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Selected Anthropogenic Contaminants in Groundwater, Papio-Missouri River Natural Resources District, Eastern Nebraska, 1992–2020

Scientific Investigations Report 2023–5018

U.S. Department of the Interior
U.S. Geological Survey

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32.$$

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L), micrograms per liter (µg/L), or nanograms per liter (ng/L).

Abbreviations

CEC	contaminant of emerging concern
DO	dissolved oxygen
IDS	isotope-dilution standard
MCL	maximum contaminant level
NFM	USGS National Field Manual for the Collection of Water-Quality Data
nitrate-N	nitrate as nitrogen
NWQL	National Water Quality Laboratory
PMRNRD	Papio-Missouri River Natural Resources District
QA	quality assurance
USGS	U.S. Geological Survey

Selected Anthropogenic Contaminants in Groundwater, Papio-Missouri River Natural Resources District, Eastern Nebraska, 1992–2020

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Abstract

A study in cooperation with the Papio-Missouri River Natural Resources District was completed in 2019 to determine the concentration of contaminants of emerging concern (CEC) in groundwater in the Papio-Missouri River Natural Resources District, eastern Nebraska. Each well was sampled twice (in June and October or November) in 2019, totaling 34 samples. Samples were analyzed for 132 CECs, which include pharmaceutical, steroid hormone, and other organic chemicals. Seven of the 132 CEC analytes were detected in samples collected during this study. The most commonly detected CEC in this study was the antibiotic sulfamethoxazole. Other CECs detected in this study were nicotine, methyl-1*H*-benzotiazole (industrial product), acetaminophen (analgesic), caffeine, and metformin (diabetes medicine). None of the detected CECs have health-based water-quality standards. The agricultural herbicide atrazine was also sampled for and was detected in 15 of 26 samples from 8 wells, but all samples were below the established water-quality standard.

Nitrate, dissolved oxygen, and iron sampling results for 2010–19 and 1992–2020 were also assessed to determine the extent and trend of anthropogenic contamination in the Papio-Missouri River Natural Resources District. Nitrate as nitrogen was detected at a concentration greater than 4 milligrams per liter in 92 samples (19 percent), and detections in 36 samples (7.6 percent) exceeded 10 milligrams per liter, which is the U.S. Environmental Protection Agency's maximum contaminant level for drinking water and Nebraska's Title 118 maximum contaminant level for groundwater. Time series analysis showed that nitrate concentrations are not increasing or decreasing in any of the aquifers except for in three specific well nests, which are in phase 2 management areas. Dissolved oxygen results indicate potential denitrification throughout the Elkhorn alluvial aquifer; iron concentrations indicate potential denitrification in parts of the Missouri River alluvial aquifer.

Introduction

Anthropogenic contamination of groundwater has been recognized for many decades (Feth, 1966). Böhlke and Denver (1995) reconstructed a 40-year record of recharge in an agricultural watershed in Maryland that showed nitrate concentration increased three- to sixfold, and the most rapid increase was in the 1970s. Within the Papio-Missouri River Natural Resources District (PMRNRD; fig. 1), anthropogenic contamination of groundwater has been detected since at least 1979 (Nebraska Department of Environment and Energy, 2021). For this report, anthropogenic contamination is considered either chemicals that do not occur naturally in the environment or naturally occurring chemicals above a background threshold concentration. Examples of anthropogenic contamination include agricultural products such as nutrients and pesticides, industrial chemicals, and many others.

Contaminants of emerging concern (CECs) are anthropogenic chemicals such as pharmaceutical compounds, hormones, personal hygiene products, and their related metabolite compounds. CECs are not commonly regulated in the environment and have been widely detected in environmental waters for more than two decades (Noguera-Oviedo and Aga, 2016), more commonly in groundwater that is more recently recharged into aquifers (Bexfield and others, 2019). The relatively recent detection (compared to other anthropogenic contaminants like nutrients) may not only be caused by recent contamination, but also by increasingly sensitive laboratory methods and technology that allow for detection at the microgram per liter (part per billion) or even the nanogram per liter (part per trillion) level (Foreman and others, 2012; Furlong and others, 2014). Many CECs and their related metabolite compounds, which are chemicals formed from the degradation of the parent compounds, originate in wastewater from human activities, animal agriculture, and aquaculture (Noguera-Oviedo and Aga, 2016). CECs and their metabolite compounds can persist through wastewater treatment plants and septic systems (Furlong and others, 2017). CECs can be

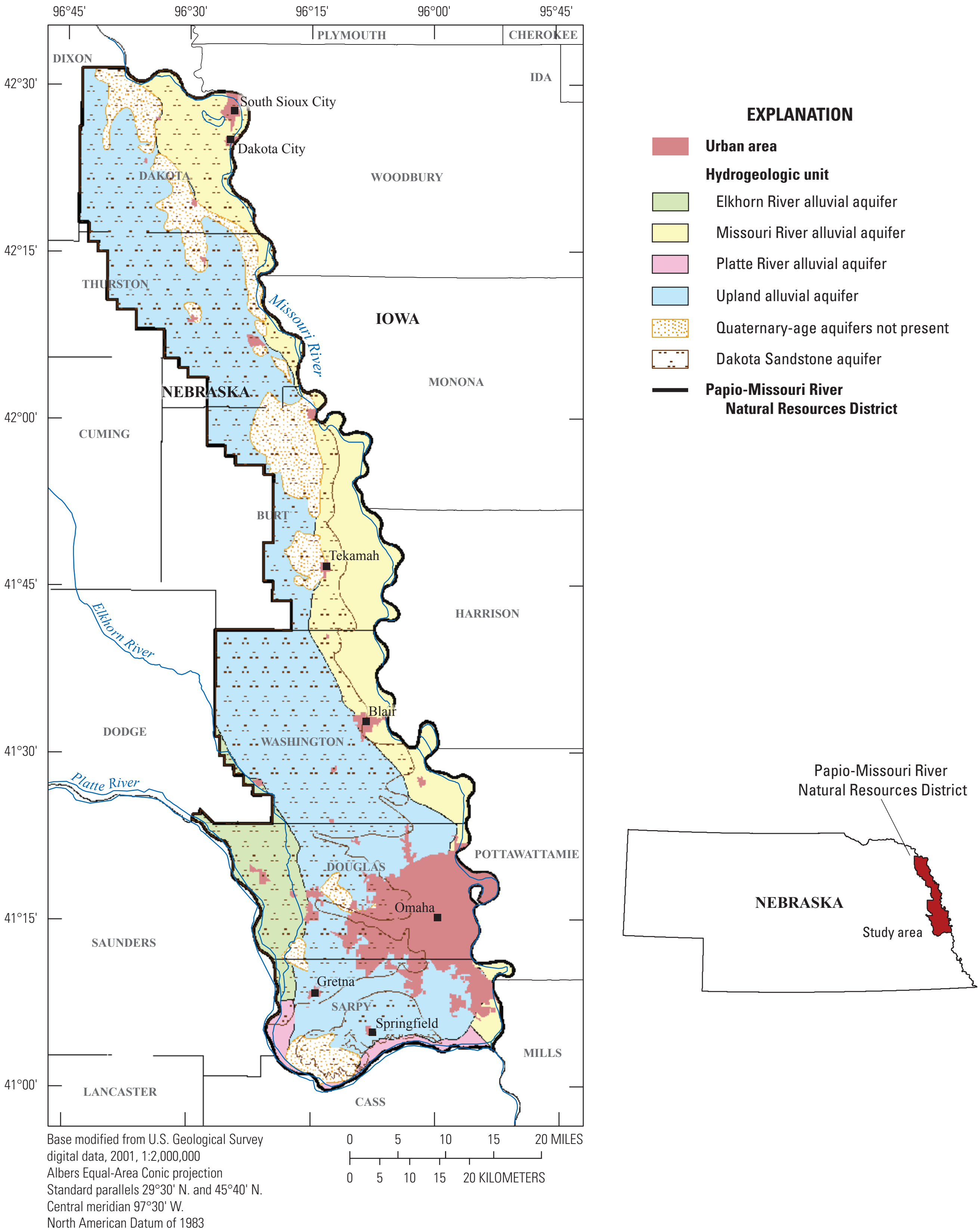

Figure 1. Aerial extent of aquifers and location of urban areas with select urban areas named, Papio-Missouri River Natural Resources District, eastern Nebraska, 2019.

introduced into surface water through discharge from wastewater treatment plants. CECs can be introduced into groundwater systems through septic system and landfill pathways and through infiltration of contaminated surface water. Many studies have detected CECs in groundwater regionally (Erickson and others, 2014; Hruby and others, 2015), across the United States (Reif and others, 2012; Furlong and others, 2017), and around the world (Estévez and others, 2012; Stuart and others, 2012), but a study of CECs in the PMRNRD had not been completed before this project.

Human health effects of most pharmaceuticals and hormones are well known from the development, testing, and use of the products. However, human health effects of the pharmaceuticals and hormones, their metabolites, and the synergistic effects of CECs when combined in environmental waters mostly are unknown (Stuart and others, 2012). Knowledge of ecological effects of CECs is minimal (Noguera-Oviedo and Aga, 2016), but endocrine disruption in fish has been reported and was documented when minnows were exposed to treated wastewater with measurable concentrations of CECs (Barber and others, 2007). The CECs analyzed in this study are not currently regulated through drinking water (Nebraska Department of Environmental Quality, 2019; U.S. Environmental Protection Agency, 2009) or groundwater (Nebraska Department of Environmental Quality, 2006) standards of the U.S. Environmental Protection Agency and the State of Nebraska through the currently (2023) reorganized Nebraska Department of Energy and Environment, which includes the previous Nebraska Department of Environmental Quality.

The U.S. Geological Survey (USGS), in cooperation with the PMRNRD, has been monitoring groundwater in the PMRNRD from 1992 (Verstraeten and Ellis, 1995; McGuire and others, 2012) to the present (2023). This sampling is referred to herein as the regular PMRNRD groundwater sampling program. As part of the regular PMRNRD groundwater sampling program, groundwater samples are collected periodically (always annually, but, in some years, more often) and are generally analyzed for major ions, selected trace elements, nutrients, and selected pesticides. The nutrient nitrate is an analyte of primary concern from previous sampling (Verstraeten and Ellis, 1995; McGuire and others, 2012). A nitrate as nitrogen (nitrate-N) concentration of 2 milligrams per liter (mg/L) is an accepted background natural limit, and a nitrate-N concentration of 4 mg/L has been used as a level indicating anthropogenic activity (Nolan and others, 2002).

Approximately 150 wells in the regular PMRNRD groundwater sampling program are each screened in 1 of the 5 primary PMRNRD aquifers (Platte River alluvial, Elkhorn River alluvial, Missouri River alluvial, upland alluvial, and the Dakota Sandstone) (fig. 1); the wells generally are sampled in a 4-year rotating schedule by aquifer or aquifer group. Each year, generally 30 to 40 selected wells are sampled along with a set of wells of special interest.

Purpose and Scope

This report presents groundwater sampling results collected in cooperation with the PMRNRD to detail the presence of selected CECs (pharmaceuticals and steroid hormones—herein referred to as hormones) and nitrate-N in the unconfined aquifers and the Dakota Sandstone aquifer in the PMRNRD in eastern Nebraska. The purpose of this study was to assess the occurrence and distribution of the selected CECs in these aquifers and was completed by collecting samples for the selected CECs and nitrate-N analysis from 17 monitoring wells in June 2019. Samples were collected again for analysis of the selected CECs in either October or November 2019 to investigate potential seasonality in CEC detection or concentration. Additionally, to illustrate the effect of other anthropogenic contamination across the PMRNRD, this report summarizes annual nitrate-N sampling results from the past decade (2010–19) as an update to the sampling results from 1992 to 2009 that were provided in McGuire and others (2012) and summarizes trends in nitrate-N results in wells with at least 10 years of sampling results from 1992 to 2020. All data summarized in this report are available in the USGS National Water Information System database (USGS, 2020).

Description of Study Area

The PMRNRD, that is entirely within the glaciated region of eastern Nebraska (Wayne, 1985), covers about 1.1 million acres and has a population of about 725,000 residents (fig. 1) (Hobza and others, 2019; Nebraska Association of Resources Districts, 2021). The PMRNRD is the most populous Nebraska Natural Resources District and contains Omaha, which is the largest urban area of Nebraska. The study area is briefly summarized here and is described more fully in Verstraeten and Ellis (1995) and McGuire and others (2012).

Hydrogeology

Verstraeten and Ellis (1995) identified five primary aquifers within the PMRNRD—the Platte River alluvial, Elkhorn River alluvial, Missouri River alluvial, upland alluvial, and the Dakota Sandstone (fig. 1). These aquifers are the surficial aquifers in the respective area, except generally the Dakota Sandstone (Verstraeten and Ellis, 1995). In the current PMRNRD groundwater management plan (PMRNRD, 2018), the Platte River alluvial and Elkhorn River alluvial aquifers are labeled as a single aquifer: the Platte/Elkhorn alluvial aquifer. However, the distinction of the Platte River alluvial aquifer and the Elkhorn River alluvial aquifer will be used in this report to facilitate comparison to historical groundwater quality data (Verstraeten and Ellis, 1995; McGuire and others, 2012), as discussed in the “Nitrate-N Time Series Analysis, 1992–2020” section of this report.

Land and Water Use

Land use within the PMRNRD is predominantly agriculture (cropland and rangeland) and includes minimal urban land (mainly in the Omaha metro area) (McGuire and others, 2012). Urban areas within towns or cities generally have municipal wastewater collection and treatment systems, and rural regions are dominated by individual septic systems to treat household wastewater. Groundwater and surface water are substantial water sources within the PMRND, and overall groundwater usage is higher than surface-water usage for all sources other than power generation (McGuire and others, 2012).

Study Design

This study of groundwater within the PMRNRD was designed to describe the occurrence and distribution of selected CECs, to assess nitrate-N concentrations for the previous decade (2010–19), and to determine nitrate-N concentrations trends from 1992 to 2020. The PMRNRD owns and maintains a network of monitoring wells. Many of the wells are in clusters of two or three wells, which are screened at different depths for groundwater-quality monitoring. The five aquifers within the PMRNRD are sampled on a 4-year rotational basis for analysis of major ions, selected trace elements, nutrients, and selected pesticides using a combination of the relevant network wells and private wells, including irrigation, industrial, and domestic wells.

