Prepared in cooperation with the North Dakota Department of Health and the North Dakota State Water Commission

Modeled Sulfate Concentrations in North Dakota Streams, 1993–2008, Based on Spatial Basin Characteristics

Scientific Investigations Report 2014–5092

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

Cover photograph: Little Missouri River at Medora, North Dakota (Photograph by Dennis R. Rosenkranz, U.S. Geological Survey, 2008).

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Conversion Factors

Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
liter (L)	61.02	cubic inch (in^3)

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

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

Altitude, as used in this report, refers to distance above the vertical datum.

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Abbreviations

DEM	digital elevation model
GIS	Geographic Information System
HLSP	High-Low Flow Sampling Program
HU	hydrologic unit
LANDSAT	Land Remote Sensing Satellite images
MAP	mean annual precipitation
NDDH	North Dakota Department of Health
NDSWC	North Dakota State Water Commission
PRISM	Parameterization-Elevation Regressions on Independent Slopes Model
SCC	mean percent soil clay content
SOF	mean percent saturation overland flow
STATSGO	State Soil Geographic dataset
USGS	U.S. Geological Survey

Modeled Sulfate Concentrations in North Dakota Streams, 1993–2008, Based on Spatial Basin Characteristics

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Abstract

Sulfate concentration data collected from North Dakota streams during recent (1993–2008) years indicates generally higher sulfate concentrations across much of the State compared to concentrations during earlier years. The higher sulfate concentrations have been attributed in other studies to wetter climatic conditions, associated increases in contributing drainage areas, and rising water tables. The State's current (2013) stream classification system, which includes a standard for 30-day average sulfate concentration, is based on earlier data and thus may not reflect natural conditions for more recent years. The U.S. Geological Survey, in cooperation with the North Dakota Department of Health and the North Dakota State Water Commission, completed a study to evaluate the relation of maximum seasonal (30-day moving average) sulfate concentrations during 1993–2008 to characteristics of the contributing basins to model expected naturally-occurring sulfate concentrations in North Dakota streams.

Sulfate concentration data for 75 stream sampling sites in North Dakota were analyzed for this study. A spatial analysis was conducted with digital data using a Geographic Information System to obtain selected basin characteristics, which were in turn used as explanatory variables in a regression analysis to model the maximum seasonal (30-day moving average) sulfate concentration. Characteristics used in the regression analysis included mean annual precipitation, mean percent soil clay content, and mean percent saturation overland flow.

Modeled sulfate concentrations generally were highest (greater than 750 milligrams per liter) in basins in western North Dakota and lowest (less than 250 milligrams per liter) in basins in the upper Sheyenne River and upper James River. Area-weighted means for the basin characteristics also were computed for 10-digit and 8-digit hydrologic units for streams in North Dakota and modeled sulfate concentrations were computed from the characteristics. The resulting distribution of modeled sulfate concentrations was similar to the distribution of estimates for the 12-digit hydrologic units, but less variable because the basin characteristics were averaged over larger areas.

Introduction

Soils across North Dakota have naturally high sulfur content that readily oxidizes to highly soluble sulfate ions (Franzen, 2007). Therefore, sulfate concentrations in North Dakota streams tend to be relatively high. North Dakota water-quality standards, specifically for sulfate, are intended for the protection of municipal drinking water supplies and aquatic life (North Dakota Department of Health, 2010). The sulfate standards are 250 milligrams per liter (mg/L) (expressed as a 30-day arithmetic average) for Class I streams and 450 mg/L (expressed as a 30-day arithmetic average) for Class IA and II streams. The sulfate standard for all Class III streams in North Dakota, as well as the Sheyenne River from its headwaters to 0.1 mile downstream from Baldhill Dam (located at site 34 on fig. 1), is 750 mg/L (expressed as a 30-day arithmetic average). The standards for Class I, IA, and II streams are intended for the protection of drinking water use, whereas the 750 mg/L sulfate standard is intended to be protective of aquatic life (North Dakota Department of Health, 2010).

Recent analyses of water-quality data collected from streams in North Dakota indicated trends of increasing sulfate concentrations across the State (Galloway and others, 2012; Vecchia, 2003; Vecchia, 2005). Water-quality analysis by the North Dakota Department of Health (NDDH) also indicated that the sulfate standards have been exceeded at a number of stream water-quality monitoring locations across the State, some by an order of magnitude (Michael Ell, North Dakota Department of Health, written commun., 2013). Previous studies (Vecchia, 2005; Schuh and Hove, 2006) have indicated that the increasing sulfate concentrations probably were caused by generally wetter conditions that resulted in increases in contributing drainage areas and water tables beginning about 1993. The increasing sulfate across the State has prompted questions about whether the State's current stream classification system still appropriately reflects natural conditions. Where natural conditions cause exceedances of the existing sulfate standards, the NDDH may consider changes to the classification status of certain streams to reflect the higher sulfate concentrations.

The U.S. Geological Survey (USGS), in cooperation with the North Dakota Department of Health (NDDH) and the North Dakota State Water Commission (NDSWC), conducted a study to evaluate the relation of maximum seasonal (30-day moving average) sulfate concentrations at monitoring sites in North Dakota to characteristics of the contributing basins. Characteristics that can potentially mobilize sulfate from the soil were used to model the expected naturally-occurring sulfate concentrations in streams. These characteristics included runoff from precipitation, the presence of clay in soil (often associated with higher sulfate content; Franzen, 2007), and characteristics that reflect the interaction of the runoff water with soils in the contributing basins.

Purpose and Scope

The purpose of this report is to describe a regression analysis to provide modeled maximum seasonal (30-day moving average) sulfate concentrations for 1993–2008 in streams in North Dakota based on basin characteristics derived using spatial data on soil properties, runoff characteristics, and precipitation. Modeled sulfate concentrations will be used by the NDDH to determine if the existing classifications of streams in North Dakota are appropriate in light of the higher sulfate concentrations. Estimates of the maximum seasonal sulfate concentrations at selected sites used in the regression analyses were obtained using measured sulfate concentration data from Galloway and others (2012).

Methods

A regression model was developed from regression analysis to model maximum seasonal sulfate concentrations in basins across North Dakota from selected characteristics of the basins. Sites and associated sulfate concentration data are a subset of the sites and data presented in Galloway and others (2012). The period selected for analysis of sulfate concentrations was from 1993 through 2008. This period was selected to maximize the number of sites with a common period of record and to make the results representative of current conditions. Compared to earlier years, climatic conditions in North Dakota generally became wetter and more variable after 1993 (Hoerling and others, 2010; Vecchia, 2008), and thus streamflow and sulfate concentration data collected in the recent period are expected to better represent future conditions than streamflow and concentration data collected before 1993. Sites from Galloway and others (2012) that had at least 10 samples between 1993 and 2008 were used in the initial dataset for the regression analysis in this report. From the initial dataset, sites were further eliminated that had most of their basin located in Canada and that were located below major dams and may not reflect seasonal sulfate concentrations associated with characteristics of the upstream watersheds. Sites that may redundantly represent a large basin such as multiple sites on the Red River of the North that did not have much variation in basin size were also removed (fig. 1). The final dataset used for the regression analysis included 75 sites (table 1; figs. 1 and 2). The site identification numbers in table 1 and figs. 1 and 2 are the same as the site numbers from Galloway and others (2012). The concentration data used for this analysis are based on samples collected by the North Dakota Department of Health, North Dakota State Water Commission, and U.S. Geological Survey and are described in more detail in Galloway and others (2012). This section describes the methods used for obtaining selected basin characteristics and the statistical methods used for developing relations between basin characteristics and sulfate concentrations at the selected sites.

Spatial Data Computation

A spatial analysis was conducted with digital data using a Geographic Information System (GIS) to obtain selected basin characteristics. Characteristics from several datasets were extracted for each 12-digit Hydrologic Unit (HU) (U.S Geological Survey and others, 2012) that encompassed streams in North Dakota (fig. 2). Characteristics extracted for each HU included the mean annual precipitation (MAP), mean percent soil clay content (SCC), and mean percent saturation overland flow (SOF). A much larger set of potential basin characteristics was considered for inclusion in the regression analysis, but exploratory analysis of the larger set using the stepwise procedure from the statistical package S-Plus (TIBCO Software Inc., 2010) with the “exhaustive” option to evaluate all possible subsets of explanatory variables and determine the subsets with the smallest mean-squared errors, indicated the three selected characteristics described in this section provided the best combination of explanatory variables.

Precipitation is an important variable for evaluating sulfate concentrations because basins with higher precipitation (especially snow that produces spring snowmelt runoff) can result in more dilution of shallow groundwater runoff and hence lower sulfate concentration compared to basins with less precipitation. The mean annual precipitation (MAP) from 1981 to 2010 was obtained from Parameter-Elevation Regressions on Independent Slopes Model (PRISM) data (PRISM Climate Group, 2012). The PRISM model is an analytical model that uses point data and an underlying grid such as a digital elevation model (DEM) or a 30-year climatological average to generate gridded estimates of monthly and annual precipitation and temperature (as well as other climatic parameters). The MAP was extracted for each 12-digit HU polygon associated with streams in North Dakota and some surrounding states from an 800-meter grid of mean annual precipitation. A mean value of the grid cells that were within each HU was computed for each HU.

Soil clay content (SCC) is also an important variable for evaluating sulfate concentrations. North Dakota soils often contain gypsum (calcium carbonate) caused by the weathering of geologic materials (Franzen, 2012). Gypsum dissolved

Table 1. Selected stream sites and sulfate statistics for North Dakota from 1993 through 2008.

