District (2012), *2011 Water Quality Report*, Ord, Nebr. [Available at http://www.llnrd.org/images/2011WaterQuality.pdf.]

Lower Niobrara Natural Resources District (2003), *Groundwater Management Plan*, Butte, Nebr.

Mueller, D. K., and D. R. Helsel (1996), Nutrients in the nation's waters – too much of a good thing?, *U.S. Geol. Surv. Circ., 1136*, 24 pp.

Nolan, B. T., and K. J. Hitt (2006), Vulnerability of shallow groundwater and drinking-water wells to nitrate in the United States, *Environ. Sci. Technol.*, *40*, 7834–7840, doi:10.1021/es060911u.

Nolan, B. T., B. C. Ruddy, K. J. Hitt, and D. R. Helsel (1997), Risk of nitrate in groundwater of the United States–a national perspective, *Environ. Sci. Technol.*, *31*, 2229–2236, doi:10.1021/es960818d.

Nolan, B. T., K. J. Hitt, and B. C. Ruddy (2002), Probability of nitrate contamination of recently recharged groundwaters in the conterminous United States, *Environ. Sci. Technol.*, *36*, 2138–2145, doi:10.1021/es0113854.

Oregon Department of Environmental Quality (2011), *Groundwater Quality Protection in Oregon, Report to the Environmental Quality Commission and Legislature*, Oregon Department of Environmental Quality, Portland, Oreg. [Available at http://www.deq.state.or.us/wq/pubs/reports/2011GWReport.pdf.]

Rhoades, M. G., J. L. Meza, C. L. Beseler, P. J. Shea, A. Kahle, J. M. Vose, K. M. Eskridge, and R. F. Spalding (2013), Atrazine and nitrate in public drinking water supplies and non-Hodgkin lymphoma in Nebraska, USA, *Environ. Health Perspect.*, *7*, 15–27, doi:10.4137/EHI.S10629.

Rupert, M. G. (2008), Decadal-scale changes of nitrate in ground water of the United States, 1988–2004, *J. Environ. Qual.*, *37*, S-240-S-248, doi:10.2134/jeq2007.0055.

Schepers, J. S., D. L. Martin, D. G. Watts, and R. B. Ferguson (1991a), Integrated water and nitrogen management, in *Nitrate Contamination: Exposure, Consequences, and Control, NATO ASI Ser. G: Ecolo. Sci.*, vol. 30, edited by I. Bogardi and R. D. Kuzelka, pp. 163–171, Springer, Berlin.

Schepers, J. S., M. G. Moravek, E. E. Alberts, and K. D. Frank (1991b), Maize production impacts on groundwater quality, *J. Environ. Qual.*, *20*, 12–16, doi:10.2134/jeq1991.00472425002000010004x.

Souders, V. L., and F. B. Shaffer (1969), *Water Resources of Antelope County, Nebraska, Hydrol. Invest. Atlas, HA-316*, U.S. Geol. Surv., Washington, D. C.

Spalding, R. F., and M. E. Exner (1993), Occurrence of nitrate in groundwater—A review, *J. Environ. Qual.*, *22*, 392–402, doi:10.2134/jeq1993.00472425002200030002x.

Spalding, R. F., and L. A. Kitchen (1988), Nitrate in the intermediate vadose zone beneath irrigated cropland, *Ground Water Monit. Rev.*, *8*, 89–95, doi:10.1111/j.1745-6592.1988.tb00994.x.

Spalding, R. F., J. R. Gormly, B. H. Curtiss, and M. E. Exner (1978), Nonpoint nitrate contamination of groundwater in Merrick County, Nebraska, *Ground Water*, *16*, 86–95, doi:10.1111/j.1745-6584.1978.tb03207.x.

Spalding, R. F., D. G. Watts, J. S. Schepers, M. E. Burbach, M. E. Exner, R. J. Poreda, and G. E. Martin (2001), Controlling nitrate leaching in irrigated agriculture, *J. Environ. Qual.*, *30*, 1184–1194, doi:10.2134/jeq2001.3041184x.