The CEC samples were collected in 2019 when the Platte River and Elkhorn River alluvial aquifers were the focus of the regular PMRNRD groundwater sampling program. The Platte River and Elkhorn River alluvial aquifers were selected as the focus for CEC sampling partly because McGuire and others (2012) reported the highest soil infiltration rates in the bottomlands of the river valleys of the PMRNRD, partly because of the shallow depth to water in these aquifers and partly because the Platte and Elkhorn River alluvial aquifers are substantial groundwater sources for drinking water within the PMRNRD.

For this study, samples were collected for pharmaceutical and hormone CECs from 9 wells and for only pharmaceutical CECs from 8 wells (table 1), including 13 wells in 5 clusters (fig. 2). Age-dating analysis performed by McGuire and others (2012) determined that the water in shallow wells has more recently recharged into the groundwater, and Bexfield and others (2019) detected higher concentrations of CECs, including hormones, in shallower wells and more recently recharged groundwater, so only samples collected in 9 shallow wells were analyzed for the 20 hormone analytes (table 1). The 17 wells selected for pharmaceutical analysis are screened in the Platte River alluvial aquifer (8 wells—3 shallow, 3 medium depth, and 2 deep wells), the Elkhorn River alluvial aquifer (5 wells—2 shallow, 1 medium depth, and 2 deep wells), the Missouri River alluvial aquifer (1 shallow well), the upland alluvial aquifer (1 shallow well), and the Dakota Sandstone aquifer (2 shallow wells). The 9 wells selected for hormone analysis were all screened in the upper part of the aquifer: Platte River alluvial aquifer (3 shallow wells), Elkhorn River alluvial aquifer (2 shallow wells), Missouri River alluvial aquifer (1 shallow well), upland alluvial aquifer (1 shallow well), and Dakota Sandstone aquifer (2 shallow wells), (table 1). All 17 wells were sampled in June 2019 and again in October or November 2019, totaling 34 samples for pharmaceutical analysis and 18 samples for hormone analysis. In June 2019, the CEC samples were collected along with the regular PMRNRD groundwater samples; in fall 2019, only pharmaceutical and hormone CEC samples were collected to investigate a potential seasonality in pharmaceutical and hormone CEC detection or concentration.

All samples collected for this study were analyzed at the USGS National Water Quality Laboratory (NWQL, Lakewood, Colorado) for 132 chemicals in pharmaceutical and hormone analyses. NWQL analysis that was used for pharmaceutical compounds and metabolites includes 113 chemicals, including the herbicide atrazine (Furlong and others, 2014) (table 2), which is not considered a CEC but is a regulated chemical in groundwater in Nebraska and in drinking water in the United States (Nebraska Department of Environmental Quality, 2006, 2019; U.S. Environmental Protection Agency, 2009). The NWQL analysis that was used for hormones (Foreman and others, 2012) includes 20 hormones and metabolites. One hormone, norethindrone, is included in both analyses, giving 132 unique chemicals included in the CEC analysis.

Land and water use around the nine well locations sampled for CECs varies between sites. Four sites are in urban areas: 2 sites (Valley [wells P-Va1 and D-Va2] and Tekamah [well D-T2]; fig. 2) are within a town (urban area) that has a sewer and wastewater system, and 2 other sites (Springfield [city; well D-Sp2] and Decatur [well D-D2]; fig. 2) are near areas with several properties with septic systems for household wastewater. The remaining sites are in agricultural areas with scattered houses with septic systems for household wastewater.

Samples have been collected by the USGS in the PMRNRD since 1992; these samples have been analyzed for nutrients, major ions, trace elements, pesticides, and other analytes. The analytical results from 1992 through 2009 are summarized by Verstraeten and Ellis (1995) and McGuire and others (2012). For this study, the nitrate-N, dissolved oxygen (DO), and iron analytical results were assessed for samples collected from 2010 to 2019 as part of the regular PMRNRD groundwater monitoring program from wells with construction information (tables 1, 3), and concentration trends in nitrate-N results from 1992 to 2020 were determined for wells with at least 10 years of results. Regular sampling results are available from the USGS National Water Information System database (USGS, 2020) and, primarily the nutrient and pesticide results, are also available from the Nebraska Department of Environment and Energy (2021). Nitrate-N is

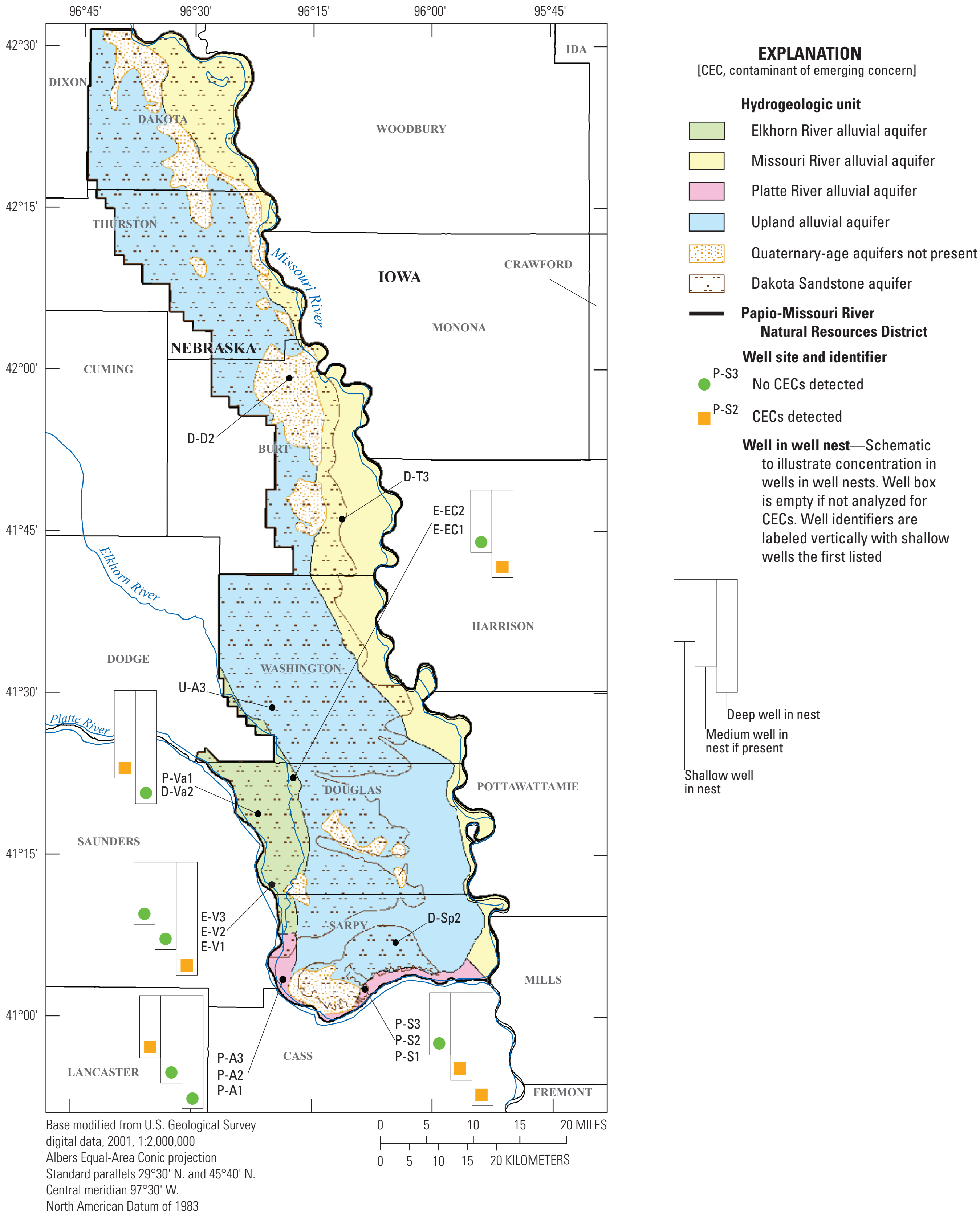

Figure 2. Spatial distribution of analytical results for contaminants of emerging concern in groundwater, Papio-Missouri River Natural Resource District, eastern Nebraska, 2019.

Table 1. Selected information for wells sampled for contaminants of emerging concern and the regular groundwater sampling program, Papio-Missouri River Natural Resources District, eastern Nebraska, 2019.

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). ft BGS, foot below ground surface]

USGS station number	Well identifier (fig. 2)	Well name	Aquifer (fig. 2)	Well depth (ft BGS)	Screen interval (ft BGS)	Depth to water, June 2019 (ft BGS)	Hormone sample	Innundated by March 2019 flooding
410243096082001	P-S1	Springfield (Buffalo Road) deep	Platte River alluvial	83	78–83	12.88	No	No
410243096082002	P-S2	Springfield (Buffalo Road) medium	Platte River alluvial	70	65–70	12.79	No	No
410243096082003	P-S3	Springfield (Buffalo Road) shallow	Platte River alluvial	55	45–55	12.44	Yes	No
410334096182801	P-A1	Ashland deep	Platte River alluvial	55	50–55	3.31	No	Yes
410334096182802	P-A2	Ashland medium	Platte River alluvial	37.5	32.5–37.5	4.05	No	Yes
410334096182803	P-A3	Ashland shallow	Platte River alluvial	21	11–21	4.23	Yes	Yes
410613096071102	D-Sp2	Springfield (city, shallow)	Dakota Sandstone	125	115–125	34.82	Yes	No
411231096193201	E-V1	Venice deep	Elkhorn River alluvial	98	93–98	6.84	No	Yes
411231096193202	E-V2	Venice medium	Elkhorn River alluvial	58	53–58	6.94	No	Yes
411231096193203	E-V3	Venice shallow	Elkhorn River alluvial	22	12–22	7.71	Yes	Yes
411845096211201	P-Va1	Valley shallow	Platte River alluvial	30	20–30	3.47	Yes	Yes
411845096211202	D-Va2	Valley medium	Platte River alluvial	94	84–94	3.43	No	Yes
412151096180801	E-EC1	Elkhorn Crossing deep	Elkhorn River alluvial	33	28–33	6.00	No	Yes
412151096180802	E-EC2	Elkhorn Crossing shallow	Elkhorn River alluvial	25	15–25	7.80[a]	Yes	Yes
412758096222803	U-A3	Arlington shallow	Upland alluvial	151	141–151	110.12	Yes	No
414700096134903	D-T3	Tekamah shallow	Dakota Sandstone	71	61–71	29.14	Yes	No
415958096152202	D-D2	Decatur shallow	Missouri River alluvial	85	75–85	33.98[b]	Yes	No

[a]Water level measured in October 2019.

[b]Water level measured in July 2020.

Table 2. Selected nutrient, hormone, and pharmaceutical chemicals, U.S. Geological Survey parameter codes, and reporting limits of chemicals analyzed in groundwater samples, Papio-Missouri River Natural Resources District, eastern Nebraska, 2019.

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). USGS, U.S. Geological Survey; CASRN, Chemical Abstracts Service Registry Number; mg/L, milligram per liter; NA, not applicable; ng/L, nanogram per liter; --, no detection level set]

Chemical	USGS parameter code	CASRN[1]	Laboratory detection level	Laboratory reporting level	Unit
Selected nutrients					
Nitrite[2]	00613	14797-65-0	0.001	0.002	mg/L
Nitrate plus nitrite as nitrogen[3]	00631	NA	0.04	0.08	mg/L
Hormone chemicals[4]					
11-Ketotestosterone	64507	564-35-2	2.5	20	ng/L
17α-Estradiol	64508	57-91-0	1	2	ng/L
17α-Ethynylestradiol	64509	57-63-6	1	2	ng/L
17β-Estradiol	64510	50-28-2	1	2	ng/L
3β-Coprostanol	64512	360-68-9	--	200	ng/L
4-Androstene-3,17-dione	64513	63-05-8	2.5	20	ng/L
Bisphenol A	67304	80-05-7	--	100	ng/L
Cholesterol	64514	57-88-5	--	400	ng/L
Dihydrotestosterone	64524	521-18-6	3	6	ng/L
Epitestosterone	64517	481-30-1	2	4	ng/L
Equilenin	64518	517-09-9	2	4	ng/L
Equilin	64519	474-86-2	8	20	ng/L
Estriol	64520	50-27-1	1	2	ng/L
Estrone	64521	53-16-7	2	4	ng/L
Mestranol	64522	72-33-3	3	6	ng/L
Norethindrone	64511	68-22-4	2	4	ng/L
Progesterone	64523	57-83-0	6	12	ng/L
Testosterone	64525	58-22-0	3	6	ng/L
cis-Androsterone	64515	53-41-8	1	2	ng/L
trans-Diethylstilbestrol	64516	56-53-1	--	1.3	ng/L
Pharmaceutical chemicals[5]					
1,7-Dimethylxanthine	67446	611-59-6	21	88	ng/L
10-Hydroxy-amitriptyline	67995	64520-05-4	1.7	8.3	ng/L
Abacavir	68022	136470-78-5	1	2	ng/L
Acetaminophen	67436	103-90-2	42	84	ng/L
Acyclovir	67484	59277-89-3	4.4	80	ng/L
Albuterol	67437	18559-94-9	1.2	6.7	ng/L
Alprazolam	68250	28981-97-7	6.6	21	ng/L
Amitriptyline	67522	50-48-6	19	37	ng/L
Amphetamine	67461	300-62-9	1.1	4.4	ng/L
Antipyrine	67477	60-80-0	25	50	ng/L
Atenolol	67502	29122-68-7	4.8	20	ng/L
Atrazine	65065	1912-24-9	10	20	ng/L
Benztropine	67997	86-13-5	22	44	ng/L
Betamethasone	67485	378-44-9	57	114	ng/L
Bupropion	67439	34911-55-2	3.6	18	ng/L
Caffeine	67440	58-08-2	43	91	ng/L

Table 2. Selected nutrient, hormone, and pharmaceutical chemicals, U.S. Geological Survey parameter codes, and reporting limits of chemicals analyzed in groundwater samples, Papio-Missouri River Natural Resources District, eastern Nebraska, 2019.—Continued

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). USGS, U.S. Geological Survey; CASRN, Chemical Abstracts Service Registry Number; mg/L, milligram per liter; NA, not applicable; ng/L, nanogram per liter; --, no detection level set]