[USGS, U.S. Geological Survey; mg/L, milligrams per liter; —, no site identification number available because site was only monitored by the North Dakota Department of Health; NC not computed because of insufficient data; HL, selected sampling where samples are collected only 2 times a year, once during high-flow and once during low-flow conditions]

Site identification number (fig. 1)	USGS site identification number	Site name	Latitude, in decimal degrees	Longitude, in decimal degrees	Total number of sulfate samples 1993–2008[1]	Maximum seasonal sulfate concentration, in mg/L	Number of HL samples[2]	Median of HL samples, in mg/L	75th percentile of HL samples, in mg/L	90th percentile of HL samples, in mg/L
1	—	Bois De Sioux River near Doran, Minn.	46.1500	-96.5700	34	NC	13	411	599	698
7	05051600	Wild Rice River near Rutland., N. Dak.	46.0222	-97.5111	17	NC	17	640	1,000	1,324
10	05053000	Wild Rice River near Abercrombie, N. Dak.	46.4681	-96.7833	69	510	25	436	581	617
11	05054000	Red River of the North at Fargo, N. Dak.	46.8611	-96.7833	66	197	25	113	164	186
15	05054500	Sheyenne River above Harvey, N. Dak.	47.7028	-99.9486	39	NC	21	320	421	467
17	—	Sheyenne River at Warwick, N. Dak.	47.7900	-98.5800	37	NC	18	207	221	249
18	05056000	Sheyenne River near Warwick, N. Dak.	47.8056	-98.7158	46	NC	24	205	240	264
19	05056060	Mauvais Coulee Tributary No. 3 near Cando, N. Dak.	48.4575	-99.2239	16	NC	16	237	340	533
20	05056100	Mauvais Coulee near Cando, N. Dak.	48.4481	-99.1022	72	362	27	290	408	502
21	05056200	Edmore Coulee near Edmore, N. Dak.	48.3367	-98.6600	74	357	28	246	382	498
22	05056215	Edmore Coulee Tributary near Webster, N. Dak.	48.2664	-98.6806	19	NC	17	325	431	602
24	05056239	Starkweather Coulee near Webster, N. Dak.	48.3206	-98.9403	69	287	26	187	285	391
32	05057000	Sheyenne River near Cooperstown, N. Dak.	47.4328	-98.0272	99	260	27	200	234	260
33	05057200	Baldhill Creek near Dazey, N. Dak.	47.2292	-98.1244	23	NC	21	213	248	265
34	05058000	Sheyenne River below Baldhill Dam, N. Dak.	47.0339	-98.0833	94	254	28	219	258	271
36	05058700	Sheyenne River at Lisbon, N. Dak.	46.4469	-97.6789	91	287	31	270	305	336
37	05059000	Sheyenne River near Kindred, N. Dak.	46.6317	-97.0003	99	237	28	220	255	286
38	05059300	Sheyenne River above Sheyenne River diversion near Horace, N. Dak.	46.7503	-96.9264	34	NC	23	220	238	282
41	05059500	Sheyenne River at West Fargo, N. Dak.	46.8911	-96.9067	26	NC	17	215	249	276
42	05059600	Maple River near Hope, N. Dak.	47.3250	-97.7903	11	NC	11	630	951	1,060
43	05059700	Maple River near Enderlin, N. Dak.	46.6217	-97.5736	19	NC	19	490	542	549
45	05060100	Maple River below Mapleton, N. Dak.	46.9053	-97.0522	51	NC	21	410	443	599
47	05060500	Rush River at Amenia, N. Dak.	47.0167	-97.2139	22	NC	21	340	420	448
53	05064900	Beaver Creek near Finley, N. Dak.	47.5947	-97.7092	18	NC	14	415	545	730
55	05066500	Goose River at Hillsboro, N. Dak.	47.4100	-97.0600	92	527	29	441	484	520

Table 1. Selected stream sites and sulfate statistics for North Dakota from 1993 through 2008.—Continued

[USGS, U.S. Geological Survey; mg/L, milligrams per liter; —, no site identification number available because site was only monitored by the North Dakota Department of Health; NC not computed because of insufficient data; HL, selected sampling where samples are collected only 2 times a year, once during high-flow and once during low-flow conditions]

Site identification number (fig. 1)	USGS site identification number	Site name	Latitude, in decimal degrees	Longitude, in decimal degrees	Total number of sulfate samples 1993–2008[1]	Maximum seasonal sulfate concentration, in mg/L	Number of HL samples[2]	Median of HL samples, in mg/L	75th percentile of HL samples, in mg/L	90th percentile of HL samples, in mg/L
57	05082625	Turtle River at Turtle River State Park near Arvilla, N. Dak.	47.9319	-97.5142	72	247	28	228	266	374
58	05083000	Turtle River at Manvel, N. Dak.	48.0786	-97.1842	53	NC	22	429	523	670
61	05084000	Forest River near Fordville, N. Dak.	48.1972	-97.7303	24	NC	24	224	260	293
62	05085000	Forest River near Minto, N. Dak.	48.2694	-97.3694	79	286	29	230	270	298
67	05090000	Park River at Grafton, N. Dak.	48.4247	-97.4117	70	346	28	283	337	394
76	05101000	Tongue River at Akra, N. Dak.	48.7783	-97.7464	22	NC	22	98	110	138
88	05120500	Wintering River near Karlsruhe, N. Dak.	48.1383	-100.5394	28	NC	19	250	436	463
90	05123400	Willow Creek near Willow City, N. Dak.	48.5889	-100.4417	41	NC	19	283	415	578
92	05123510	Deep River near Upham, N. Dak.	48.5842	-100.8622	39	NC	18	170	256	376
101	06331000	Little Muddy River below Cow Creek near Williston, N. Dak.	48.2844	-103.5725	24	NC	19	623	665	740
106	06332515	Bear Den Creek near Mandaree, N. Dak.	47.7872	-102.7681	32	NC	21	680	780	840
108	06332523	East Fork Shell Creek near Parshall, N. Dak.	47.9486	-102.2144	37	NC	18	1,113	1,221	1,302
109	06332770	Deepwater Creek near Mandaree, N. Dak.	47.7378	-102.1072	39	NC	21	570	659	704
110	06335500	Little Missouri River at Marmarth, N. Dak.	46.2978	-103.9175	25	NC	18	509	610	761
112	06336000	Little Missouri River at Medora, N. Dak.	46.9194	-103.5278	73	795	27	593	881	1,194
113	06336600	Beaver Creek near Trotters, N. Dak.	47.1631	-103.9922	20	NC	14	1,000	1,130	1,164
114	06337000	Little Missouri River near Watford City, N. Dak.	47.5958	-103.2639	86	840	28	550	741	818
116	06339100	Knife River at Manning, N. Dak.	47.2361	-102.7694	18	NC	18	442	554	687
120	06339500	Knife River near Golden Valley, N. Dak.	47.1544	-102.0594	62	692	25	580	710	792
125	06340000	Spring Creek at Zap, N. Dak.	47.2861	-101.9253	70	600	26	496	559	608
127	06340500	Knife River at Hazen, N. Dak.	47.2853	-101.6217	93	556	28	461	550	640
135	06341410	Turtle Creek above Washburn, N. Dak.	47.3850	-100.9119	53	NC	17	290	343	514
136	06341800	Painted Woods Creek near Wilton, N. Dak.	47.2750	-100.7917	52	NC	17	660	762	796
140	06342260	Square Butte Creek below Center, N. Dak.	47.0575	-101.1953	21	NC	19	440	525	541
141	06342450	Burnt Creek near Bismarck, N. Dak.	46.9150	-100.8133	16	NC	16	350	395	470

Table 1. Selected stream sites and sulfate statistics for North Dakota from 1993 through 2008.—Continued

[USGS, U.S. Geological Survey; mg/L, milligrams per liter; —, no site identification number available because site was only monitored by the North Dakota Department of Health; NC not computed because of insufficient data; HL, selected sampling where samples are collected only 2 times a year, once during high-flow and once during low-flow conditions]

Site identification number (fig. 1)	USGS site identification number	Site name	Latitude, in decimal degrees	Longitude, in decimal degrees	Total number of sulfate samples 1993–2008[1]	Maximum seasonal sulfate concentration, in mg/L	Number of HL samples[2]	Median of HL samples, in mg/L	75th percentile of HL samples, in mg/L	90th percentile of HL samples, in mg/L
147	06344600	Green River near New Hradec, N. Dak.	47.0278	-103.0528	15	NC	15	230	290	394
149	06345500	Heart River near Richardton, N. Dak.	46.7456	-102.3083	74	630	26	514	603	754
150	06345780	Heart River above Lake Tschida near Glen Ullin, N. Dak.	46.6569	-102.0789	17	NC	17	520	620	678
152	06347500	Big Muddy Creek near Almont, N. Dak.	46.6944	-101.4669	20	NC	19	560	587	850
154	06348300	Heart River at Stark Bridge near Judson, N. Dak.	46.7033	-101.2136	18	NC	18	444	508	540
156	06349000	Heart River near Mandan, N. Dak.	46.8339	-100.9742	85	500	27	428	472	524
157	06349215	Long Lake Creek above Long Lake near Moffit, N. Dak.	46.6331	-100.2414	15	NC	15	240	260	290
158	06349500	Apple Creek near Menoken, N. Dak.	46.7944	-100.6569	21	NC	19	416	520	560
162	06350000	Cannonball River at Regent, N. Dak.	46.4267	-102.5514	17	NC	17	727	768	1,040
164	06351200	Cannonball River near Raleigh, N. Dak.	46.1269	-101.3328	64	805	28	650	736	1,136
166	06352000	Cedar Creek near Haynes, N. Dak.	46.1553	-102.4753	19	NC	19	696	965	1,100
169	06353000	Cedar Creek near Raleigh, N. Dak.	46.0917	-101.3333	65	787	27	550	777	1,154
170	06354000	Cannonball River at Breien, N. Dak.	46.3761	-100.9344	73	619	27	471	634	785
172	06354580	Beaver Creek below Linton, N. Dak.	46.2686	-100.2514	21	NC	21	260	290	303
173	06354815	Porcupine Creek near Fort Yates, N. Dak.	46.1933	-100.7514	29	NC	12	286	318	349
175	06467600	James River near Manfred, N. Dak.	47.6444	-99.8278	17	NC	6	174	184	208
176	06468170	James River near Grace City, N. Dak.	47.5581	-98.8625	79	281	27	191	245	314
177	06468250	James River above Arrowwood Lake near Kensal, N. Dak.	47.3997	-98.7972	106	232	28	189	229	264
179	06468500	James River near Pingree, N. Dak.	47.1417	-98.7833	80	271	26	213	239	283
180	06469400	Pipestem Creek near Pingree, N. Dak.	47.1675	-98.9686	32	NC	21	298	353	387
182	06470000	James River at Jamestown, N. Dak.	46.8897	-98.6817	92	238	25	240	306	341
183	06470500	James River at Lamoure, N. Dak.	46.3556	-98.3042	89	224	27	240	295	331
184	06470800	Bear Creek near Oakes, N. Dak.	46.2253	-98.0714	29	NC	23	370	479	508
185	06470830	James River at Oakes, N. Dak.	46.1389	-98.1153	22	NC	8	236	274	298
186	06470878	James River at N. Dak.-S. Dak. State Line	45.9364	-98.1739	17	NC	11	298	320	390

[1]Excluding samples collected in winter months (November–February).