Tarkalson, D. D., J. O. Payero, S. M. Ensley, and C. A. Shapiro (2006), Nitrate accumulation and movement under deficit irrigation in soil receiving cattle manure and commercial fertilizer, *Agric. Water Manage.*, *85*, 201–210, doi:10.1016/j.agwat.2006.04.005.

Thorburn, P. J., J. S. Biggs, K. L. Weier, and B. A. Keating (2003), Nitrate in ground waters of intensive agricultural areas in coastal Northeastern Australia, *Agric. Ecosyst. Environ.*, *94*, 49–58.

Tri-Basin Natural Resources District (1992), *Rules and Regulations for Management and Protection of Land and Water Resources*, Holdrege, Nebr.

Twomey, K. M., A. S. Stillwell, and M. E. Webber (2010), The unintended energy impacts of increased nitrate contamination from biofuels production, *J. Environ. Monit.*, *12*, 218–224, doi:10.1039/b913137j.

University of Nebraska-Lincoln (2000), *Quality-Assessed Agrichemical Contaminant Database for Nebraska Ground Water. A Cooperative Project of the Nebraska Departments of Agriculture, Environmental Quality, and Natural Resources and the University of Nebraska-Lincoln*. Nebraska Department of Natural Resources, Lincoln, Nebraska. [Available at http://dnrdata.dnr.ne.gov/clearinghouse, last accessed 3 Oct. 2012.]

Upper Big Blue Natural Resources District (1995), *Upper Big Blue Natural Resources District Groundwater Management Rules and Regulations*, York, Nebr.

Upper Elkhorn Natural Resources District (1997), *Upper Elkhorn Natural Resources District Ground Water Management Plan Rules and Regulations for the Enforcement of the Nebraska Ground Water Management and Protection Act*, O'Neill, Nebr.

U.S. Department of Agriculture (2009), *2007 CENSUS of Agriculture, U.S. Summary and State Data, Geogr. Area Ser. Part 51*, vol. 1. U.S. Dept. of Agriculture and National Agricultural Statistics Service, Washington, D.C. [Available at http://www.agcensus.usda.gov/Publications/2007/Full_Report/usv1.pdf.]

U.S. Environmental Protection Agency (2007), *Nitrates and Nitrites, TEACH Chemical Summary*. U.S. Environmental Protection Agency, Washington, D.C. [Available at http://www.epa.gov/teach/chem_summ/Nitrates_summary.pdf.]

U.S. Public Health Service (1962), *Public Health Service Drinking Water Standards, Publ. 956*, pp. 47–51, U.S. Dept. of Health, Education and Welfare, Public Health Service, Washington, D. C. [Available at http://archive.org/details/gov.law.usphs.956.1962.]

Walton, G. (1951), Survey of literature relating to infant methemoglobinemia due to nitrate-contaminated water, *Am. J. Public Nations Health*, *41*, 986–996.

Ward, M. H., T. M. deKok, P. Levallois, J. Brender, G. Gulis, B. T. Nolan, and J. VanDerslice (2005), Workgroup report: drinking-water nitrate and health—Recent findings and research needs, *Environ. Health Perspect.*, *113*, 1607–1614, doi:10.1289/ehp.8043.

Washington Administrative Code (2013), *Ground water Management Areas and Programs*, chap. 173-100. Office of the Code Reviser, Olympia, Washington. [Available at https://fortress.wa.gov/ecy/publications/publications/173100.pdf.]

Wassenaar, L. I., M. J. Hendry, and N. Harrington (2006), Decadal geochemical and isotopic trends for nitrate in a transboundary aquifer and implications for agricultural beneficial management practices, *Environ. Sci. Technol.*, *40*, 4626–4632, doi:10.1021/es060724w.

Weyer, P. J., J. R. Cerhan, B. C. Kross, G. R. Hallberg, J. Kantamneni, G. Breuer, M. P. Jones, W. Zheng, and C. F. Lynch (2001), Municipal drinking water nitrate level and cancer risk in older women: The Iowa women's health study, *Epidemiology*, *12*, 327–338.

Zlotnik, V. A., R. F. Spalding, M. E. Exner, and M. E. Burbach (1993), Sampling of non-point source contamination in high-capacity wells, *Water Sci. Technol.*, *28*, 409–413.