Chemical	USGS parameter code	CASRN[1]	Laboratory detection level	Laboratory reporting level	Unit
Pharmaceutical chemicals[5]—Continued					
Carbamazepine	67441	298-46-4	2.2	11	ng/L
Carisoprodol	67498	78-44-4	6	20	ng/L
Chlorpheniramine	67497	132-22-9	27	54	ng/L
Cimetidine	67442	51481-61-9	60	140	ng/L
Citalopram	67505	59729-33-8	3.3	6.6	ng/L
Clonidine	67518	4205-90-7	30	61	ng/L
Codeine	67443	76-57-3	16	32	ng/L
Cotinine	67444	486-56-6	1.7	6.4	ng/L
Dehydronifedipine	67445	67035-22-7	4	20	ng/L
Desvenlafaxine	68251	93413-62-8	42	84	ng/L
Dextromethorphan	67468	125-71-3	1.6	8.2	ng/L
Diazepam	67499	439-14-5	2	4	ng/L
Diltiazem	67519	42399-41-7	5.1	10	ng/L
Diphenhydramine	67447	147-24-0	24	48	ng/L
Duloxetine	67448	116539-59-4	7.3	40	ng/L
Erythromycin	67449	114-07-8	27	80	ng/L
Ezetimibe	67487	163222-33-1	80	205	ng/L
Fadrozole	68012	102676-47-1	6.3	13	ng/L
Famotidine	68000	76824-35-6	17	34	ng/L
Fenofibrate	67489	49562-28-9	3.2	14	ng/L
Fexofenadine	67510	83799-24-0	22	96	ng/L
Fluconazole	67478	86386-73-4	15	30	ng/L
Fluoxetine	67450	54910-89-3	13	26	ng/L
Fluticasone propionate	67529	80474-14-2	10	30	ng/L
Fluvoxamine	67521	54739-18-3	27	80	ng/L
Gabapentin	52817	60142-96-3	80	160	ng/L
Glipizide	68001	29094-61-9	16	80	ng/L
Glyburide	68002	10238-21-8	2	4	ng/L
Guanylurea	52816	141-83-3	70	400	ng/L
Hexamethylenetetramine	52815	100-97-0	--	150	ng/L
Hydrocodone	67506	125-29-1	20	40	ng/L
Hydrocortisone	67459	50-23-7	73	147	ng/L
Hydroxyzine	68005	68-88-2	1.5	7.4	ng/L
Iminostilbene	67481	256-96-2	73	145	ng/L
Ketoconazole	68014	65277-42-1	56	113	ng/L
Lamivudine	68018	134678-17-4	3.2	16	ng/L
Lidocaine	67462	137-58-6	2	38	ng/L
Loperamide	67515	53179-11-6	40	80	ng/L
Loratadine	67488	79794-75-5	1.4	7	ng/L
Lorazepam	67470	846-49-1	101	202	ng/L

Table 2. Selected nutrient, hormone, and pharmaceutical chemicals, U.S. Geological Survey parameter codes, and reporting limits of chemicals analyzed in groundwater samples, Papio-Missouri River Natural Resources District, eastern Nebraska, 2019.—Continued

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). USGS, U.S. Geological Survey; CASRN, Chemical Abstracts Service Registry Number; mg/L, milligram per liter; NA, not applicable; ng/L, nanogram per liter; --, no detection level set]

Chemical	USGS parameter code	CASRN[1]	Laboratory detection level	Laboratory reporting level	Unit
Pharmaceutical chemicals[5]—Continued					
Meprobamate	67464	57-53-4	6	86	ng/L
Metaxalone	67504	1665-48-1	7.8	16	ng/L
Metformin	67492	657-24-9	6.6	20	ng/L
Methadone	67500	76-99-3	3.8	10	ng/L
Methocarbamol	67501	532-03-6	5.6	11	ng/L
Methotrexate	67525	59-05-2	26	52	ng/L
Methyl-1*H*-benzotriazole	67514	29385-43-1	28	80	ng/L
Metoprolol	67523	51384-51-1	5	10	ng/L
Morphine	67458	57-27-2	20	80	ng/L
N-Desmethyldiltiazem	67999	85100-17-0	35	70	ng/L
Nadolol	68006	42200-33-9	4	20	ng/L
Nevirapine	68017	129618-40-2	23	46	ng/L
Nicotine	67493	54-11-5	29	80	ng/L
Nizatidine	67479	76963-41-2	40	80	ng/L
Nordiazepam	68252	1088-11-5	10	20	ng/L
Norethindrone	67434	68-22-4	10	20	ng/L
Norfluoxetine	67451	56161-73-0	40	80	ng/L
Norsertraline	67532	87857-41-8	40	80	ng/L
Norverapamil	68007	67018-85-3	4.3	40	ng/L
Omeprazole + Esomprazole	67512	NA	8.2	16	ng/L
Oseltamivir	67511	196618-13-0	2.9	15	ng/L
Oxazepam	67469	604-75-1	113	226	ng/L
Oxycodone	67495	76-42-6	5	25	ng/L
Paroxetine	67527	61869-08-7	36	264	ng/L
Penciclovir	68021	39809-25-1	40	80	ng/L
Pentoxifylline	67480	6493–05–6	4.7	9.4	ng/L
Phenazopyridine	68008	94-78-0	4.1	13	ng/L
Phendimetrazine	67496	634-03-7	5	31	ng/L
Phenytoin	67466	57-41-0	94	188	ng/L
Piperonyl butoxide	67435	51-03-6	20	60	ng/L
Prednisolone	67483	50-24-8	75	150	ng/L
Prednisone	67467	53-03-2	35	168	ng/L
Promethazine	67524	60-87-7	57	114	ng/L
Propoxyphene	68009	469-62-5	14	28	ng/L
Propranolol	67516	525-66-6	4.5	26	ng/L
Pseudoephedrine + Ephedrine	67460	NA	1.5	6	ng/L
Quinine	68011	130-95-0	16	80	ng/L
Ractopamine	52814	97825-25-7	9	20	ng/L
Raloxifene	67530	84449-90-1	40	80	ng/L
Ranitidine	67452	66357-35-5	96	192	ng/L

Table 2. Selected nutrient, hormone, and pharmaceutical chemicals, U.S. Geological Survey parameter codes, and reporting limits of chemicals analyzed in groundwater samples, Papio-Missouri River Natural Resources District, eastern Nebraska, 2019.—Continued

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). USGS, U.S. Geological Survey; CASRN, Chemical Abstracts Service Registry Number; mg/L, milligram per liter; NA, not applicable; ng/L, nanogram per liter; --, no detection level set]

Chemical	USGS parameter code	CASRN[1]	Laboratory detection level	Laboratory reporting level	Unit
Pharmaceutical chemicals[5]—Continued					
Sertraline	67528	79617-96-2	3.2	16	ng/L
Sitagliptin	67531	486460-32-6	19	97	ng/L
Sulfadimethoxine	67503	122-11-2	7	14	ng/L
Sulfamethizole	67476	144-82-1	21	104	ng/L
Sulfamethoxazole	67454	723-46-6	5	26	ng/L
Tamoxifen	68015	10540-29-1	--	270	ng/L
Temazepam	67471	846-50-4	9.2	18	ng/L
Theophylline	67494	58-55-9	40	80	ng/L
Thiabendazole	67455	148-79-8	2	11	ng/L
Tiotropium	67508	186691-13-4	25	200	ng/L
Tramadol	67517	27203-92-5	3.7	20	ng/L
Triamterene	67475	396-01-0	2.6	5.2	ng/L
Trimethoprim	67456	738-70-5	1.6	20	ng/L
Valacyclovir	67507	124832-26-4	33	163	ng/L
Venlafaxine	67534	93413-69-5	2.6	5.2	ng/L
Verapamil	67472	52-53-9	70	140	ng/L
Warfarin	67457	81-81-2	3	20	ng/L

[1]This report contains Chemical Abstracts Service Registry Numbers (CASRNs), which are a registered trademark of the American Chemical Society. The CASRN online database provides the latest registry number information: https://www.cas.org/. Chemical Abstracts Service recommends the verification of the CASRNs through CAS Client Services.

[2]Fishman (1993).

[3]Patton and Kryskalla (2011).

[4]Foreman and others (2012).

[5]Furlong and others (2014).

Table 3. Selected information for wells only sampled for the regular groundwater monitoring program, Papio-Missouri River Natural Resources District, eastern Nebraska, 2010–19.

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). ft BGS, foot below ground surface; --, data missing]

USGS station number	Well identifier	Aquifer (fig. 1)	Well depth (ft BGS)	Screen interval (ft BGS)
410032096105501	P-100	Platte River alluvial	46	36–46
410113096145701	P-135	Platte River alluvial	47	25–45
410157096175401	M04-11	Platte River alluvial	71.5	61.5–71.5
410207096180401	M04-10	Platte River alluvial	64.5	54.5–64.5
410221096181701	M04-7	Platte River alluvial	64	54–64
410232096095301	U-232	Upland alluvial	85	73–83
410316096062501	Sp34	Platte River alluvial	70	--
410335096150101	D-SWSarpy1	Dakota Sandstone	117	107–117
410335096150102	D-SWSarpy2	Upland alluvial	76	66–76
410339095563301	P-133	Platte River alluvial	39	29–39
410341096053101	P-104	Platte River alluvial	45	35–45
410350096081001	U-013	Upland alluvial	66	42–66
410355096162301	S-D-008	Dakota Sandstone	173	163–173
410407096032701	P-003	Platte River alluvial	74	54–74
410417096051701	Sp26	Dakota Sandstone	100	--
410420096074401	S-D-012	Dakota Sandstone	145	133–143
410427096042601	D-134	Dakota Sandstone	80	70–80
410448096152501	S-D-013	Dakota Sandstone	222	210–220
410503096073801	D-013	Dakota Sandstone	195	157–195
410505096030901	U-130	Upland alluvial	64	54–64
410519096040201	U-131	Upland alluvial	85	72–82
410523096014401	U-132	Upland alluvial	100.5	90.5–100.5
410524095530601	M-244	Missouri River alluvial	100	--
410524096010301	D-135	Dakota Sandstone	122	112–122
410604096171101	E-130	Elkhorn River alluvial	113	103–113
410613096071101	D-Sp1	Dakota Sandstone	215	205–215
410624095595201	U-133	Upland alluvial	236	226–236
410628096120601	S-D-001	Dakota Sandstone	150	143–148
410645096155901	D-132	Dakota Sandstone	334	309.6–329.6
410707096003401	D-133	Dakota Sandstone	165	150–160
410707096010301	U-134	Upland alluvial	134	130–134
410708096004901	D-136	Dakota Sandstone	135	123–133
410719096180601	P-004A	Platte River alluvial	51	31–51
410725096092601	D-131	Dakota Sandstone	165	150–160
410728096170001	U-135	Upland alluvial	81	70–80
410730095525401	M-100	Missouri River alluvial	90	70–90
410749096030401	D-145	Dakota Sandstone	130	110–130
410802096040401	P-136	Platte River alluvial	78	68–78
410806096151001	D-011B	Dakota Sandstone	311	--
410824096141901	D-011	Dakota Sandstone	315	230–315
410835096062901	U-136	Upland alluvial	166	156–166

Table 3. Selected information for wells only sampled for the regular groundwater monitoring program, Papio-Missouri River Natural Resources District, eastern Nebraska, 2010–19.—Continued

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). ft BGS, foot below ground surface; --, data missing]

USGS station number	Well identifier	Aquifer (fig. 1)	Well depth (ft BGS)	Screen interval (ft BGS)
410902096102701	U-137	Upland alluvial	134	130–134
411001096100901	D-146	Dakota Sandstone	250	238–248
411025096171101	E-108	Elkhorn River alluvial	120	104–114
411028095564401	U-138	Upland alluvial	107	95–105
411029095532501	M-237	Missouri River alluvial	101.5	72–97
411116096164701	D-130	Dakota Sandstone	263	251–261
411307096181901	E-103	Elkhorn River alluvial	50	43–50
411309096202101	E-121	Elkhorn River alluvial	93	73–93
411423096205901	E-109	Elkhorn River alluvial	54	47–54
411444096210001	E-105	Elkhorn River alluvial	50	42–50
411507096154801	E-010	Elkhorn River alluvial	50	15–35
411723096211601	E-007	Elkhorn River alluvial	58	21–58
411729096172901	E-136	Elkhorn River alluvial	62	52–62
411821096214301	E-133	Elkhorn River alluvial	43	36–43
411845096211203	D-Va3	Dakota Sandstone	204	194–204
411855095551901	M-011	Missouri River alluvial	80	65–80
411920095583901	U-139	Upland alluvial	217	205–215
411937096213701	E-004	Elkhorn River alluvial	82	64–82
412050096143101	D-008	Dakota Sandstone	325	275–325
412115095595801	U-140	Upland alluvial	200	190–200
412322096264201	E-101	Elkhorn River alluvial	86	44–86
412434095585201	U-141	Missouri River alluvial	246	228–243
412448096074701	U-151	Upland alluvial	338	327–337
412527096081201	U-BA1	Upland alluvial	225	220–225
412527096081202	U-BA2	Upland alluvial	193.5	188.5–193.5
412616096031601	U-142	Upland alluvial	154	142–152
412637095565901	M-BC1	Missouri River alluvial	100	95–100
412637095565902	M-BC2	Missouri River alluvial	60	55–60
412637095565903	M-BC3	Missouri River alluvial	25	10–25
412709096161501	D-137	Dakota Sandstone	275	263–273
412736096022201	M-238	Missouri River alluvial	96	76–96
412736096221001	U-052	Upland alluvial	280	226–276
412754096060001	U-125	Upland alluvial	218	198–218
412758096035101	M-243	Missouri River alluvial	222	210–220
412758096222801	D-A1	Dakota Sandstone	297	287–297
412758096222802	D-A2	Dakota Sandstone	237	227–237
412835096065701	U-144	Upland alluvial	217	204–214
412844096042801	M-233	Missouri River alluvial	70	60–70
412907096241501	D-138	Dakota Sandstone	260	240–260
413003096030201	M-240	Missouri River alluvial	30	23–30
413011096040101	M-232	Missouri River alluvial	203	188–198

Table 3. Selected information for wells only sampled for the regular groundwater monitoring program, Papio-Missouri River Natural Resources District, eastern Nebraska, 2010–19.—Continued

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). ft BGS, foot below ground surface; --, data missing]