[2]Samples collected about April 15 and August 15 (high/low samples).

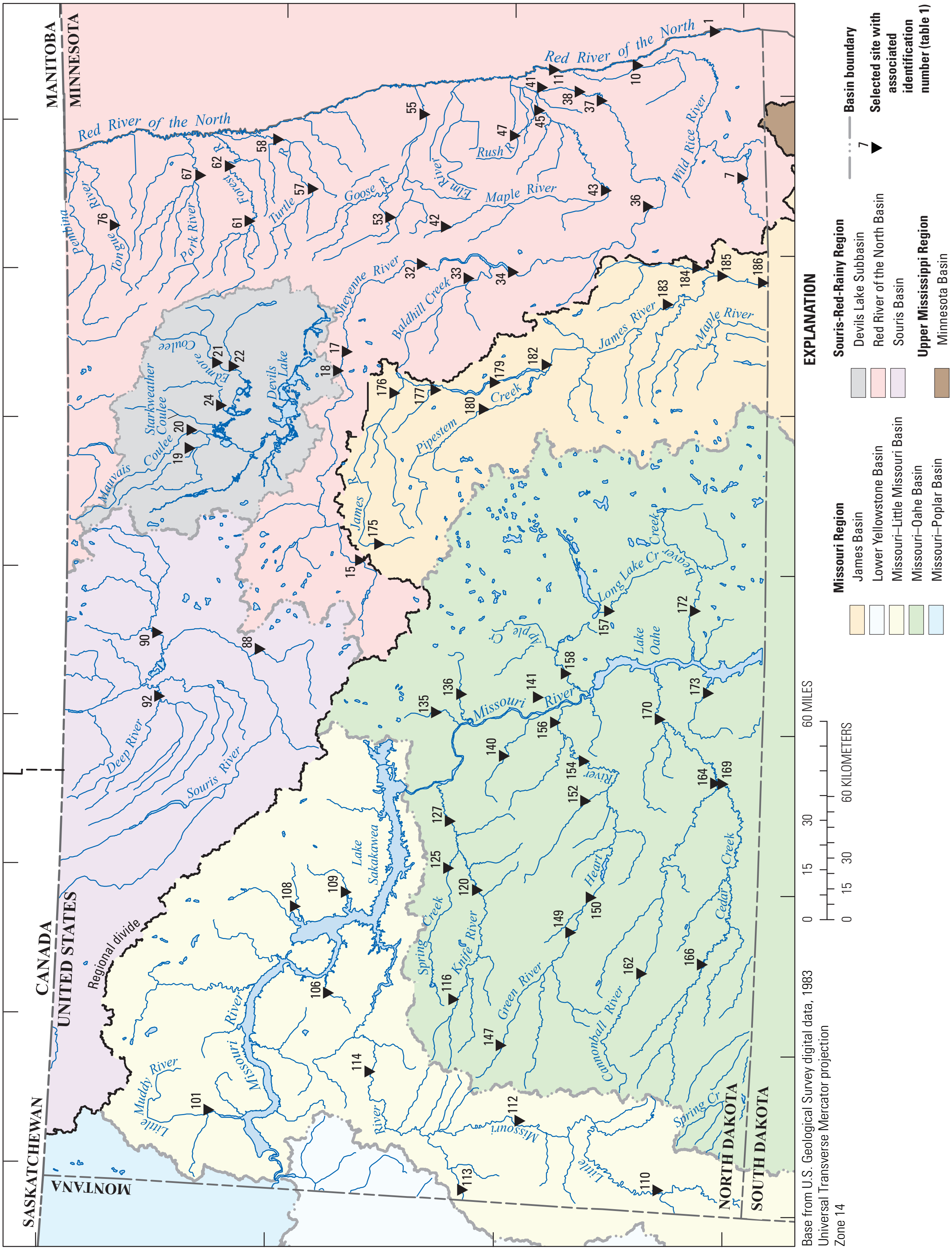

Figure 1. Locations of selected sites in North Dakota.

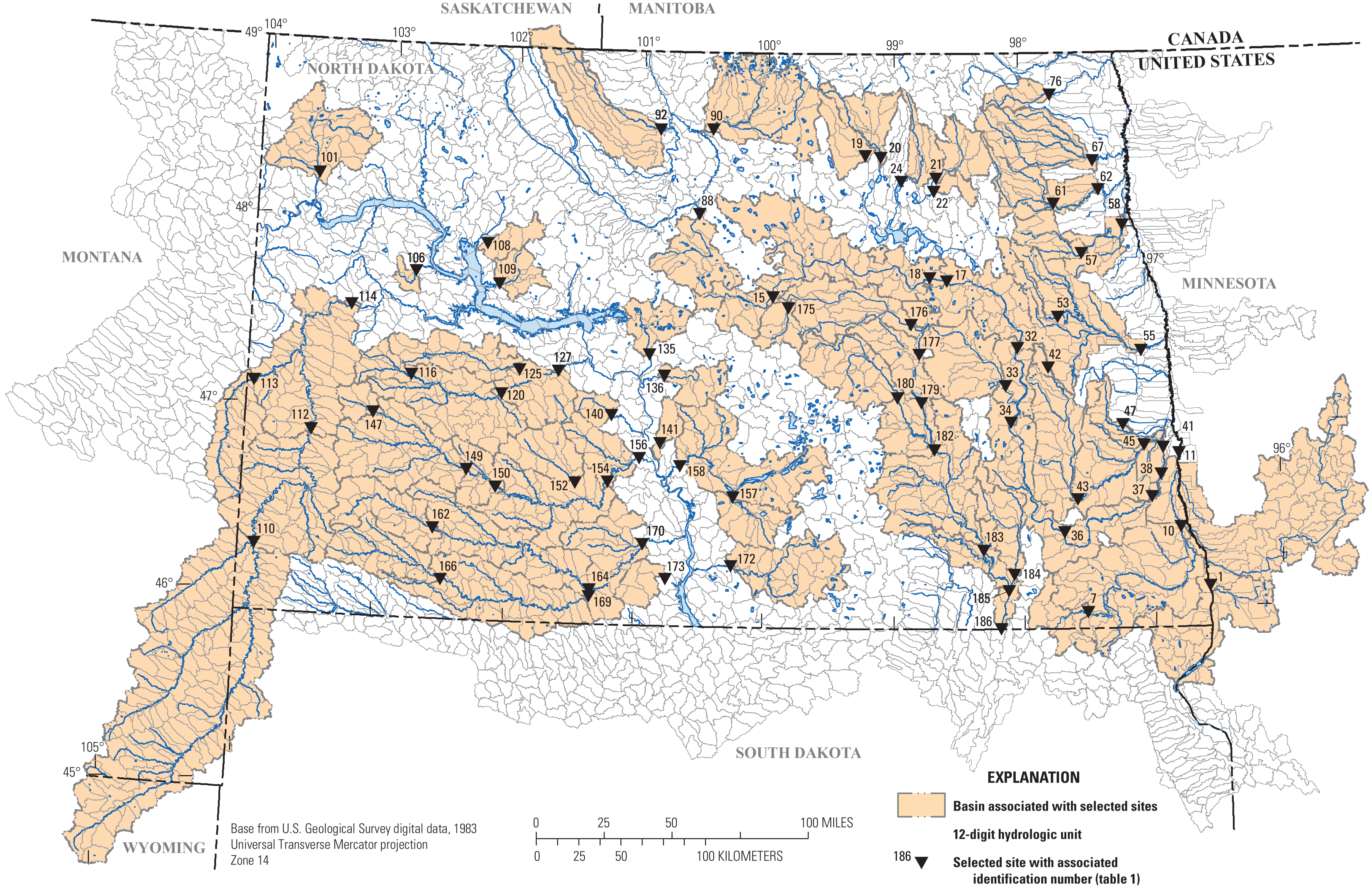

Figure 2. Contributing basins for selected sites in North Dakota.

in water can return to the surface more readily in soils with greater clay content than in soils with greater sand content because of capillary rise, resulting in accumulation of gypsum near the soil surface (Franzen, 2012). In addition, soil clays will attract positively charged calcium ions and allow negatively charged sulfate ions to remain in solution (Rehm, 2002). The sulfate can then be washed off during rainfall events leading to potentially higher stream concentrations. The percent SCC was obtained from the U.S. General Soil Map (U.S. Department of Agriculture, 2006). The U.S. General Soil Map dataset consists of general soil association units developed by the National Cooperative Soil Survey and supersedes the State Soil Geographic (STATSGO) dataset published in 1994 (U.S. Department of Agriculture, 2006). The dataset was created by generalizing more detailed soil survey maps. Where more detailed soil survey maps were not available, data on geology, topography, vegetation, and climate were assembled together with Land Remote Sensing Satellite (LANDSAT) images (U.S. Department of Agriculture, 2006). The U.S. General Soil Map dataset consists of georeferenced vector digital data and tabular digital data. The soil map units are linked to attributes in the National Soil Information System database (U.S. Department of Agriculture, 2006), which give the proportionate extent of the component soils and their properties. The mean percent SCC (coded in the U.S. General Soil Map dataset as the representative value) was computed for each HU in GIS by using an area-weighted-mean value based on the area of each soil unit that was located within each HU. The percent SCC is described as “mineral particles less than 0.002 millimeter (mm) in equivalent diameter as a weight percentage of the less than 2.0 mm fraction” (U.S. Department of Agriculture, 2006).

Saturation overland flow (SOF) is a measure of the amount of runoff that comes from shallow groundwater sources rather than from excess precipitation runoff. Therefore, runoff from basins with high SOF would be expected to have more contact with shallow soils and hence higher sulfate concentration than would runoff from basins with low SOF. The percent SOF was obtained from digital datasets described in Wolock (2003a and 2003b). The SOF was estimated for the conterminous United States using the watershed model TOPMODEL (Beven and Kirkby, 1979). TOPMODEL simulates the movement of water through a watershed from the time that it enters the watershed as precipitation to the time that it exits the watershed as streamflow. TOPMODEL predicts streamflow, estimates overland and subsurface flow, and estimates the depth to the water table. The SOF is calculated from the areal extent of the saturated land-surface area and the precipitation intensity. Subsurface flow is computed as a function of the maximum subsurface-flow rate (determined by topography and soil characteristics) and the watershed average depth to the water table. The watershed average depth to the water table is computed by water balance; that is, by tracking input (precipitation) and output (overland flow, subsurface flow, and evapotranspiration) (Wolock, 2003a and 2003b). The TOPMODEL was applied to a grid with a 5-by-5 kilometer cell size for the conterminous United States. The mean SOF was extracted from the grid for each 12-digit HU polygon associated with streams in North Dakota and some surrounding states.

For the regression analysis, a single value for each characteristic was needed for each site that had associated sulfate data. For each site, all of the 12-digit HUs upstream from the site were combined and an area-weighted mean based on the area of each 12-digit HU was computed for the MAP, mean percent SCC, and percent SOF for the basin upstream from the site. If a site was not located on a HU boundary, and located somewhere within the most downstream HU, the most downstream HU may or may not have been selected to include in the combined basin. For example, if a site was located closer to the upstream boundary of its most downstream 12-digit HU, the HU was not included. However, if a site was located closer to the downstream boundary of its most downstream HU, then the HU was included. Because the exact drainage area for each site was not delineated, the published drainage area for each site (U.S. Geological Survey, 2013) may not match exactly to the drainage area computed for the analysis in this report (fig. 2, table 2). Also, 12-digit HUs that were denoted in the GIS data file to be closed basins (basins that have no defined outflow) were not included in the accumulated basins, and may, therefore, create differences between the published drainage area and the computed drainage area.

Statistical Analysis

The sulfate standards for various stream classifications for North Dakota, as determined by the NDDH, are based on a 30-day average concentration (North Dakota Department of Health, 2010). However, the sulfate data used in this analysis consists of samples collected on discrete days and the number and timing of the concentration samples within each year varied widely among sites. This variability required different statistical analyses depending upon the number of samples at a site. As indicated earlier, the concentration data used for this analysis are based on samples collected by the NDDH, NDSWC, and USGS as part of various sampling programs described in more detail in Galloway and others (2012). For example, some of the sites given in table 1, such as site 11 (Red River of the North at Fargo, N.Dak.), were part of the NDDH Ambient Water-Quality Network (hereafter referred to as the ambient network) and were sampled eight times per year whereas other sites, such as site 7 (Wild Rice River near Rutland, N.Dak.), were part of the NDSWC High-Low Flow Sampling Program (HLSP) and were sampled twice per year during a high-flow period (usually in April) and a low-flow period (usually in August) (Galloway and others, 2012).

For sites with sufficient number of samples, the maximum 30-day moving average sulfate concentration, hereafter called the maximum seasonal sulfate concentration, was estimated in the following manner. First, winter (November through February) samples were excluded so that the

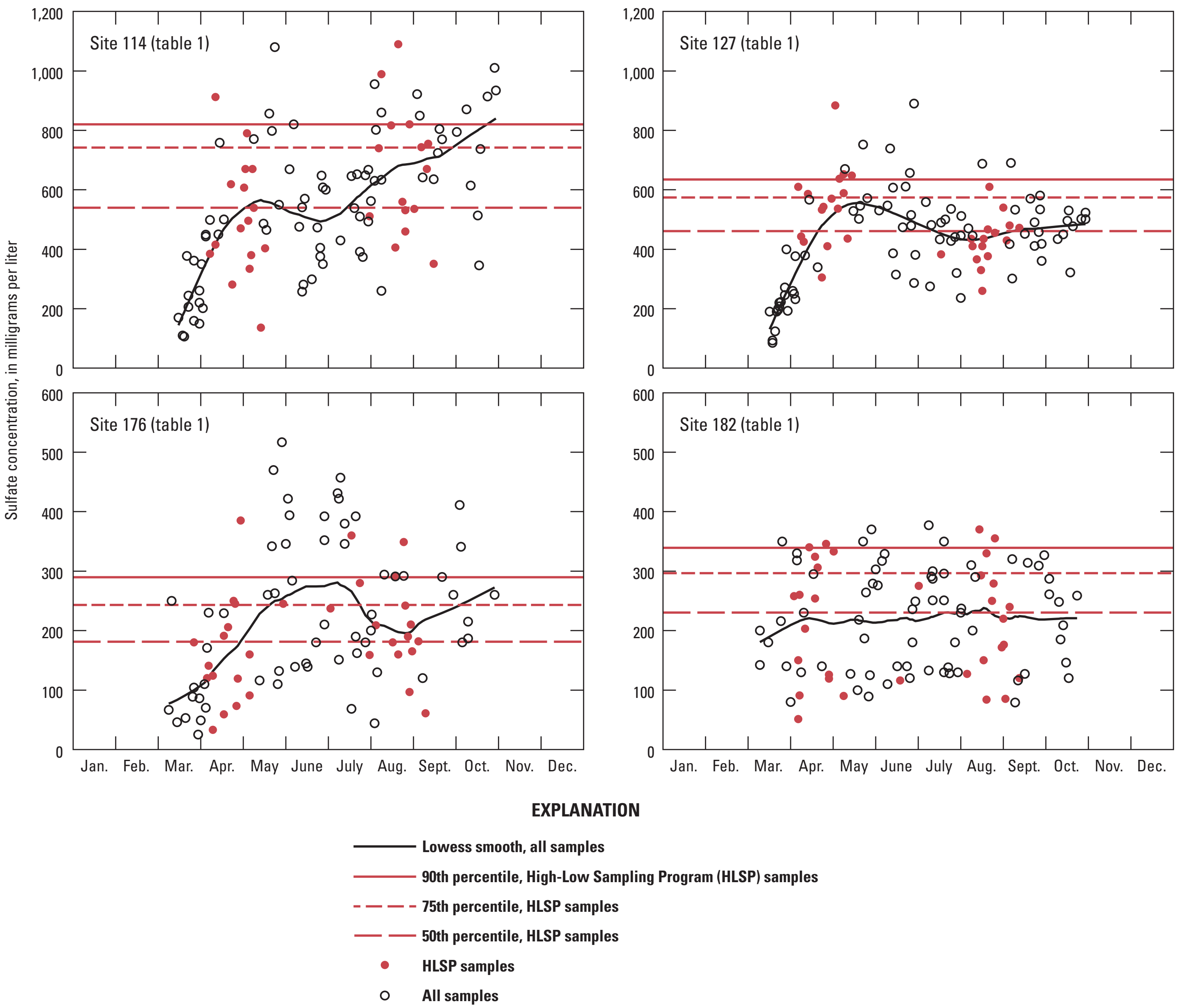

Figure 3. Comparison of sulfate concentrations and time of year for selected sites for 1993–2008.

concentrations represented open-water conditions. Then, if there were at least 60 samples during the remaining period (March through October), a continuous curve was fitted to the concentrations using the nonparametric smoothing procedure known as lowess (locally weighted scatterplot smoother) from the statistical package S-Plus (TIBCO Software Inc., 2010). The maximum value attained by the continuous curve was used as the estimate of the maximum seasonal sulfate concentration. Examples of this procedure for several sites are shown in figure 3. For site 114, the maximum seasonal concentration was about 800 mg/L and was attained in mid-October. For the remaining sites in figure 3 the maximum seasonal concentrations were about 556 mg/L (site 127, early May), about 281 mg/L (site 176, early July), and about 238 mg/L (site 182, mid-August). The maximum seasonal concentrations were determined in this manner for 28 of the sites that had at least 60 samples during March through October (table 1).

To allow for consistent estimation of the maximum seasonal concentration for all 75 sites, including the less frequently sampled HLSP sites, percentiles of the HLSP samples were computed and compared with the maximum seasonal concentrations for the sites with sufficient data to apply the previously described smoothing procedure. To simulate HLSP sampling, in each year, only the concentration samples nearest to April 15 (high flow) and August 15 (low flow) were selected. The selected HLSP samples for the example sites are shown in figure 3 as red points. The 50th, 75th, and 90th percentiles of the HLSP samples were compared with the estimated maximum seasonal concentrations described previously. For sites 114 and 176 (fig. 3), the 90th percentile of the HLSP

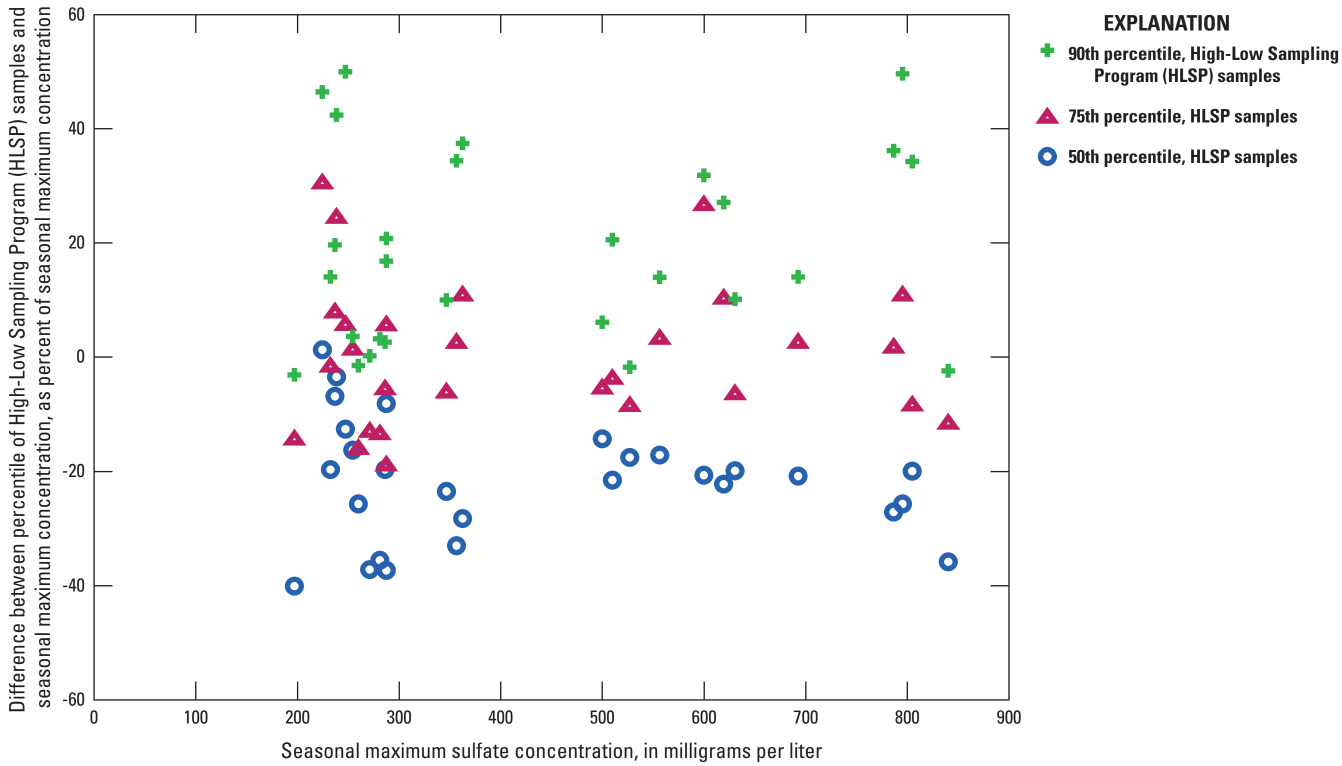

Figure 4. Relative percent difference between sulfate concentration percentiles for High-Low Sampling Program (HLSP) samples and maximum seasonal sulfate concentration for sites with sufficient samples to estimate maximum seasonal concentration.