USGS station number	Well identifier	Aquifer (fig. 1)	Well depth (ft BGS)	Screen interval (ft BGS)
413030096055101	M-246	Missouri River alluvial	176	164–174
413036096223201	U-145	Upland alluvial	152	140–150
413040096230601	U-146	Upland alluvial	249	237–247
413053096060001	M-229	Missouri River alluvial	235	228–233
413220096103801	U-147	Upland alluvial	144	129–139
413245096072401	M-222	Missouri River alluvial	118	98–118
413400096113801	U-149	Upland alluvial	207	192–202
413507096095001	M-245	Missouri River alluvial	96	76–96
413511096073801	M-247	Missouri River alluvial	88	78–88
413548096162101	D-141	Dakota Sandstone	236	226–236
413701096161901	U-148	Upland alluvial	185.5	174–184
414019096080901	U-236	Upland alluvial	80	60–80
414422096143401	U-230	Upland alluvial	258	218–258
414453096141201	M-242	Missouri River alluvial	245	235–245
414526096144701	D-125	Dakota Sandstone	132	120–130
414622096131801	M-213	Missouri River alluvial	114.5	84.5–114.5
414700096134901	D-T1	Dakota Sandstone	171	166–171
414700096134902	D-T2	Dakota Sandstone	139	133.5–138.5
414702096131201	M-204	Missouri River alluvial	96	66–96
414825096071001	M-234	Missouri River alluvial	94.5	84.5–94.5
415220096085001	M-241	Missouri River alluvial	98	78–98
415245096091401	M-203	Missouri River alluvial	100	90–100
415432096095001	M-231	Missouri River alluvial	90	80–90
415835096190701	D-140	Dakota Sandstone	220	208–218
415958096152201	D-D1	Dakota Sandstone	180	170–180
420012096210201	D-127	Dakota Sandstone	300	290–300
420012096247101	U-150	Upland alluvial	280	268–278
420129096180101	U-104	Upland alluvial	140	128–138
420840096290901	D-W1	Dakota Sandstone	162	157–162
420840096290902	D-W2	Dakota Sandstone	133	128–133
420840096290903	D-W3	Dakota Sandstone	104.5	94.5–104.5
421406096294901	D-Th1	Dakota Sandstone	370	360–370
421406096294902	D-Th2	Dakota Sandstone	275	265–275
421406096294903	D-Th3	Dakota Sandstone	100	90–100
421704096290401	D-128	Dakota Sandstone	125	85–125
421716096322601	D-144	Dakota Sandstone	240	210–240
421730096390001	PM D-1	Dakota Sandstone	440	410–440
421848096371801	D-002	Dakota Sandstone	565	535–565
421907096321801	D-142	Missouri River alluvial	146	116–146
421939096311201	D-143	Dakota Sandstone	232	202–232
422035096281901	M-H1	Missouri River alluvial	129	118–128

Table 3. Selected information for wells only sampled for the regular groundwater monitoring program, Papio-Missouri River Natural Resources District, eastern Nebraska, 2010–19.—Continued

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). ft BGS, foot below ground surface; --, data missing]

USGS station number	Well identifier	Aquifer (fig. 1)	Well depth (ft BGS)	Screen interval (ft BGS)
422035096281902	M-H2	Missouri River alluvial	93	87–93
422035096281903	M-H3	Missouri River alluvial	53	43–53
422316096353301	D-036	Dakota Sandstone	149	110–149
422524096250801	M-201B	Missouri River alluvial	187	117–187
422616096343801	D-J1	Dakota Sandstone	270	460–470
422616096343802	D-J2	Dakota Sandstone	280	270–280
422616096343803	D-J3	Dakota Sandstone	150	140–150
422618096401501	U-102	Upland alluvial	61	48–58
422643096313101	M-221	Missouri River alluvial	133	123–133
422652096353601	D-129	Dakota Sandstone	296	266–296

used in this report to evaluate anthropogenic contamination, and DO and iron are used to assess denitrification potential in the groundwater.

Historical groundwater sampling in the PMRNRD since 1992 (Verstraeten and Ellis, 1995; McGuire and others, 2012) has shown areas with low nitrate-N concentrations and anoxic aquifer conditions (DO concentrations less than 0.5 mg/L). Anoxic conditions with low nitrate-N concentrations generally result from microbial consumption of available oxygen, followed by denitrification, which is microbial conversion of nitrate to other forms of nitrogen. Field measurements of DO, which are regularly collected during sampling, are used to identify areas with anoxic conditions.

Historical groundwater sampling in the PMRNRD from 2010 to 2019 included 473 nitrate-N samples collected from 150 wells, including the wells sampled for CECs (tables 1, 3). The total number of samples collected and the number of wells sampled in each aquifer were as follows: 77 samples from 15 wells in the Platte River alluvial aquifer, 70 samples from 17 wells in the Elkhorn River alluvial aquifer, 80 samples from 34 wells in the Missouri River alluvial aquifer, 58 samples from 32 wells in the upland alluvial aquifer, and 188 samples from 52 wells in the Dakota Sandstone aquifer.

Sample Collection and Analysis Methods

Groundwater samples were collected in June and October or November 2019 and were analyzed for selected CECs (pharmaceuticals and hormones) along with quality assurance (QA) samples as discussed in the “Quality Assurance” section of this report. The regular PMRNRD groundwater monitoring program samples were collected from all CEC wells concurrently with this study during the June 2019 sampling.

Groundwater Sample Collection

All groundwater samples were collected following the USGS National Field Manual for the Collection of Water-Quality Data (NFM; USGS, variously dated). All sampling equipment was cleaned at the Nebraska Water Science Center laboratory (Lincoln, Nebraska) before sampling. Cleaning for all sampling equipment followed a sequence of nonphosphate laboratory soap and tap water solution soak, tap water rinse, deionized water rinse, methanol spray, and organic-free blank water final rinse as specified in the NFM. On the day of CEC sampling, the two-person crews refrained from using any potential contaminants, such as caffeine or nicotine, to avoid contamination of the samples during collection.

Before samples were collected at each location, water was purged from the well to ensure the sample collected was representative of the aquifer. The pumps for monitoring wells owned by the PMRNRD that were used for CEC and regular sampling were dedicated stainless steel submersible positive pressure Grundfos pumps, which were already installed in the wells. Other wells included in the regular sampling used either a spigot or hose fitting from an existing pump in the selected domestic, irrigation, industrial, and monitoring wells or, for monitoring wells without a dedicated pump, a portable pump. Plastic splitters with Teflon O-rings were fitted to the spigots on the wells (the spigots were brass for the PMRNRD-owned wells and varied material on other wells), which then split the discharge into two streams. One side of the splitter accepted a garden hose running to a bucket for collection of physical properties of groundwater, including pH, specific conductance, DO, water temperature, and turbidity. The physical properties pH, specific conductance, DO, and water temperature were measured with a multiparameter meter (YSI ProDSS, YSI, Inc., Yellow Springs, Ohio); turbidity was measured with a portable turbidimeter (Hach 2100P, Hach, Loveland, Colorado); and all physical properties were recorded according to guidance in the NFM. The other side of the splitter held a Teflon adapter to a polytetrafluoroethylene tube running to a lab truck for collection of groundwater samples. Once the wells were purged, hormone samples were collected (Foreman and others, 2012) by filtering the water through a 0.45-micrometer (µm) filter into a 0.5-liter (L) high-density polyethylene bottle. Pharmaceutical samples were collected using a syringe to capture unfiltered sample water, and then 10 milliliters (mL) of sample water were processed through a 0.45-µm filter into a 20-mL baked glass container. Nitrate samples were collected using the same field setup and were filtered through a 0.45-µm filter into a 125-mL amber bottle. Iron samples were filtered (though the same filter used for nutrients) into a 250-mL bottle and acidified in the field with nitric acid. After collection, the samples were packed with ice and shipped overnight for analysis by the NWQL.

Laboratory Analytical Methods

All laboratory analyses were performed at the NWQL. Analytical details for pharmaceutical, hormone, and nitrate-N methods are discussed in brief and are covered in depth in the method development reports (Patton and Kryskalla, 2011; Foreman and others, 2012; Furlong and others, 2014). The reporting limits for some CEC analytes changed during the period of data analysis at the NWQL. For these analytes, the higher reporting limit is given in table 2.

The pharmaceutical method (Furlong and others, 2014) determines the concentration to a nanogram per liter level for 113 compounds consisting of pharmaceutical chemicals, pharmaceutical metabolites, and a few select chemically similar compounds of environmental interest, including the herbicide atrazine that is included in the analysis to compare performance to other analysis methods. Chemicals within the sample are separated using high-performance liquid chromatography, ionized using a positive ion electrospray ionization source, and detected and quantified using tandem mass spectrometers.

The hormone method (Foreman and others, 2012) determines the concentration to a nanogram per liter level of 20 steroidal hormone compounds. Chemicals within the sample are separated and isolated twice using solid-phase extraction, and eludation solvents are evaporated to dryness. The chemicals are then reacted to form ester derivatives for analysis using a gas chromatograph and tandem mass spectrometry.

The nitrate-N method (Patton and Kryskalla, 2011) determines the concentration of nitrite plus nitrate as nitrogen to a milligram per liter level and has a reporting level of 0.04 milligram per liter (mg/L). Nitrate is reduced to nitrite and then colorimetric reagents are used to determine the combined nitrite plus nitrate as nitrogen concentration using automated discrete analysis. Nitrite is also measured independently through a different method (Fishman, 1993), and nitrite as nitrogen concentration can be subtracted from nitrate plus nitrite as nitrogen to get the nitrate-N concentration. Because nitrite was detected in less than 25 percent of samples during the 2010–19 sampling, and the maximum concentration was 0.035 mg/L as nitrogen (less than the detection limit for the nitrate plus nitrite analysis), the results of the nitrate plus nitrite analysis were taken as the nitrate-N concentration without correction for nitrite; and the abbreviation nitrate-N is used herein when discussing nitrogen results.

Quality Assurance

Several QA measures were incorporated into the study design of the CEC study to ensure reliable results. Field QA samples collected for this study included replicate and blank samples and were collected during the June 2019 sampling efforts for the CEC sampling and annually for the regular sampling. Laboratory QA steps are regularly completed at the NWQL for pharmaceutical and hormone analyses, and laboratory QA checks for all methods and instrumentation are also completed regularly (Maloney, 2005). Field and laboratory QA steps and results for the regular sampling are checked regularly but are not discussed in this report.

Field Quality Assurance

QA samples were collected for selected CECs (pharmaceuticals and hormones) at three pre-selected wells during the June 2019 sampling. These QA samples included 1 replicate and 1 field blank sample each time at each well, totaling 6 QA samples. QA samples were collected from the first and last wells with a hormone sample and from one other randomly selected well with a hormone sample. Replicates were collected for quantification of variability between samples. Blanks were collected for characterization of potential contamination introduced during collection activities.

In the three blank samples for analysis of selected CECs, all analyte concentrations were non-detects, indicating no source of contamination in the field sampling procedures or equipment. The three pre-selected sites had no CECs detected in the environmental samples collected at the same time, but one replicate (station 411231096193203, well E-V3) did have an atrazine detection of 25.6 nanograms per liter (ng/L), which compared to an environmental atrazine concentration of 24 ng/L (a relative percent difference of 6.5 percent) and an atrazine detection limit of 20 ng/L. With all other environmental and paired replicate data censored by detection limits, this data point for selected CEC analytes is insufficient to evaluate variability in sampling and analysis.

Laboratory Quality Assurance

Several laboratory QA steps are completed at the NWQL during analyses. Blank, replicate, and spike samples are regularly run at the NWQL to check instrumentation and method performance and calibration. Additionally, for pharmaceutical and hormone analyses, another QA step is done: isotope-dilution standards (IDSs), surrogate compounds, or both are added to each sample during analysis. A summary of the IDS step is provided here, and further details are available in the method development and laboratory quality management documentation (Maloney, 2005; Foreman and others, 2012; Furlong and others, 2014).

Before analysis of pharmaceutical and hormone samples, an aliquot of an IDS, surrogates, or both was added to each sample. The IDS is a cocktail of compounds of method analytes that are isotopically labeled (typically using deuterium or carbon-13) and is therefore analytically distinguishable from the target analyte. Surrogates are chemical analogs to analytes that are also isotopically labeled. All 20 hormone analytes have an IDS or surrogate compound, but only 41 of the 113 pharmaceutical analytes do. The concentration of the IDS or surrogate compound is then determined using the same methods used for the pharmaceutical and hormone analytes. After analysis is complete, the concentration of IDS and surrogate compounds were converted to recovery percentages based upon the introduced amount of each analyte. These recovery percentages aid in data interpretation and detection confidence because they demonstrate potential matrix effects of the environmental water and equipment performance. A theoretical recovery percentage of 100 percent indicates all the introduced IDS was detected by the equipment, and that the water matrix did not cause interference, amplification, or degradation. Average recovery percentages for the four detected analytes with IDS ranged from 95 to 106 percent (table 4) and indicate reliable detections for those four analytes.

Data Censoring Criteria

The NWQL's analytical results are reported without qualification for values above the laboratory reporting level, and as estimated values, or "E" coded values, for concentrations between the laboratory reporting level and the detection level. Non-detects are reported as less than the laboratory reporting level (Foreman and others, 2021). Reporting and detection limits are set independently for each analyte and vary throughout time because of updated information from the ongoing laboratory QA measures, changing equipment, and new analytical techniques. The reporting limits for some CEC analytes changed during the period of data analyses at NWQL. For these analytes the higher reporting limit is given in table 2.

Nitrate Analysis Methods

For this study, nitrate-N concentrations in groundwater trends were investigated in two ways. The first was to examine changes in the median nitrate-N concentrations in each aquifer over time in 4-year periods. The second was to quantify these trends using a Mann-Kendall test. Trend analyses were performed considering the Platte River and Elkhorn River alluvial aquifers separately because differing trends were noticed between them when separated. Where multiple samples were collected at the same well within the same calendar year, the median of those concentrations was used. The median nitrate-N concentration for each year was calculated for each aquifer, and then a Mann-Kendall test (Helsel and others, 2020) was used to determine if the nitrate-N concentration had a

Table 4. Laboratory isotope-dilution standard recovery statistics for analytes that were detected in the environmental samples, Papio-Missouri River Natural Resources District, eastern Nebraska, 2019.

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020).]

Recovery statistic	Acetaminophen	Caffeine	Metformin	Sulfamethoxazole
Number of laboratory isotope-dilution standard spikes	34	34	34	34
Average percent recovery	100	95	104	106
Standard deviation of percent recovery	17	6	12	11

significant trend over the period of study. The wells sampled more frequently had enough data to test each well for trends in nitrate-N concentration over time. For 10 wells where there were more than 10 years with sampling data, a Mann-Kendall test was used to determine if nitrate-N concentration significantly increased, decreased, or had no trend in the individual wells.

Physical Properties and Concentrations of Selected Anthropogenic Contaminants in Groundwater

Physical properties and concentrations of selected CECs and nitrate-N in samples of groundwater collected from monitoring wells in the PMRNRD in 2019 are presented in this section of the report, followed by a summary of nitrate-N data from 2010 to 2019 and a time series analysis of nitrate-N data from 1992 to 2020. Also provided is an analysis of health-based and regulatory standards compared to sample concentrations, and a description of potential environmental effects.

Physical Properties of Groundwater

Physical properties (water temperature, specific conductance, DO, pH, and turbidity) were collected in the field for most samples using a multiparameter meter. These results are included for each well sampled for selected CECs in table 5 and are summarized in table 6 for the wells sampled for selected CEC by aquifer (for wells screened in the Elkhorn and Platte River alluvial aquifers) or by well (for wells screened in the Dakota Sandstone, upland alluvial, and Missouri River alluvial aquifers). The physical properties for these wells varied minimally during the 5 months between CEC samples. Well depth and physical properties, which were collected during the regular sampling from 2010 to 2019, are summarized by aquifer in table 7. Comparing average well depths by the aquifer, the Platte and Elkhorn River alluvial aquifer samples were collected from the wells with the shallowest depth (60–62 ft below ground surface), the Missouri River alluvial aquifer samples were collected from wells with a middle depth (108 ft below ground surface), and the Dakota Sandstone and upland alluvial aquifer samples were collected from wells with the deepest depth (170–174 ft below ground surface.). Temperature, pH, and turbidity did not greatly differ between the aquifers. Specific conductance was lowest in the Platte and Elkhorn River alluvial aquifers and highest in the Missouri River alluvial aquifer. The Elkhorn and Missouri River alluvial aquifers had the lowest average DO concentrations that were just above 1 mg/L. These aquifers had many samples under the anoxic threshold of 0.5 mg/L, and anoxic conditions also were present in some samples from the other three aquifers.

Presence of Contaminants of Emerging Concern in Groundwater

Seven of the 132 contaminants in the CEC analysis were detected during this study (U.S. Geological Survey, 2020). In total, 6 different CECs were detected 11 times, and atrazine was detected 15 times among the 34 samples collected from 17 wells (table 8). Surrogate recovery percentages for the four analytes with IDS or surrogates in the laboratory QA procedure ranged from 95 to 106 percent (table 4), giving added confidence to the reliability of these results. No hormones were detected in the 18 samples collected from 9 of the 17 wells sampled for CEC analysis. The detected pharmaceuticals, not including atrazine, were found in samples from 6 of the 17 wells (fig. 2). The pharmaceutical results varied for some wells from the June to the October or November sampling event. The deep well in the Venice cluster (E-V1) had no detections in the June 2019 sample and one analyte detected in the October 2019 sample. The shallow well in the Ashland cluster (P-A3) had one detected analyte in the June 2019 sample and no detections in the October 2019 sample. The deep well in the Elkhorn Crossing cluster (E-EC1) had no detections in June 2019 and three analytes detected in the October 2019 sample. Three wells, two in the Springfield cluster (P-S1 and P-S2) and one in the Valley cluster (P-Va1), had one analyte detected in both the June 2019 and October or November 2019 samples. A total of 25 samples did not have any detected pharmaceutical or hormone CECs in either the June 2019 or October or November 2019 samples. All pharmaceutical and hormone CECs detected in this study were from wells in the Platte River and Elkhorn River alluvial aquifers (fig. 2), which are unconfined aquifers with shallow depth to water (table 1).

The most frequently detected CEC in this study was the antibiotic sulfamethoxazole. It was detected in the summer and fall samples from the deep (P-S1) and medium-depth (P-S2) wells in the Springfield cluster but was not detected in the shallow well (P-S3). The concentration of sulfamethoxazole was higher in the fall samples collected from both wells (table 8). Nicotine was detected in two samples from different wells (P-A3 and E-EC1) at a concentration below the reporting level but above the detection limit. The other CEC detected in both samples from one well was methyl-1*H*-benzotiazole, an industrial product with a variety of applications. It was detected in the summer and fall samples from the shallow well of the Valley cluster (P-Va1). The concentration decreased in the 5 months between samples. In the second sample, the concentration was lower than the reporting level but above the

Table 5. Physical properties for samples collected for contaminants of emerging concern analysis, June–November 2019; Papio-Missouri River Natural Resources District, eastern Nebraska.

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). Dates are given in month/day/year. °C, degree Celsius; µS/cm, microsiemen per centimeter at 25 °C; mg/L, milligram per liter; NTRU, nephelometric turbidity ratio unit; --, data missing]

Aquifer	USGS station number	Well identifier	Date	Water temperature (°C)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	pH (standard units)	Turbidity (NTRU)
Platte River alluvial	410243096082001	P-S1	6/12/2019	12.7	591	7.4	6.9	0.2
Platte River alluvial	410243096082001	P-S1	10/24/2019	12.5	599	7.4	6.8	--
Platte River alluvial	410243096082002	P-S2	6/12/2019	12.7	582	6.5	6.9	0.1
Platte River alluvial	410243096082002	P-S2	10/24/2019	12.5	586	5.6	6.8	--
Platte River alluvial	410243096082003	P-S3	6/12/2019	12.9	552	3.0	7.0	0.2
Platte River alluvial	410243096082003	P-S3	10/24/2019	12.7	558	3.2	6.9	--
Platte River alluvial	410334096182801	P-A1	6/25/2019	13.4	513	0.6	7.3	0.3
Platte River alluvial	410334096182801	P-A1	10/29/2019	13.0	517	0.8	7.0	--
Platte River alluvial	410334096182802	P-A2	6/25/2019	13.3	604	0.6	7.3	1.0
Platte River alluvial	410334096182802	P-A2	10/29/2019	13.0	614	1.0	7.0	--
Platte River alluvial	410334096182803	P-A3	6/25/2019	11.5	652	0.5	7.0	0.9
Platte River alluvial	410334096182803	P-A3	10/29/2019	13.8	702	0.7	6.6	--
Dakota Sandstone	410613096071102	D-Sp2	6/25/2019	13.8	384	1.4	6.7	0.4
Dakota Sandstone	410613096071102	D-Sp2	10/23/2019	13.0	374	2.9	6.3	--
Elkhorn River alluvial	411231096193201	E-V1	6/11/2019	12.5	544	1.0	7.0	0.1
Elkhorn River alluvial	411231096193201	E-V1	10/28/2019	12.3	553	1.2	6.9	--
Elkhorn River alluvial	411231096193202	E-V2	6/11/2019	12.3	550	0.2	6.9	0.1
Elkhorn River alluvial	411231096193202	E-V2	10/28/2019	12.0	537	0.3	6.8	--
Elkhorn River alluvial	411231096193203	E-V3	6/11/2019	11.0	832	0.2	6.8	0.1
Elkhorn River alluvial	411231096193203	E-V3	10/28/2019	13.5	844	0.3	6.7	--
Platte River alluvial	411845096211201	P-Va1	6/17/2019	14.3	565	0.1	6.7	0.2
Platte River alluvial	411845096211201	P-Va1	11/14/2019	13.6	577	0.2	6.7	--
Platte River alluvial	411845096211202	D-Va2	6/17/2019	14.1	517	0.2	7.2	0.2
Platte River alluvial	411845096211202	D-Va2	11/14/2019	11.8	526	0.2	7.2	--
Elkhorn River alluvial	412151096180801	E-EC1	6/26/2019	11.9	637	0.5	7.0	5.2
Elkhorn River alluvial	412151096180801	E-EC1	10/31/2019	12.2	644	0.8	7.1	--
Elkhorn River alluvial	412151096180802	E-EC2	6/26/2019	11.5	622	0.9	7.1	--
Elkhorn River alluvial	412151096180802	E-EC2	10/31/2019	12.6	626	1.2	7.3	--

Table 5. Physical properties for samples collected for contaminants of emerging concern analysis, June–November 2019; Papio-Missouri River Natural Resources District, eastern Nebraska.—Continued

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). Dates are given in month/day/year. °C, degree Celsius; µS/cm, microsiemen per centimeter at 25 °C; mg/L, milligram per liter; NTRU, nephelometric turbidity ratio unit; --, data missing]

Aquifer	USGS station number	Well identifier	Date	Water temperature (°C)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	pH (standard units)	Turbidity (NTRU)
Upland alluvial	412758096222803	U-A3	6/13/2019	13.6	956	0.1	7.1	0.2
Upland alluvial	412758096222803	U-A3	11/12/2019	12.8	951	0.4	7.2	--
Dakota Sandstone	414700096134903	D-T3	6/20/2019	12.9	879	7.3	7.0	0.3
Dakota Sandstone	414700096134903	D-T3	11/5/2019	12.6	883	7.9	7.0	--
Missouri River alluvial	415958096152202	D-D2	6/20/2019	11.3	675	0.2	7.0	0.1
Missouri River alluvial	415958096152202	D-D2	11/12/2019	10.9	678	0.2	7.1	--

Table 6. Summary statistics of physical properties for samples collected for contaminants of emerging concern analysis, June–November 2019, Papio-Missouri River Natural Resources District, eastern Nebraska.

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). µS/cm, microsiemen per centimeter at 25 °C; mg/L, milligram per liter; NTRU, nephelometric turbidity ratio unit; ft BGS, foot below ground surface]

Aquifer	Statistic	Number of samples/number of wells	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	pH (standard unit)	Turbidity (NTRU)	Well depth (ft BGS)
Platte River alluvial	Average	16/8	578	2.4	7.0	0.4	56
Platte River alluvial	Standard deviation		51	2.8	0.2	0.4	26
Platte River alluvial	Maximum		702	7.4	7.3	1.0	94
Platte River alluvial	Minimum		513	0.1	6.6	0.1	21
Elkhorn River alluvial	Average	10/5	639	0.7	7.0	1.4	47
Elkhorn River alluvial	Standard deviation		113	0.4	0.2	2.6	32
Elkhorn River alluvial	Maximum		844	1.2	7.3	5.2	98
Elkhorn River alluvial	Minimum		537	0.2	6.7	0.1	22
Missouri River alluvial	Average	2/1	677	0.2	7.1	0.1	75
Upland alluvial	Average	2/1	954	0.3	7.2	0.2	141
Dakota sandstone (USGS station 414700096134903)	Average	2/1	881	7.6	7.0	0.3	61
Dakota sandstone (USGS station 410613096071102)	Average	2/1	379	2.1	6.5	0.4	115

Table 7. Summary statistics of physical properties for samples collected for nitrate plus nitrite as nitrogen analysis, 2010–19, Papio-Missouri River Natural Resources District, eastern Nebraska.

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). µS/cm, microsiemen per centimeter at 25 °C; mg/L, milligram per liter; NTRU, nephelometric turbidity ratio unit; ft BGS, foot below ground surface]

Aquifer	Statistic	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	pH (standard units)	Turbidity (NTRU)	Well depth (ft BGS)
Platte River alluvial	Average	609	4.3	7.0	0.6	60
Platte River alluvial	Standard deviation	170	2.8	0.2	0.4	17
Platte River alluvial	Maximum	1,280	9.1	7.7	1.4	98
Platte River alluvial	Minimum	450	0.1	6.5	0.1	21
Platte River alluvial	Number of samples	50	48	48	15	54
Elkhorn River alluvial	Average	589	1.1	7.1	0.9	62
Elkhorn River alluvial	Standard deviation	92	2.0	0.2	1.5	31
Elkhorn River alluvial	Maximum	832	8.7	7.6	5.2	120
Elkhorn River alluvial	Minimum	422	0.1	6.6	0.1	22
Elkhorn River alluvial	Number of samples	57	48	63	10	63
Missouri River alluvial	Average	1,050	1.2	7.0	2.4	108
Missouri River alluvial	Standard deviation	363	1.8	0.2	5.8	68
Missouri River alluvial	Maximum	2,210	8.5	7.3	28.0	440
Missouri River alluvial	Minimum	565	0.1	6.5	0.1	25
Missouri River alluvial	Number of samples	66	51	66	21	66
Upland alluvial	Average	816	3.6	7.0	1.4	170
Upland alluvial	Standard deviation	270	3.0	0.2	0.7	63
Upland alluvial	Maximum	1,590	10.6	7.4	2.6	338
Upland alluvial	Minimum	402	0.1	6.5	0.8	61
Upland alluvial	Number of samples	54	47	54	5	54
Dakota sandstone	Average	803	3.7	6.9	4.4	174
Dakota sandstone	Standard deviation	348	3.5	0.2	18.0	80
Dakota sandstone	Maximum	2,100	11.6	7.4	140	565
Dakota sandstone	Minimum	284	0.1	6.2	0.1	71
Dakota sandstone	Number of samples	148	137	148	65	148

Table 8. Detected contaminants of emerging concern, nitrate plus nitrite as nitrogen concentrations, and dissolved oxygen, Papio-Missouri River Natural Resources District, eastern Nebraska, 2019.