samples was closest to the maximum seasonal concentration; for site 127 the 75th percentile was closest; and for site 182 the 50th percentile was closest. The relative percent difference between the HLSP sample concentration percentiles and the maximum seasonal concentration (expressed as a percent of the maximum seasonal concentration) for each of the 28 sites for which the lowess smoothing procedure was applied is shown in figure 4. For 21 of the 28 sites (including sites 114 and 127, fig. 3), the 75th percentile was within plus or minus 15 percent of the maximum seasonal concentration and for the remaining sites (including sites 176 and 182, fig. 3) the 75th percentile was within 30 percent greater to 20 percent less than the maximum seasonal concentration. For the 90th percentile, most (23 of 28) sites were between 0 and 60 percent greater than the maximum seasonal concentration and for the 50th percentile, most (27 of 28) sites were between 0 and 40 percent less than the maximum seasonal concentration. Based on this analysis, the 75th percentile of the selected samples used to simulate HLSP samples was selected as the estimate of the maximum seasonal concentration and was used in the regression analysis described in the "Modeled Sulfate Concentrations in North Dakota" section. The percentiles of the selected HLSP samples for all of the sites are given in table 1.

The modeled sulfate concentration described in the "Modeled Sulfate Concentrations in North Dakota" section was obtained using ordinary least-squares regression (Helsel and Hirsch, 1995) with the 75th percentile of the selected HLSP samples as the dependent variable and the three spatial variables described previously (MAP, percent SCC, and percent SOF) as the explanatory variables.

Modeled Sulfate Concentrations in North Dakota

As described in the "Methods" section, MAP, percent SCC, and percent SOF were extracted for all of the 12-digit HUs for associated streams in North Dakota and surrounding States and weighted averages of these variables computed for the basins associated with the selected stream sites (table 2). The MAP (1981 to 2010) generally increased from west to east across North Dakota and ranged from 306 to 668 mm (fig. 5). The SCC was variable, although most of the lower values were distributed in a linear pattern running from the northwest to the south-central part of the state. The highest SCC values were distributed along the Red River of the North (eastern border of North Dakota) and in the far southern parts of the Little Missouri River Basin in Wyoming and in basins draining to Lake Oahe (Missouri River) in north-central South Dakota (figs. 1, 2, and 5). Values ranged from 0 to 55 percent SCC. The distribution of SOF generally had the lowest values in a horseshoe shape from north-central and northwestern North Dakota, extending south through eastern Montana and

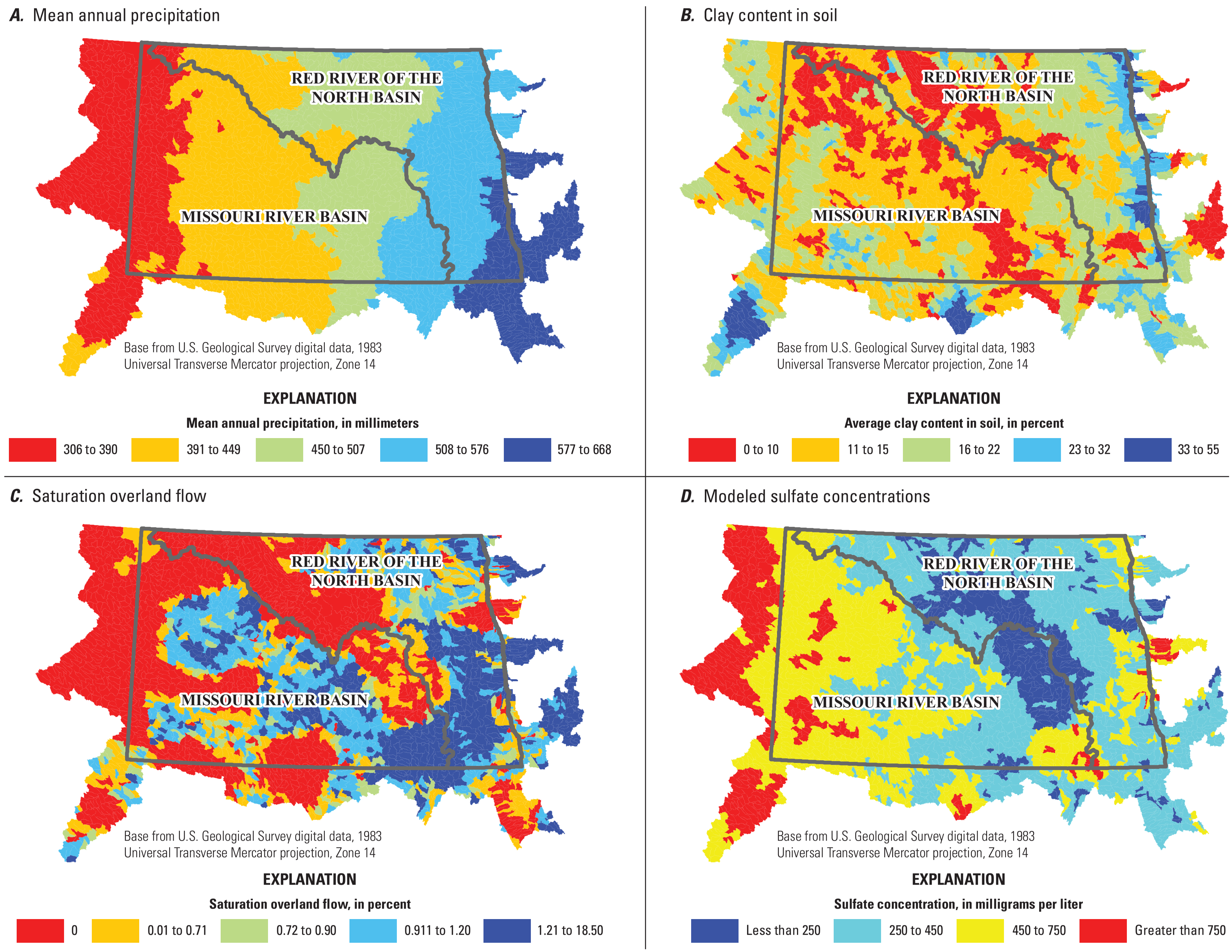

Figure 5. Mean annual precipitation (1981–2010), mean percent soil clay content, mean percent saturation overland flow, and modeled maximum seasonal sulfate concentrations for 12-digit hydrologic units in North Dakota and parts of surrounding states.

Table 2. Basin characteristics, and estimated and modeled maximum seasonal sulfate concentration for selected sites in North Dakota.

[USGS, U.S. Geological Survey; —, no site identification number available because site was only monitored by the North Dakota Department of Health; HU, hydrologic unit; km^2, square kilometers; mm, millimeters; mg/L, milligrams per liter]

Site identification number (fig. 1)	USGS site identification number	Site name	Computed drainage area of contributing HUs upstream of site, in km^2	Mean clay content of soils in HUs upstream of site, in percent	Mean saturation overland flow in HUs upstream of site, in percent	Mean annual precipitation (1981–2010), in mm	Estimated maximum seasonal sulfate concentration, in mg/L	Modeled maximum seasonal sulfate concentration, in mg/L
1	—	Bois De Sioux River near Doran, Minn.	2,616	22.9	0.7	618	599	375
7	05051600	Wild Rice River near Rutland, N. Dak.	875	20.6	2.6	576	1,000	627
10	05053000	Wild Rice River near Abercrombie, N. Dak.	4,965	22.2	1.4	585	581	470
11	05054000	Red River of the North at Fargo, N. Dak.	17,599	20.6	0.2	617	164	275
15	05054500	Sheyenne River above Harvey, N. Dak.	919	16.9	0.0	439	421	374
17	—	Sheyenne River at Warwick, N. Dak.	4,507	15.0	0.1	467	221	234
18	05056000	Sheyenne River near Warwick, N. Dak.	4,571	15.0	0.1	466	240	239
19	05056060	Mauvais Coulee Tributary No. 3 near Cando, N. Dak.	730	19.5	0.7	477	340	336
20	05056100	Mauvais Coulee near Cando, N. Dak.	931	18.3	0.9	480	408	352
21	05056200	Edmore Coulee near Edmore, N. Dak.	819	21.7	1.1	498	382	420
22	05056215	Edmore Coulee Tributary near Webster, N. Dak.	244	21.0	0.7	499	431	353
24	05056239	Starkweather Coulee near Webster, N. Dak.	668	22.0	1.0	491	285	409
32	05057000	Sheyenne River near Cooperstown, N. Dak.	6,532	15.6	0.5	486	234	262
33	05057200	Baldhill Creek near Dazey, N. Dak.	1,714	17.7	0.2	514	248	242
34	05058000	Sheyenne River below Baldhill Dam, N. Dak.	9,110	16.5	0.5	495	258	272
36	05058700	Sheyenne River at Lisbon, N. Dak.	10,696	17.1	0.5	500	305	279

Table 2. Basin characteristics, and estimated and modeled maximum seasonal sulfate concentration for selected sites in North Dakota.—Continued