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). Dates are given in month/day/year. ng/L, nanogram per liter; p code, USGS parameter code; mg/L, milligram per liter; --, no detection; <, less than; E, estimated; *, no sample]

USGS station number	Well name	Well identifier	Sample date	Atrazine, ng/L, p code 65065	Acetaminophen, ng/L, p code 67436	Caffeine, ng/L, p code 67440	Metformin, ng/L, p code 67492	Methyl-1H-benzotriazole, ng/L, p code 67514	Nicotine, ng/L, p code 67493	Sulfamethoxazole, ng/L, p code 67454	Nitrate plus nitrite as nitrogen, mg/L, p code 00631	Dissolved oxygen (mg/L)
410243096082001	Springfield (Buffalo Road) deep	P-S1	06/12/19	--	--	--	--	--	--	10.9	10.8	7.4
410243096082001	Springfield (Buffalo Road) deep	P-S1	10/24/19	--	--	--	--	--	--	12.2	*	7.4
410243096082002	Springfield (Buffalo Road) medium	P-S2	06/12/19	--	--	--	--	--	--	9.11	10.5	6.5
410243096082002	Springfield (Buffalo Road) medium	P-S2	10/24/19	9.68	--	--	--	--	--	13.6	*	5.6
410334096182801	Ashland deep	P-A1	06/25/19	56.5	--	--	--	--	--	--	<0.040	0.6
410334096182801	Ashland deep	P-A1	10/29/19	57.3	--	--	--	--	--	--	*	0.8
410334096182802	Ashland medium	P-A2	06/25/19	40.2	--	--	--	--	--	--	<0.040	0.6
410334096182802	Ashland medium	P-A2	10/29/19	35.7	--	--	--	--	--	--	*	1.0
410334096182803	Ashland shallow	P-A3	06/25/19	--	--	--	--	--	E31.3	--	<0.040	0.5
411231096193201	Venice deep	E-V1	06/11/19	94.7	--	--	--	--	--	--	<0.040	1.0
411231096193201	Venice deep	E-V1	10/28/19	77.8	5.13	--	--	--	--	--	*	1.2
411231096193202	Venice medium	E-V2	06/11/19	43.7	--	--	--	--	--	--	<0.040	0.2
411231096193202	Venice medium	E-V2	10/28/19	49.9	--	--	--	--	--	--	*	0.3
411231096193203	Venice shallow	E-V3	06/11/19	24.0	--	--	--	--	--	--	0.121	0.2
411231096193203	Venice shallow	E-V3	10/28/19	4.28	--	--	--	--	--	--	*	0.3
411845096211201	Valley shallow	P-Va1	06/17/19	51.4	--	--	--	47.3	--	--	0.152	0.1
411845096211201	Valley shallow	P-Va1	11/14/19	52.8	--	--	--	E27.3	--	--	*	0.2
411845096211202	Valley medium	D-Va2	06/17/19	29.9	--	--	--	--	--	--	0.055	0.2
411845096211202	Valley medium	D-Va2	11/14/19	36.7	--	--	--	--	--	--	*	0.2
412151096180801	Elkhorn Crossing deep	E-EC1	10/31/19	--	--	E20.2	11.3	--	E38.1	--	*	0.8

detection limit. Pharmaceutical analytes detected in only one sample during this study were acetaminophen (analgesic), caffeine, and metformin (diabetes medicine).

Atrazine was detected in 15 samples from 8 wells in 4 well clusters in the Platte River and Elkhorn River alluvial aquifers (table 8). Seven of the wells, in three clusters, had atrazine detected in the summer and fall samples. Previous sampling for atrazine has been performed at six of the sites with detections in this study (USGS, 2020). Data analysis for the previous testing used different analytical methods with a higher detection level than this study (50 ng/L for previous testing as compared to 10 ng/L for this study), but all six sites had low levels of atrazine detected at least once since 1999.

The only wells with a detection of CECs and nitrate-N concentration above 0.2 mg/L were at the Springfield (Buffalo Road) deep (P-S1) and medium-depth (P-S2) wells (table 8). The samples from these wells (P-S1 and P-S2) were also the only CEC detections with a DO concentration above 1.2 mg/L (table 8), suggesting that anoxic conditions and denitrification were present in all other wells with CEC detections.

March 2019 brought unprecedented flooding to eastern Nebraska, including much of the PMRNRD and the Platte and Elkhorn Rivers along the western and southern boundaries of the PMRNRD (Nebraska Department of Natural Resources, 2019). Several of the PMRNRD monitoring well clusters were inundated during the flooding, and all CEC sampling occurred after the flooding. The ground at 10 of the 17 wells sampled for CECs (in 4 clusters) was inundated during the flooding (table 1). Five of the 6 detected CECs (from 4 of 6 wells with detections) were from wells that were inundated during the flood. Additionally, 14 of the 15 atrazine detections (from 7 of the 8 wells with detections) were from wells inundated during the flooding. All detections in non-inundated wells (4 sulfamethoxazole and 1 atrazine detection) were from one cluster that was very near, but not within, the area inundated by the flood. Because the sampling only occurred 3–8 months after the flooding, and there are no data about CECs in the floodwater, the effect of the flooding on the CEC detection in this study cannot be determined. However, specific conductance and DO concentrations were similar during regular PMRNRD groundwater sampling before and after the flood at all wells with CEC detection (USGS, 2020), suggesting that dilution of the local groundwater was not a major effect from the flood.

Presence of Nitrate-N in Groundwater, 2010–19

From 2010 to 2019, 473 samples were collected for nitrate-N analysis from 150 wells (including the wells sampled for CECs) as part of the regular PMRNRD groundwater sampling program (fig. 3) (USGS, 2020). Nitrate-N was detected at a level above 4 mg/L in 92 samples (19 percent) from 33 wells, and results exceeded 10 mg/L in 36 samples (7.6 percent) from 15 wells (table 9). The Dakota Sandstone aquifer had the highest percentage of samples with nitrate-N concentrations above 10 mg/L, whereas the Platte River alluvial aquifer had the highest percentage of samples with concentrations above 4 mg/L. Groundwater nitrate-N concentrations decrease with depth with little to no nitrate occurring deeper than 300 ft (fig. 4). Naturally occurring nitrate exists in ecosystems at concentrations usually below 2 mg/L (Nolan and others, 2002) as part of the nitrogen cycle, whereas non-naturally occurring nitrate is introduced into the ecosystem through anthropogenic inputs such as commercial fertilizers.

DO concentrations were taken for 1,913 of the 2,095 samples collected since 1992. Nitrate-N concentrations in groundwater were lowest at DO concentrations less than 0.5 mg/L, indicating redox conditions appropriate for nitrate removal through denitrification, but nitrate-N ranged from 0 to 24.7 mg/L for all DO concentrations from 2010 to 2019 (512 samples) (fig. 5). DO concentrations less than 0.5 mg/L indicate potential denitrifying conditions; however, denitrification may occur at DO concentrations as high as 2 mg/L (Erickson and others, 2021). Low nitrate-N concentrations at high (>2 mg/L) DO concentrations do not indicate denitrification, but rather a lack of non-naturally occurring nitrate, which is why there is a range of nitrate-N concentrations at these DO concentrations. Median DO concentrations were lowest in the Elkhorn and Missouri River alluvial aquifers (table 9). The Elkhorn River alluvial aquifer also had the highest percentage of wells and samples with DO less than 0.5 mg/L, indicating potential denitrification throughout this aquifer. Previous work in this area has quantified the amount of denitrification for 17 wells throughout the study area (McGuire and others 2012). The upland alluvial aquifer and Missouri River alluvial aquifer have the highest median iron concentrations (table 9). Groundwater iron concentrations greater than 100 µg/L are also an indicator of potential denitrification (Erickson and others, 2021).

Nitrate-N Time Series Analysis, 1992–2020

Nitrate-N concentrations in groundwater have varied in the samples collected as part of the regular PMRNRD groundwater sampling program from 1992 to 2020. When looking at the median nitrate-N concentration in 4-year periods from the entire sampling period of 1992–2019 (calendar year) (table 10), the Platte River alluvial aquifer median nitrate-N concentration has been increasing from 0.36 mg/L in 1992 to 8.33 mg/L in 2015; however, concentration was lower (4.52 mg/L) during 2016–19. Median nitrate-N concentrations in the Elkhorn River alluvial aquifer have been decreasing since 1992 and have been below the detection limit since 2008–11; however, some wells sampled previously have not been resampled since 2010 for all aquifers in this study area (USGS, 2020). After 2010, sampling shifted from mostly irrigation wells with long well screens to sampling mostly domestic wells with shorter well screens. This change may have influenced nitrate trends in the aquifers. The long well screens of irrigation wells make it difficult to pinpoint where the nitrate-N contamination is occurring in the aquifer, and

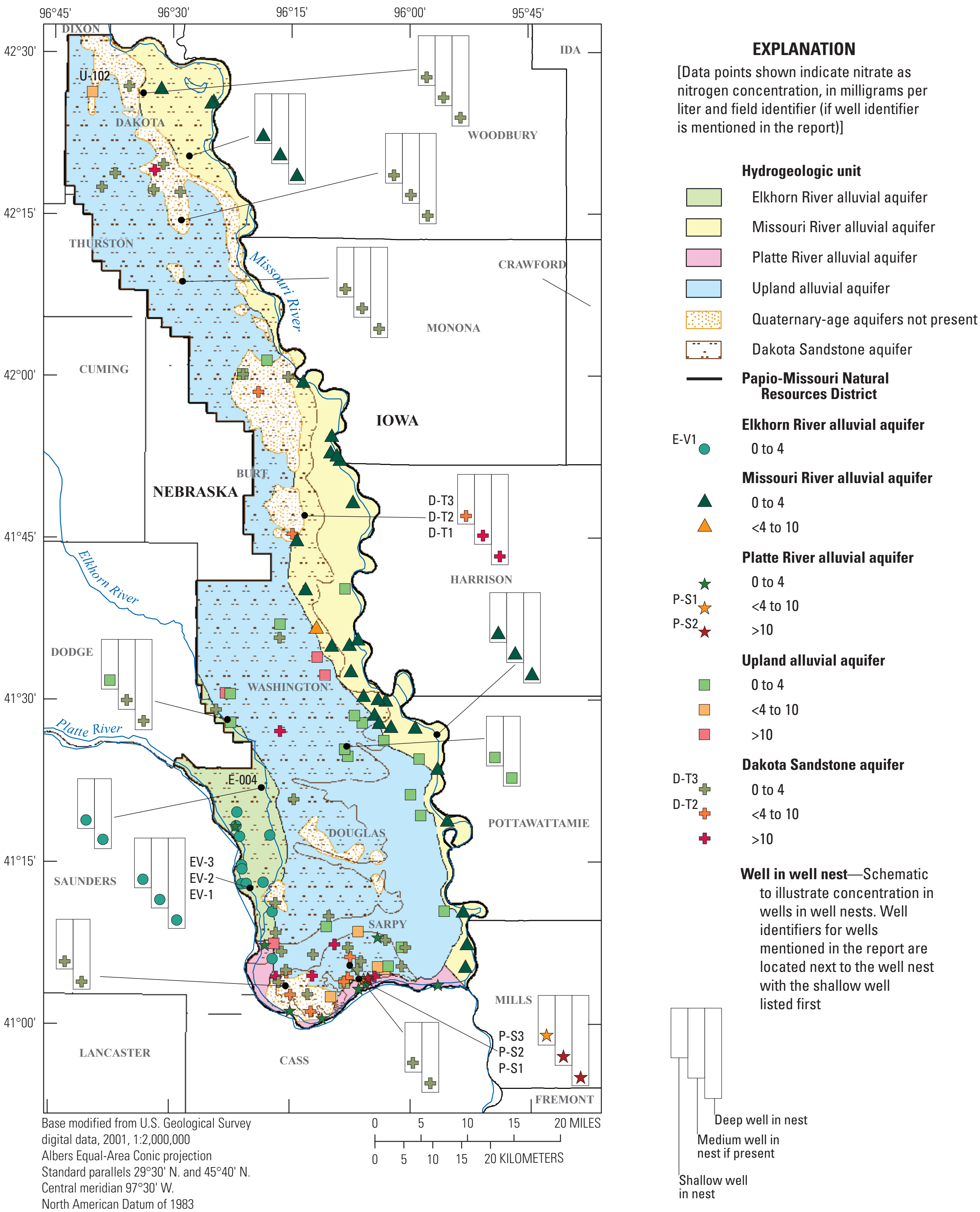

Figure 3. Spatial distribution of the most recent nitrate plus nitrite as nitrogen concentration for each sampled well, Papio-Missouri River Natural Resources District, eastern Nebraska, 2010–19.

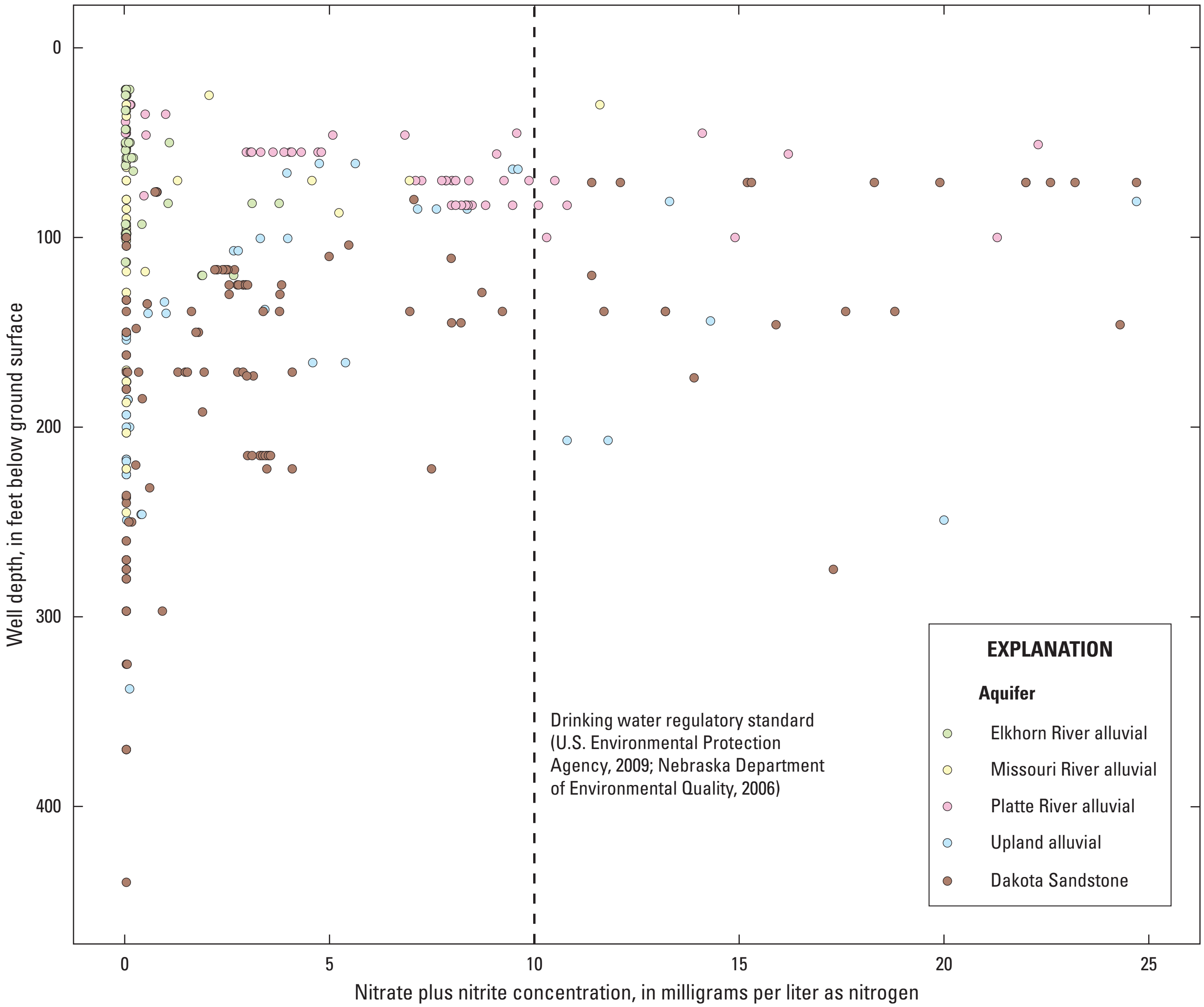

Figure 4. Most recent nitrate plus nitrite as nitrogen concentration results in groundwater samples as a function of well depth, Papio-Missouri River Natural Resources District, eastern Nebraska, 2010–19.

Table 9. Summary of nitrate plus nitrite as nitrogen concentrations by aquifer, Papio-Missouri River Natural Resources District, eastern Nebraska, 2010–19.

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). nitrate-N, nitrate plus nitrite as nitrogen; mg/L, milligram per liter; ≥, greater than or equal to; µg/L, micrograms per liter; <, less than the method detection value; ≤, less than or equal to]

Aquifer	Number of wells	Number of samples	Median nitrate-N concentration, mg/L	Maximum nitrate-N concentration, mg/L	Number of wells (samples) with nitrate-N ≥2 and <4 mg/L	Number of wells (samples) with nitrate-N ≥ 4 mg/L	Percentage of wells (samples) with nitrate-N ≥4 mg/L	Number of wells (samples) with nitrate-N ≥10 mg/L	Percentage of wells (samples) with nitrate-N ≥10 mg/L	Median iron concentration, µg/L	Number of wells (samples) with iron ≥100 µg/L	Median dissolved-oxygen concentration, mg/L	Number of wells (samples) with dissolved-oxygen concentration ≤0.5 mg/L
Platte River alluvial	15	77	0.50	22.3	1 (6)	5 (30)	33 (39)	3 (4)	20 (5)	10	7 (20)	3.7	5 (9)
Elkhorn River alluvial	17	70	<0.04	3.8	2 (3)	0 (0)	0 (0)	0 (0)	0 (0)	10.7	8 (18)	0.4	10 (36)
Missouri River alluvial	34	80	<0.04	11.6	3 (3)	4 (5)	12 (6)	1 (1)	3 (1)	5,500	31 (69)	0.8	15 (19)
Upland alluvial	32	58	0.12	24.7	4 (6)	10 (17)	31 (29)	3 (5)	9 (9)	66.4	14 (28)	3.3	9 (12)
Dakota Sandstone	52	188	0.78	24.7	10 (40)	14 (40)	27 (21)	8 (26)	15 (14)	10	23 (54)	3.1	18 (42)
All sites	150	473	0.05	24.7	20 (58)	33 (92)	22 (19)	15 (36)	10 (8)	18.4	83 (187)	1.5	57 (118)

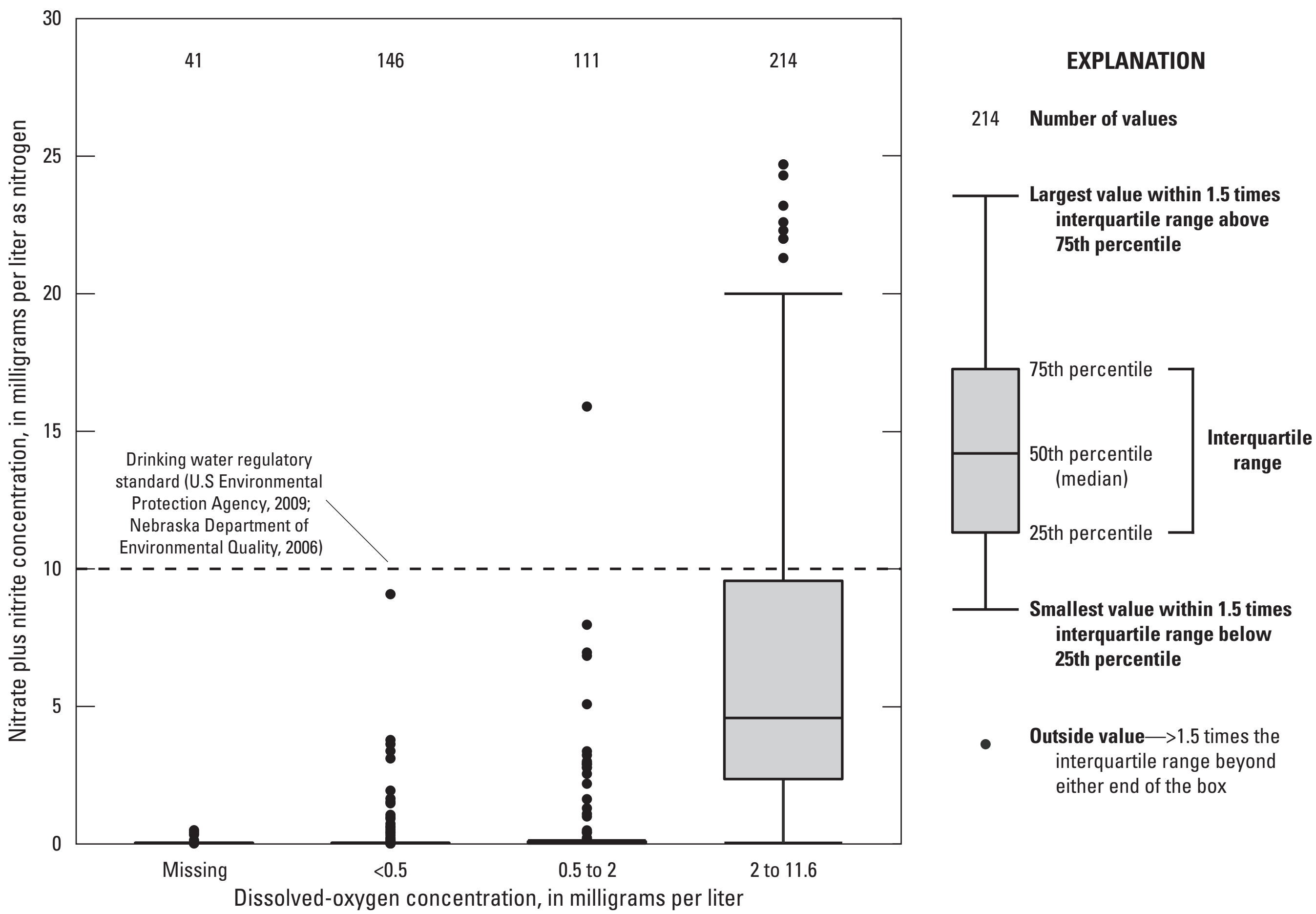

Figure 5. Frequency distribution of nitrate plus nitrite as nitrogen concentrations in groundwater by dissolved-oxygen concentration range, in the most recent samples, Papio-Missouri River Natural Resources District, eastern Nebraska, 2010–19.

Table 10. Median concentration and sample counts of nitrate plus nitrite as nitrogen in groundwater samples by 4-year intervals for each aquifer, Papio-Missouri River Natural Resources District, eastern Nebraska, 1992–2019.

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). ft, foot; mg/L, milligram per liter; <, less than the method detection value]

Aquifer	Average well depth (ft)	Metric	Summary statistics for nitrate plus nitrite as nitrogen by sampling						
			1992–95	1996–99	2000–3	2004–7	2008–11	2012–15	2016–19
Platte River alluvial	65	Median (mg/L)	0.36	5.20	4.69	6.02	6.74	8.33	4.52
		Count	12	35	76	90	42	18	22
Elkhorn River alluvial	56	Median (mg/L)	1.70	1.21	1.47	0.09	<0.04	<0.04	<0.04
		Count	19	80	134	108	31	22	21
Missouri River alluvial	89	Median (mg/L)	<0.05	<0.05	<0.06	<0.06	<0.04	<0.04	<0.04
		Count	14	58	164	69	36	29	23
Upland alluvial	137	Median (mg/L)	6.50	0.54	<0.06	<0.06	0.31	0.97	0.12
		Count	25	43	83	31	20	25	27
Dakota Sandstone	175	Median (mg/L)	0.19	1.55	<0.06	0.51	0.12	1.90	0.79
		Count	13	36	158	91	39	55	106

Table 11. Results of the Mann-Kendall test for nitrate plus nitrite as nitrogen concentration trends by aquifers, Papio-Missouri River Natural Resources Districts, eastern Nebraska, 1992–2020.

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). <, less than; --, no significant trend]

Aquifer	Trend in nitrate plus nitrite as nitrogen concentration, 1992 to 2020	Slope	*p*-value	Sample count
Platte River alluvial	Increasing	0.17	<0.001	324
Platte River alluvial (without annually sampled wells[1])	No trend	--	0.97	108
Elkhorn River alluvial	Decreasing	−0.13	<0.001	457
Elkhorn River alluvial (without annually sampled wells[1])	No trend	--	0.05	244
Missouri River alluvial	No trend	--	0.14	425
Upland alluvial	No trend	--	0.076	276
Dakota Sandstone	No trend	--	0.45	529
Dakota Sandstone (without annually sampled wells[1])	No trend	--	0.98	317

[1]Without annually sampled wells means wells sampled on an annual basis were excluded. Most wells in this study area are sampled on a 4-year rotation, and certain wells are sampled annually. These wells were excluded to see if they were driving the trends seen in the aquifer.

some wells are screened across multiple aquifers. Sampling domestic wells gives a more precise measurement of the nitrate-N concentrations at a point in the aquifer because of the smaller screened interval. The median nitrate-N concentration in the Missouri River alluvial aquifer was below the detection limit for the period of study. The nitrate-N concentrations in the upland alluvial and Dakota Sandstone aquifers have varied throughout the sampling period.

The significance of trends over the study period was determined for each aquifer using the Mann-Kendall test (Helsel and others, 2020) (table 11). The Missouri River alluvial, upland alluvial, and Dakota Sandstone aquifers did not show a trend in groundwater nitrate-N concentrations in the overall period of study. The Elkhorn River alluvial aquifer had a negative trend in groundwater nitrate-N concentration over time, whereas the Platte River alluvial aquifer had a positive trend in nitrate-N concentration over time. However, three well nests—one in the Platte River alluvial (wells P-S1, P-S2, and P-S3), one in the Elkhorn River alluvial (wells E-V1, E-V2, and E-V3), and one in the Dakota Sandstone (wells D-T1, D-T2, and D-T3)—are sampled on an annual basis because they are located in a groundwater management area. The wells in all the aquifers are sampled on an about 4-year rotation; however, the same wells may not be sampled each time, and sampling between these 4-year rotations is minimal. These annually sampled well nests all had one or more wells with a strong positive or negative trend. The Mann-Kendall test was run again on these three aquifers excluding the results from those well nests to see if the trend was driven by those specific wells or the aquifer as a whole. For example, if all the wells in the aquifer except these stayed constant while these specific wells increased, the entire aquifer would seem to be increasing when it is a localized occurrence. When those wells were excluded from the trend analysis, trends were not significant (p-value less than 0.05) in groundwater nitrate-N concentrations for any of the five aquifers in the PMRNRD.

Ten wells, sampled more frequently than the 4-year rotation, had 10 years of sampling data and were evaluated to determine if the concentration trend was significant within them (table 12). These wells represent 3 well nests and 1 stand-alone well in 3 different aquifers. The nest of three wells (P-S1, P-S2, and P-S3) in the Platte River alluvial aquifer is within a Phase 2 management area (Papio-Missouri River Natural Resources District, 2018) and had trends of increasing nitrate-N concentration at all depths. The increasing nitrate-N concentrations in the Platte River alluvial aquifer well nest seems to be driving the trend analysis for the whole aquifer when the wells were included, evidenced by the lack of a trend in the aquifer when those wells were excluded from analysis (table 11). In the Elkhorn River alluvial aquifer, the stand alone well (E004) had no trend, whereas the nest of three wells (E-V1, E-V2, and E-V3) had trends of decreasing nitrate-N concentration at all depths. The nest of three wells (D-T1, D-T2, and D-T3) in a Phase 2 management area (Papio-Missouri River Natural Resources District, 2018) within the Dakota Sandstone aquifer had a decreasing trend in the deepest well and an increasing trend in the shallow and medium wells.

The increase in nitrate-N in any of these wells does not necessarily reflect on current nitrate-N management strategies. Previous studies done on these wells looked at apparent groundwater age based on age dating studies (McGuire and others 2012). The well nest in the Platte River alluvial aquifer had recharge dates from the early to mid-1970s, and the well nests in the Elkhorn River alluvial and Dakota Sandstone aquifers had recharge dates from the early to mid-1960s (McGuire and others 2012). These apparent ages show a considerable time lag between current nitrate-N management practices and groundwater nitrate-N concentrations.

Comparison of Concentrations of Anthropogenic Compounds with Health-Based Water-Quality Standards and Benchmarks

Only 5 of the 132 analytes included in the CEC analysis for pharmaceuticals and hormones (table 2) have regulatory or health-based standards in Nebraska, including 1 for atrazine, which was included in this method to compare performance between compounds and between methods (table 13) (Nebraska Department of Environmental Quality, 2006; Furlong and others, 2014; Norman and others, 2018). The four CECs with health-based standards were not detected in this study.

The agricultural herbicide atrazine has a groundwater maximum contaminant level (MCL) of 3 micrograms per liter (μg/L) set by the U.S. Environmental Protection Agency (2009) and the State of Nebraska (Nebraska Department of Environmental Quality, 2006). Atrazine was detected in 15 samples in the Platte/Elkhorn alluvial aquifer at a maximum concentration of 0.0947 μg/L, substantially below the MCL.