[USGS, U.S. Geological Survey; —, no site identification number available because site was only monitored by the North Dakota Department of Health; HU, hydrologic unit; km², square kilometers; mm, millimeters; mg/L, milligrams per liter]

Site identification number (fig. 1)	USGS site identification number	Site name	Computed drainage area of contributing HUs upstream of site, in km^2	Mean clay content of soils in HUs upstream of site, in percent	Mean saturation overland flow in HUs upstream of site, in percent	Mean annual precipitation (1981–2010), in mm	Estimated maximum seasonal sulfate concentration, in mg/L	Modeled maximum seasonal sulfate concentration, in mg/L
37	05059000	Sheyenne River near Kindred, N. Dak.	11,986	16.8	0.7	507	255	305
38	05059300	Sheyenne River above Sheyenne River diversion near Horace, N. Dak.	12,051	16.9	0.7	507	238	306
41	05059500	Sheyenne River at West Fargo, N. Dak.	12,252	17.3	0.7	509	249	311
42	05059600	Maple River near Hope, N. Dak.	134	20.5	1.5	537	951	465
43	05059700	Maple River near Enderlin, N. Dak.	2,145	21.4	1.5	538	542	475
45	05060100	Maple River below Mapleton, N. Dak.	3,744	22.9	1.6	550	443	507
47	05060500	Rush River at Amenia, N. Dak.	338	23.4	2.1	562	420	586
53	05064900	Beaver Creek near Finley, N. Dak.	366	22.0	1.1	532	545	423
55	05066500	Goose River at Hillsboro, N. Dak.	3,170	21.0	1.5	547	484	471
57	05082625	Turtle River at Turtle River State Park near Arvilla, N. Dak.	735	25.5	0.6	520	266	390
58	05083000	Turtle River at Manvel, N. Dak.	1,498	25.4	0.3	526	523	345
61	05084000	Forest River near Fordville, N. Dak.	891	19.2	0.9	510	260	362
62	05085000	Forest River near Minto, N. Dak.	1,391	19.9	0.9	512	270	370
67	05090000	Park River at Grafton, N. Dak.	1,848	24.1	0.6	519	337	374
76	05101000	Tongue River at Akra, N. Dak.	457	27.0	0.8	522	110	437
88	05120500	Wintering River near Karlsruhe, N. Dak.	905	17.0	0.0	448	436	332
90	05123400	Willow Creek near Willow City, N. Dak.	2,707	19.9	0.9	474	415	375
92	05123510	Deep River near Upham, N. Dak.	2,204	15.0	0.1	445	256	338

Table 2. Basin characteristics, and estimated and modeled maximum seasonal sulfate concentration for selected sites in North Dakota.—Continued

[USGS, U.S. Geological Survey; —, no site identification number available because site was only monitored by the North Dakota Department of Health; HU, hydrologic unit; km^2, square kilometers; mm, millimeters; mg/L, milligrams per liter]

Site identification number (fig. 1)	USGS site identification number	Site name	Computed drainage area of contributing HUs upstream of site, in km^2	Mean clay content of soils in HUs upstream of site, in percent	Mean saturation overland flow in HUs upstream of site, in percent	Mean annual precipitation (1981–2010), in mm	Estimated maximum seasonal sulfate concentration, in mg/L	Modeled maximum seasonal sulfate concentration, in mg/L
101	06331000	Little Muddy River below Cow Creek near Williston, N. Dak.	1,773	17.8	0.0	377	665	677
106	06332515	Bear Den Creek near Mandaree, N. Dak.	185	20.7	1.1	410	780	716
108	06332523	East Fork Shell Creek near Parshall, N. Dak.	472	17.9	2.2	412	1,221	836
109	06332770	Deepwater Creek near Mandaree, N. Dak.	529	17.1	1.2	419	659	647
110	06335500	Little Missouri River at Marmarth, N. Dak.	12,694	29.5	0.4	381	610	851
112	06336000	Little Missouri River at Medora, N. Dak.	16,656	27.1	0.4	377	881	843
113	06336600	Beaver Creek near Trotters, N. Dak.	1,566	21.8	0.0	371	1,130	752
114	06337000	Little Missouri River near Watford City, N. Dak.	22,092	25.7	0.3	375	741	821
116	06339100	Knife River at Manning, N. Dak.	529	18.4	0.9	394	554	736
120	06339500	Knife River near Golden Valley, N. Dak.	3,136	19.4	0.4	409	710	603
125	06340000	Spring Creek at Zap, N. Dak.	1,325	17.4	2.8	419	559	885
127	06340500	Knife River at Hazen, N. Dak.	5,868	18.3	0.9	415	550	635
135	06341410	Turtle Creek above Washburn, N. Dak.	813	16.9	0.9	441	343	496
136	06341800	Painted Woods Creek near Wilton, N. Dak.	544	18.4	0.9	456	762	443
140	06342260	Square Butte Creek below Center, N. Dak.	372	16.8	1.0	444	525	496
141	06342450	Burnt Creek near Bismarck, N. Dak.	332	16.9	1.1	458	395	445
147	06344600	Green River near New Hradec, N. Dak.	441	19.9	0.0	401	290	588

Table 2. Basin characteristics, and estimated and modeled maximum seasonal sulfate concentration for selected sites in North Dakota.—Continued

[USGS, U.S. Geological Survey; —, no site identification number available because site was only monitored by the North Dakota Department of Health; HU, hydrologic unit; km², square kilometers; mm, millimeters; mg/L, milligrams per liter]

Site identification number (fig. 1)	USGS site identification number	Site name	Computed drainage area of contributing HUs upstream of site, in km²	Mean clay content of soils in HUs upstream of site, in percent	Mean saturation overland flow in HUs upstream of site, in percent	Mean annual precipitation (1981–2010), in mm	Estimated maximum seasonal sulfate concentration, in mg/L	Modeled maximum seasonal sulfate concentration, in mg/L
149	06345500	Heart River near Richardton, N. Dak.	3,243	20.1	0.1	410	603	562
150	06345780	Heart River above Lake Tschida near Glen Ullin, N. Dak.	4,007	20.1	0.1	413	620	548
152	06347500	Big Muddy Creek near Almont, N. Dak.	1,110	20.1	0.4	433	587	497
154	06348300	Heart River at Stark Bridge near Judson, N. Dak.	7,513	20.1	0.3	420	508	544
156	06349000	Heart River near Mandan, N. Dak.	8,479	20.1	0.4	422	472	550
157	06349215	Long Lake Creek above Long Lake near Moffit, N. Dak.	802	17.9	1.1	463	260	433
158	06349500	Apple Creek near Menoken, N. Dak.	3,731	16.7	1.2	466	520	420
162	06350000	Cannonball River at Regent, N. Dak.	1,541	23.6	0.9	393	768	800
164	06351200	Cannonball River near Raleigh, N. Dak.	4,300	23.0	0.7	408	736	693
166	06352000	Cedar Creek near Haynes, N. Dak.	1,445	22.2	0.6	393	965	740
169	06353000	Cedar Creek near Raleigh, N. Dak.	4,514	22.7	0.5	406	777	670
170	06354000	Cannonball River at Breien, N. Dak.	10,666	22.3	0.6	411	634	656
172	06354580	Beaver Creek below Linton, N. Dak.	1,991	17.8	1.0	478	290	361
173	06354815	Porcupine Creek near Fort Yates, N. Dak.	544	16.8	0.0	434	318	396
175	06467600	James River near Manfred, N. Dak.	588	17.1	0.1	459	184	296
176	06468170	James River near Grace City, N. Dak.	2,364	15.4	0.2	474	245	220

Table 2. Basin characteristics, and estimated and modeled maximum seasonal sulfate concentration for selected sites in North Dakota.—Continued

[USGS, U.S. Geological Survey; —, no site identification number available because site was only monitored by the North Dakota Department of Health; HU, hydrologic unit; km^2, square kilometers; mm, millimeters; mg/L, milligrams per liter]

Site identification number (fig. 1)	USGS site identification number	Site name	Computed drainage area of contributing HUs upstream of site, in km^2	Mean clay content of soils in HUs upstream of site, in percent	Mean saturation overland flow in HUs upstream of site, in percent	Mean annual precipitation (1981–2010), in mm	Estimated maximum seasonal sulfate concentration, in mg/L	Modeled maximum seasonal sulfate concentration, in mg/L
177	06468250	James River above Arrowwood Lake near Kensal, N. Dak.	2,683	15.4	0.2	479	229	216
179	06468500	James River near Pingree, N. Dak.	3,816	16.0	0.2	483	239	223
180	06469400	Pipestem Creek near Pingree, N. Dak.	1,703	17.9	0.0	489	353	215
182	06470000	James River at Jamestown, N. Dak.	6,568	17.2	0.1	486	306	222
183	06470500	James River at Lamoure, N. Dak.	9,431	17.9	0.2	499	295	244
184	06470800	Bear Creek near Oakes, N. Dak.	955	20.8	2.0	538	479	542
185	06470830	James River at Oakes, N. Dak.	11,377	18.2	0.5	505	274	292
186	06470878	James River at N. Dak.–S. Dak. State Line	11,643	18.3	0.6	506	320	308

western North Dakota, and then extending into south-central North Dakota and north-central South Dakota. The highest values were in an inverted horseshoe shape from west-central to southeastern North Dakota and then extending north (fig. 5). Values of SOF ranged from 0 to 18.5 percent.

Ordinary least-squares regression was used to model estimated maximum seasonal sulfate concentration (represented by the 75th percentile of the selected HLSP sample concentrations, as described in the "Methods" section) as a function of basin characteristics. The regression model was fitted using data for the 75 selected sites (table 2). The fitted regression model is given by

$$MSC_B = 10.0 + 146.7\ SOF_B + 11.4\ SCC_B + 4.7\ [475 - MAP_B]_+ \quad (1)$$

where

MSC	is the modeled sulfate concentration, in milligrams per liter;
SOF	is the saturation overland flow, in percent;
SCC	is the soil clay content, in percent;
MAP	is mean annual precipitation (1981–2010), in millimeters;
subscript *B*	denotes the area-weighted average over HU's in a particular basin, and
$[\ldots]_+$	is the quantity in brackets if the quantity is positive and zero otherwise.