A nitrate-N threshold of 4 mg/L was used in a previous study to represent the anthropogenic effect of groundwater when using a background nitrate-N level of 2 mg/L. (Nolan and others, 2002). The use of the 4 mg/L threshold for anthropogenic effect indicates some non-naturally occurring nitrate likely is present (Nolan and others. 2002). Additionally, Ward and others (1996) found a positive association between nitrate-N concentrations greater than 4 mg/L in Nebraska community water systems and cancer rates. In a review of published studies of nitrate in drinking water, Ward and others (2018) reported adverse health effects from drinking water nitrate levels as low as 2.46 mg/L and found the strongest evidence for adverse health effects related to elevated nitrate levels (>5.0 mg/L) for colorectal cancer, thyroid disease, and neural tube defects. The State of Nebraska's MCL for nitrate in groundwater and for the U.S. Environmental Protection Agency in drinking water is 10 mg/L as N (U.S. Environmental Protection Agency, 2009; Nebraska Department of Environmental Quality, 2006).

Table 12. Results of the Mann-Kendall test for nitrate plus nitrite as nitrogen concentration trends in groundwater for wells with 10 or more years of data, Papio-Missouri River Natural Resources District, eastern Nebraska, 1992–2020.

[Data are summarized from the U.S. Geological Survey (USGS) National Water Information System database (USGS, 2020). ft BGS, foot below ground surface; nitrate-N, nitrate plus nitrite as nitrogen; mg/L, milligram per liter; <, less than; --, no significant trend]

USGS site number	Well identifier	Aquifer	Well depth (ft BGS)	Nitrate-N trend	Slope	*p*-value	Sample count	Sampling period	Median nitrate concentration, mg/L
410243096082001	P-S1	Platte River alluvial	83	Increasing	0.062	<0.001	71	1999–2020	6.84
410243096082002	P-S2	Platte River alluvial	70	Increasing	0.052	<0.001	73	1999–2020	6.09
410243096082003	P-S3	Platte River alluvial	55	Increasing	0.026	<0.001	72	1999–2020	2.91
411231096193201	E-V1	Elkhorn River alluvial	98	Decreasing	−0.022	<0.001	70	1999–2020	0.20
411231096193202	E-V2	Elkhorn River alluvial	58	Decreasing	−0.04	<0.001	70	1999–2020	0.25
411231096193203	E-V3	Elkhorn River alluvial	22	Decreasing	−0.043	<0.001	72	1999–2020	1.88
411937096213701	E-004	Elkhorn River alluvial	82	No trend	--	1	10	1999–2020	3.25
414700096134901	D-T1	Dakota Sandstone	171	Decreasing	−0.005	0.024	71	1999–2020	0.54
414700096134902	D-T2	Dakota Sandstone	139	Increasing	0.018	0.0013	71	1999–2020	0.67
414700096134903	D-T3	Dakota Sandstone	71	Increasing	0.063	0.0094	70	1999–2020	21.25

Table 13. Health-based water quality standards and benchmarks that exist for chemicals analyzed, Papio-Missouri River Natural Resources District, eastern Nebraska, 2019.

[µg/L, microgram per liter ; mg/L, milligram per liter; NE MCL, Nebraska Title 118 maximum contaminant level for groundwater (Nebraska Department of Environmental Quality, 2006); EPA MCL, U.S. Environmental Protection Agency maximum contaminent level for drinking water (U.S. Environmental Protection Agency, 2009); USGS HBSL, U.S. Geological Survey health-based screening level (Norman and others, 2018); EPA HHBP, U.S. Environmental Protection Agency human health benchmarks for pesticides(Norman and others, 2018)]

Chemical	Standard or benchmark	Unit	Standard source	Detected in this study?
Atrazine	3	µg/L	NE MCL and EPA MCL	Yes
Bisphenol A	300	µg/L	USGS HBSL	No
Piperonyl butoxide	992	µg/L	EPA HHBP	No
Thiabendazole	210	µg/L	EPA HHBP	No
Warfarin	2	µg/L	USGS HBSL	No
Nitrate as nitrogen	10	mg/L	NE MCL and EPA MCL	Yes

Nitrate samples exceeding the 2- and 4-mg/L thresholds were collected throughout the PMRNRD and in all aquifers except the Elkhorn River alluvial aquifer, which had no samples with nitrate-N above 4 mg/L and only 3 samples between 2 and 4 mg/L (table 9). Dissolved oxygen was less than or equal to 0.5 mg/L in over 60 percent of the samples from the Elkhorn River alluvial aquifer for which it was analyzed, indicating that denitrification is a possible partial explanation for the lower nitrate-N concentrations in that aquifer.

Environmental Implications

Only one of the CECs detected during this study has been reported to have effects upon environmental processes. Underwood and others (2011) determined that low concentrations of sulfamethoxazole inhibited the nitrate reduction capabilities of an aquifer-sourced bacterial culture in anoxic conditions. The lowest tested sulfamethoxazole concentrations (1 µg/L) were about 100 times higher than the sulfamethoxazole detected in this study in the deep (P-S1) and medium-depth (P-S2) wells at the well nest Springfield (Buffalo Road) (table 8; fig. 2). Underwood and others (2011) determined that sulfamethoxazole at low concentrations of 1 µg/L decreased nitrate reduction potential by 47 percent. Nutrient samples were only collected with CEC sampling from each well in June 2019, and sample results for nitrate-N from both wells with sulfamethoxazole detections (P-S1 and P-S2, fig. 2) were greater than 10 mg/L. The shallower well from the cluster did not have any CECs detected and had a nitrate-N value less than 5 mg/L. Dissolved-oxygen concentrations from both wells with a sulfamethoxazole detection (P-S1 and P-S2) were greater than 5.4 mg/L for all samples collected from 2010 to 2019 (U.S. Geological Survey, 2020), indicating oxic conditions (no denitrification expected) within the deep and medium-depth sampled regions of the aquifer.

CECs were detected in the Platte River and Elkhorn River alluvial aquifers that were targeted with sampling. These detections demonstrate that groundwater supplies of the PMRNRD are affected by anthropogenic contamination from nonagricultural and agricultural sources. Although the extent and degree of contamination related to agricultural activities has been characterized from many years of district-wide sampling, CEC monitoring in the PMRNRD, including in the Platte River and Elkhorn River alluvial aquifers targeted by this study, has been minimal. CECs were detected in six wells screened in the Platte River and Elkhorn River alluvial aquifers (Ashland Shallow, P-A3; Venice Deep, E-V1; Valley shallow, P-Va1; Springfield [Buffalo Road] medium, P-S2, and deep, P-S1; and Elkhorn Crossing deep, E-EC1) with a depth to water ranging from 3.3 to 12.9 feet and well depths ranging from 21 to 98 feet; and none had a pattern between physical properties and CEC occurrence (U.S. Geological Survey, 2020). CEC concentrations were not detected in samples from the Missouri River alluvial aquifer, upland alluvial aquifer, or Dakota Sandstone aquifer. However, because samples were collected from only four wells screened in the Missouri River alluvial (D-D2), the upland alluvial (U-A3), and the Dakota Sandstone aquifers (D-Sp2 and D-T3), the presence of CECs in other parts of these aquifers cannot be precluded.

Summary

This study was designed and completed in cooperation with the Papio-Missouri River Natural Resources District (PMRNRD) to help better understand contaminants in the local groundwater system beyond nutrients and agrichemicals. Agricultural contamination in this region has been characterized through many years of district-wide annual sampling; however, contaminants of emerging concern (CEC) monitoring in the PMRNRD is still new. The alluvial aquifer systems are significant sources of water within the district, especially with regards to municipal water supplies. The focus of sampling was primarily on the Platte River and Elkhorn River alluvial aquifers. Samples were collected twice by U.S. Geological Survey (USGS) staff from 17 monitoring wells during routine sampling in 2019. Samples were analyzed for 132 pharmaceutical, hormone, and other organic chemicals and metabolites at a USGS laboratory. Samples for nutrients and agrichemicals have been collected by USGS in the PMRNRD since 1992, and this report updates the nitrate plus nitrite as nitrogen (nitrate-N) sampling results for 2010–19 and includes an evaluation of nitrate data from 1992-2020.

Seven of the 132 contaminants in the CEC analysis were detected during this study. In total, 6 different CECs were detected 11 times, and atrazine was detected 15 times among the 34 collected water samples, all from wells in the Platte and Elkhorn River alluvial aquifers. All six detected CECs were pharmaceuticals, and no hormones were detected in the 18 samples from 9 sampled wells. Twenty-five samples did not have any detected CECs.

The most frequently detected CEC in this study was the antibiotic sulfamethoxazole. It was detected in both samples from the two deeper wells in a cluster of wells. The concentration of sulfamethoxazole was higher in the second sample collected from both wells. Sulfamethoxazole has been shown to inhibit nitrate reduction capabilities of aquifer bacteria, and nitrate samples from both wells with sulfamethoxazole detections were greater than 10 milligrams per liter (mg/L) as nitrogen.

Other CECs detected in this study were nicotine, methyl-1*H*-benzotiazole (industrial product), acetaminophen (analgesic), caffeine, and metformin (diabetes medicine). Only four CECs included in sample analyses have health-based water quality standards, none of which had CEC detections in this study.

The agricultural herbicide atrazine was included in the pharmaceutical laboratory analysis, and it was detected in 15 samples from 8 wells in 4 well clusters in the Platte River and Elkhorn River alluvial aquifers. Seven of the wells, in three clusters, had atrazine detected in the summer and fall samples. Atrazine has established water quality standards in Nebraska, but the highest detected concentration was 0.0947 microgram per liter, which is below the groundwater and drinking water standard of 3 micrograms per liter.

March 2019 brought unprecedented flooding to eastern Nebraska, including much of the PMRNRD and the Platte and Elkhorn Rivers along the western and southern boundaries of the PMRNRD. The ground at 10 of the 17 wells sampled for CECs was inundated during the flooding. Five of the 6 detected CECs and 14 of the 15 atrazine detections were from wells that were inundated during the flood. Because the sampling occurred 3–8 months after the flooding, and there are no data about CECs in the floodwater, the effect of the flooding on the CEC detections in this study cannot be determined, but there was no indication of floodwater diluting local groundwater when analyzing physical properties measured during sampling.

Nitrate-N was detected at a level above 4 mg/L in 92 samples (19 percent) from 33 wells, and results exceeded 10 mg/L as nitrogen in 36 samples (7.6 percent) from 15 wells. A nitrate-N threshold of 4 mg/L has been used in other studies to represent the anthropogenic effect on groundwater when using a background nitrate-N level of 2 mg/L, and a positive association between nitrate concentrations above 4 mg/L as nitrogen in Nebraska community water systems and cancer rates has been reported. Nebraska has a groundwater and primary drinking water standard maximum contaminant level for nitrate of 10 mg/L as nitrogen. Nitrate samples exceeding both thresholds were collected throughout the PMRNRD and in all aquifers except the Elkhorn River alluvial aquifer.

When looking at the median nitrate-N concentration in 4-year periods from the entire sampling period of 1992–2019, the nitrate-N concentrations in the upland alluvial and Dakota Sandstone aquifers have varied throughout the sampling period. Median nitrate-N concentrations in the Elkhorn River alluvial aquifer have been decreasing since 1992 and have been below the detection limit since the 2008–11 period. However, there are wells with nitrate-N higher than 10 mg/L that have been sampled previously, but not resampled since 2010 (U.S. Geological Survey, 2020). The median nitrate-N concentration in the Missouri River alluvial aquifer was below the detection limit for the entire period of study. The Platte River alluvial aquifer median nitrate-N concentration has been increasing from 1992 to 2015 but was lower during 2016–19.

The median nitrate-N concentration for each year was calculated for each aquifer and then a Mann-Kendall test was used to determine if the nitrate-N concentration had a trend over the period of study. The Missouri River alluvial, Dakota Sandstone, and upland alluvial aquifers did not have a trend in groundwater nitrate-N concentrations in the overall period of study. The Elkhorn River alluvial aquifer groundwater nitrate-N concentration decreased over time, whereas the Platte River alluvial aquifer nitrate-N concentration increased over time. However, in the Dakota Sandstone, Platte River alluvial, and Elkhorn River alluvial aquifers, there are wells that are sampled at a much higher frequency (typically annually) than aquifer-wide monitoring of other wells. Because most of these wells are sampled more frequently because of their location in a groundwater management area, these wells were excluded from the data and the Mann-Kendall test was rerun to determine if those data were masking the trend in the remainder of the aquifer. When those wells were excluded from the trend analysis, there were no significant trends (p-value less than 0.05) in groundwater nitrate-N concentrations for any of the five aquifers in the PMRNRD.

The wells sampled more frequently (that were excluded during the second trend test) had enough data to test each well for trends in nitrate-N concentration over time. For 10 wells that each had more than 10 years of sampling data, a Mann-Kendall test was used to determine if there was a significant increase, decrease or no trend in nitrate-N concentration. These wells represent three well nests and one stand-alone well in three different aquifers. In the Elkhorn River alluvial aquifer, the stand alone well had no trend, whereas the nest of three wells had trends of decreasing nitrate-N concentration at all depths. The nest of three wells in a Phase 2 management area within the Dakota Sandstone aquifer had a decreasing trend in the deepest well and increasing trend in the shallow and medium well. The nest of three wells in a Phase 2 management area within the Platte River alluvial aquifer had trends of increasing nitrate-N concentration at all depths. The increasing nitrate-N concentrations in the Platte River alluvial aquifer well nest seems to be driving the trend analysis for the whole aquifer when the wells were included, evidenced by the lack of a trend in the aquifer when those wells were discluded from analysis.

The increase in nitrate-N in any of these wells does not necessarily reflect on current nitrate-N management strategies. Previous studies done on these wells looked at apparent groundwater age based on age dating studies. The well nests in the Dakota Sandstone and Elkhorn River alluvial aquifers had recharge dates from the early to mid-1960s and the well nest in the Platte River alluvial aquifer had recharge dates from the early to mid-1970s. These apparent ages show a considerable time lag between current nitrate-N management practices and groundwater nitrate-N concentrations.

CECs were only detected in monitoring wells from the Platte River and Elkhorn River alluvial aquifers. This demonstrates that the groundwater of the PMRNRD is affected by non-agricultural and agricultural activities. However, because only four total locations were sampled from the other three aquifers, the presence of CECs in other parts of the PMRNRD cannot be precluded.

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For more information about this publication, contact:
Director, USGS Nebraska Water Science Center
5231 South 19th Street
Lincoln, NE 68512
402–328–4100

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