Equation 1 indicates that MSC increases by 146.7 mg/L per 1-percent increase in SOF, 11.4 mg/L per 1-percent increase in SCC, and 4.7 mg/L per 1 millimeter (mm) decrease in MAP for MAP below 475 mm. In the wetter part of the State, where MAP is greater than 475 mm (covering about the eastern 1/3 of the State, fig. 5), MSC does not vary with MAP. In the drier part of the State, precipitation is an important factor for MSC. Each of the coefficients for the explanatory variables was highly significant (*p*-values less than 0.001) and the direction of the relations between MSC and each of the explanatory variables was consistent with physical expectations (see "Spatial Data Computation" section). The comparison of modeled to estimated sulfate concentrations for the selected sites are shown in figure 6. The coefficient of determination was 80 percent and there was no obvious lack of model fit. Plots showing the comparison of residuals to the modeled concentrations and the explanatory variables (fig. 7) indicated an adequate model fit in all cases (random pattern of the residuals). Comparison of residuals to longitude and latitude of the centroid of the contributing basins for each site (fig. 7) did not indicate any obvious spatial patterns in the residuals.

Although equation 1 is expressed in terms of average values of each variable for a given basin, note that it is assumed to be valid for basins consisting of a single HU, and thus equation 1 can be used to compute modeled sulfate concentrations for each HU for mapping purposes (fig. 5).

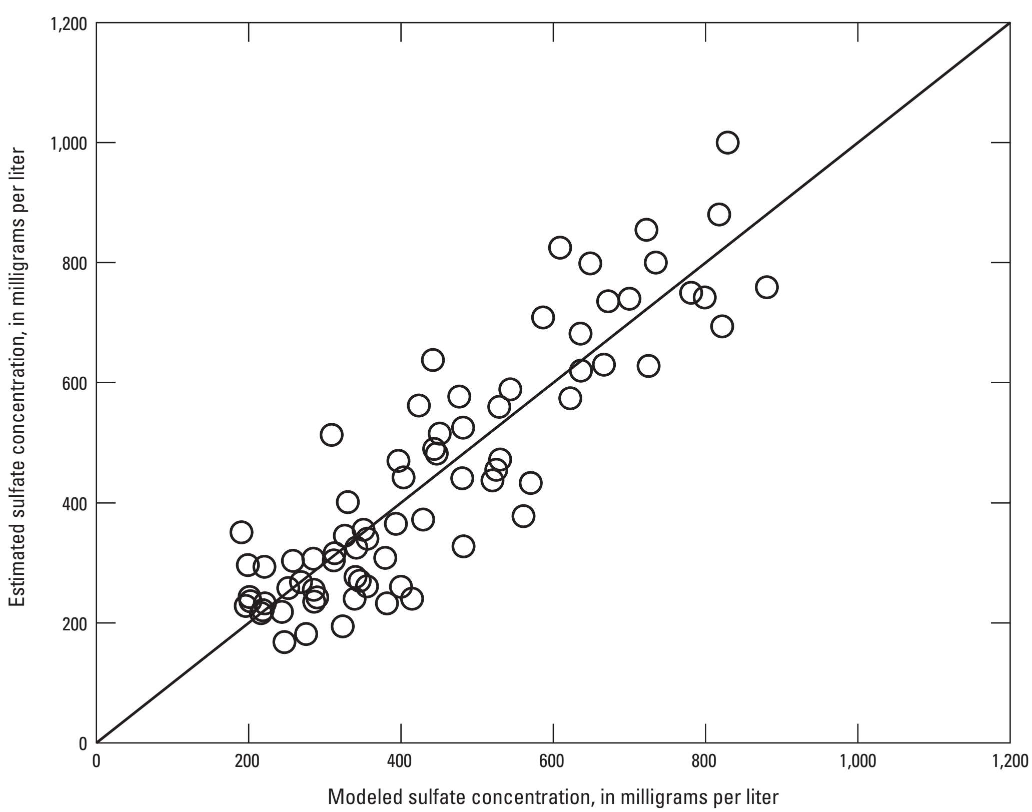

Figure 6. Comparison of modeled to estimated maximum seasonal sulfate concentrations for selected sites in North Dakota.

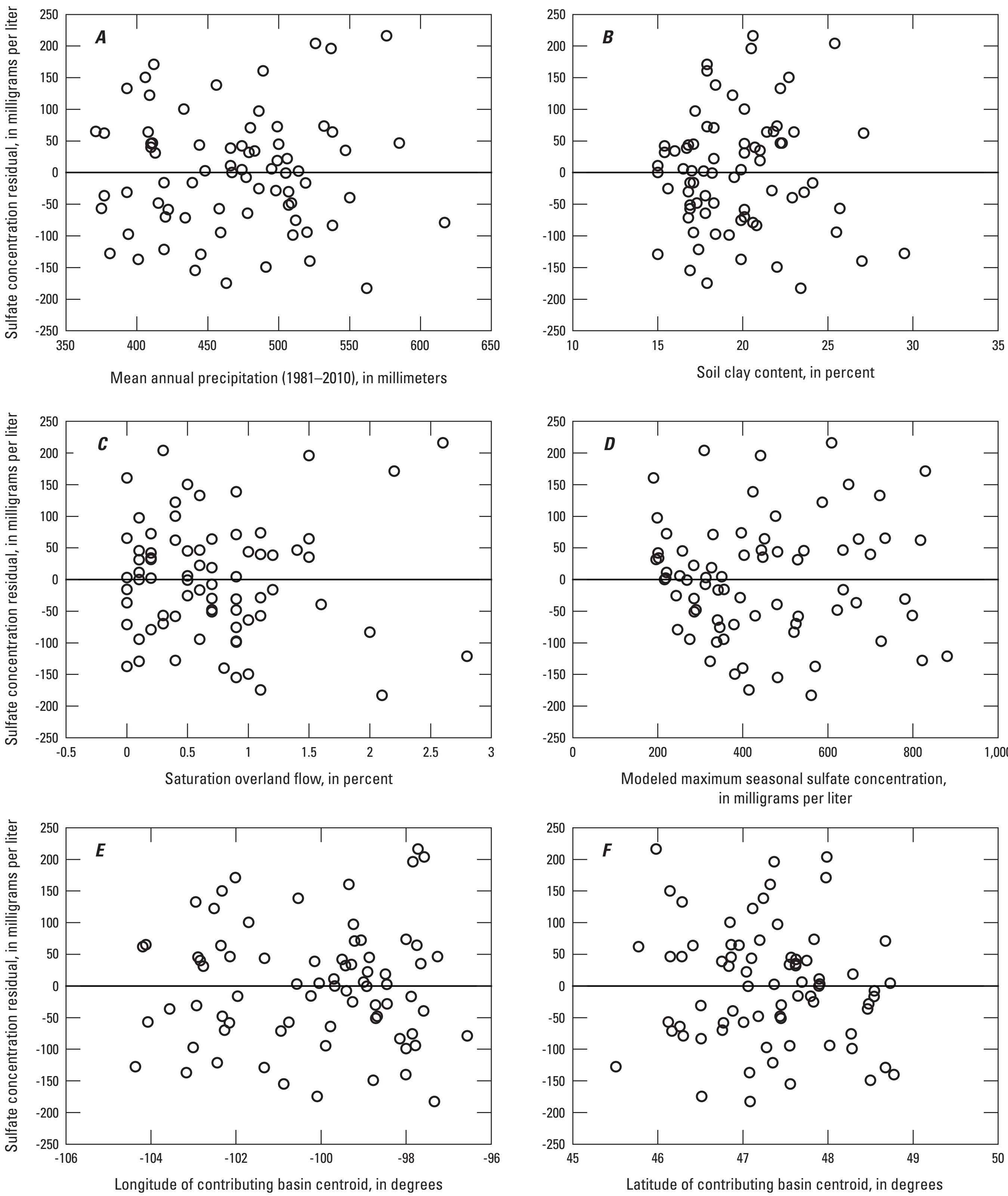

Figure 7. Comparison of sulfate concentration residuals to modeled concentrations and basin characteristics for selected sites in North Dakota. *A*, mean annual precipitation, 1981–2010; *B*, soil clay content; *C*, saturation overland flow; *D*, modeled maximum seasonal sulfate concentration; *E*, longitude of contributing basin centroid; and *F*, latitude of contributing basin centroid.

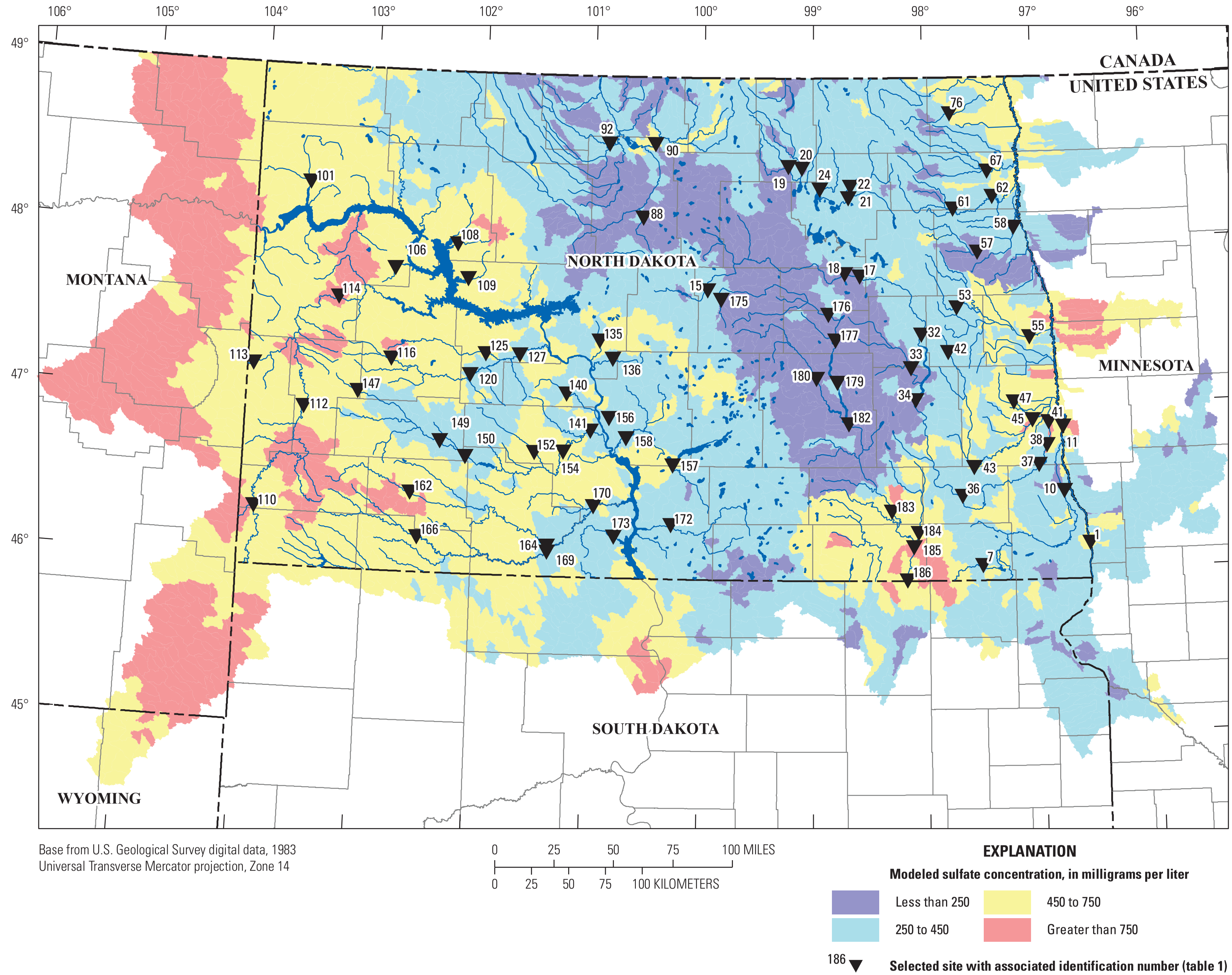

Figure 8. Modeled sulfate concentrations for 12-digit hydrologic units in North Dakota and parts of surrounding states.

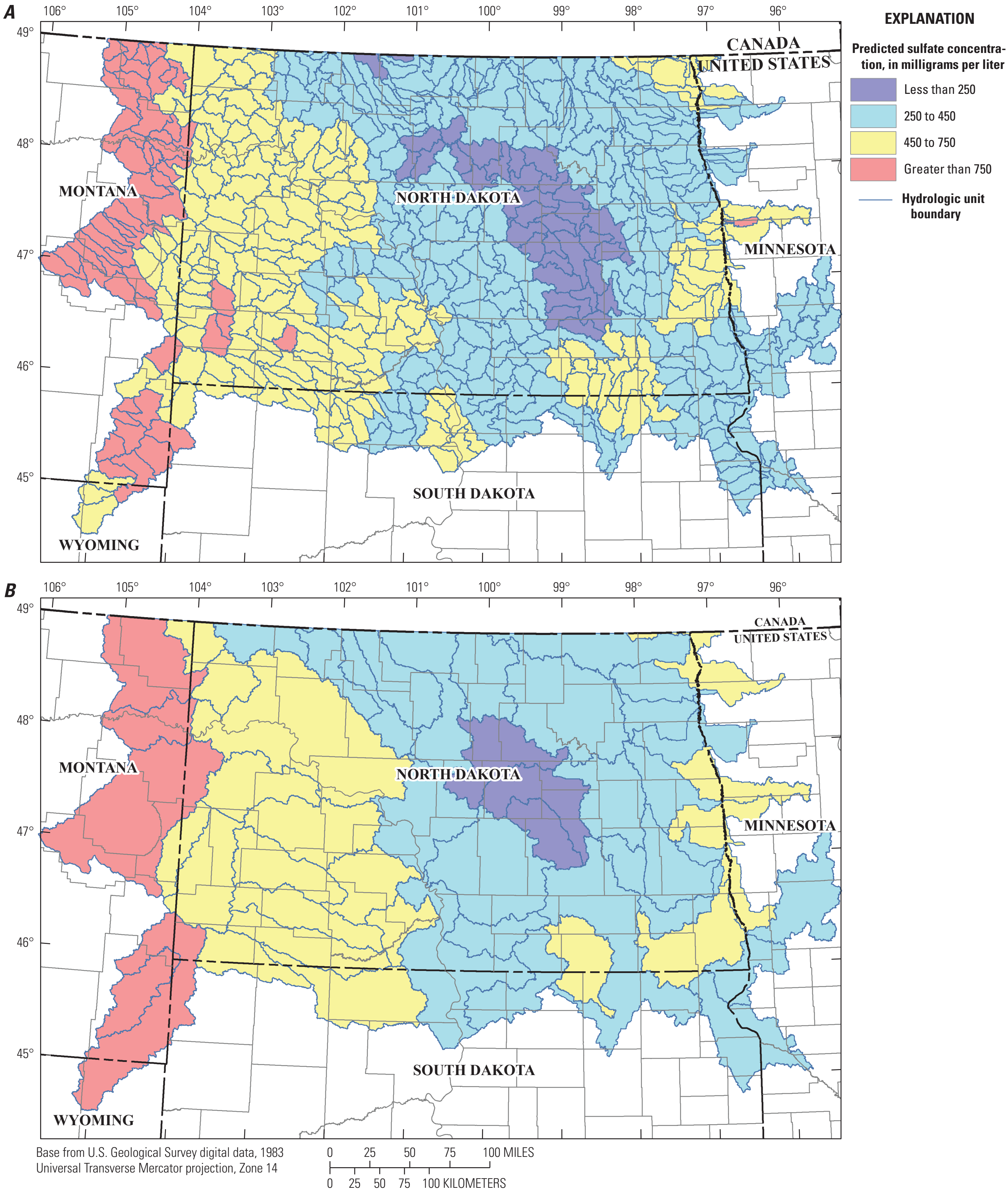

Figure 9. Modeled sulfate concentrations for *A*, 10-digit and *B*, 8-digit hydrologic units in North Dakota and parts of surrounding states.

Furthermore, because none of the variables in the regression model were transformed, the modeled sulfate concentration for a particular basin consisting of one or more HU's can be obtained either by using equation 1 directly or by computing a weighted average of the modeled sulfate concentrations for the HU's in the basin. Equation 1 was applied using characteristics extracted for each 12-digit HU to compute modeled sulfate concentrations for North Dakota and surrounding contributing basins (fig. 8). Modeled sulfate concentrations generally were highest (greater than 750 mg/L) in HUs in eastern Montana and western North Dakota and lowest (less than 250 mg/L) in HUs contributing to the upper Sheyenne River and upper James River (figs. 1, 2, and 8). HUs contributing to the James River and Sheyenne River were unique in that although the lowest modeled sulfate concentrations in North Dakota were observed in the upper James and Sheyenne Rivers (less than 250 mg/L) some of the higher values (450–750 mg/L) were observed in HUs in the lower James and Sheyenne Rivers. Most of the difference in modeled sulfate concentrations in the James and Sheyenne River Basins was because of the low SOF and SCC in the upper basins and the high SOF and SCC in the lower basins (fig. 5). Area-weighted means for the modeled sulfate concentrations also were computed for 10-digit and 8-digit HUs for streams in North Dakota and surrounding contributing basins (fig. 9). The resulting distribution of modeled sulfate concentrations was similar to the distribution for the 12-digit HUs (fig. 8), but less variable because the basin characteristics were averaged over larger areas.

Summary

Recent analyses of water-quality data collected from North Dakota's streams indicated trends of increasing sulfate concentrations across the State. Water-quality analysis by the North Dakota Department of Health also indicated that the sulfate standards for various stream classifications, which are based on 30-day moving average sulfate concentration, have been exceeded at a number of stream water-quality monitoring locations across the State, some by an order of magnitude. Previous studies have indicated that the increasing sulfate concentrations probably were caused by generally wetter conditions and resulting increases in contributing drainage areas and water tables beginning about 1993. The increasing sulfate across the State has prompted questions about whether the State's current stream classification system, which includes the sulfate concentration standards, still appropriately reflects natural conditions. Where natural conditions cause exceedances of the existing sulfate standards, the North Dakota Department of Health may consider changes to the classification status of certain streams to reflect the higher sulfate concentrations.

A study was conducted by the U.S. Geological Survey in cooperation with the North Dakota Department of Health and the North Dakota State Water Commission to evaluate the relation of maximum seasonal (30-day moving average) sulfate concentrations at monitoring sites to characteristics of the contributing basins in North Dakota to model the expected naturally-occurring sulfate concentrations in streams.

A spatial analysis was conducted with digital data using a Geographic Information System to obtain selected basin characteristics for each 12-digit hydrologic unit associated with North Dakota streams. Characteristics used in the regression analysis extracted for each hydrologic unit included the mean annual precipitation (1981–2010), mean percent soil clay content, and mean percent saturation overland flow. For the regression analysis, a single value for each characteristic was needed for each of 75 stream sampling sites that had associated sulfate data during 1993–2008. For each site, all of the 12-digit hydrologic units upstream from the site were combined and an area-weighted mean based on the area of each 12-digit hydrologic unit was computed for the mean annual precipitation, percent soil clay content, and percent saturation overland flow for the basin upstream from the site.

Many of the sites used in this study were sampled as part of the North Dakota State Water Commission High-Low sampling program, and were sampled two times per year (once during high-flow conditions and once during low-flow conditions). These sites did not have enough data to estimate the maximum seasonal sulfate concentration. However, 28 sites had sufficient sampling frequencies to estimate the maximum seasonal sulfate concentration, and for those sites it was determined that the 75th percentile of the high-low samples was a good estimate of the maximum seasonal sulfate concentration. Therefore, to allow for consistent estimation of the maximum seasonal concentration for the selected 75 sites, including the High-Low Sampling Program sites, the 75th percentiles of the High-Low Sampling Program samples were computed and used to estimate the maximum seasonal sulfate concentrations. To simulate High-Low Sampling Program sampling for sites that had higher sampling frequencies in each year, only the concentration samples nearest to April 15 (high flow) and August 15 (low flow) were selected. The modeled sulfate concentration was obtained using ordinary least-squares regression with the 75th percentile of the selected High-Low Sampling Program samples as the dependent variable and the three spatial variables as the explanatory variables.

The regression results indicated that modeled sulfate concentration increased by 146.7 milligrams per liter per 1-percent increase in saturation overland flow, 11.4 milligrams per liter per 1-percent increase in soil clay content, and 4.7 milligrams per liter per 1 millimeter decrease in mean annual precipitation for mean annual precipitation below 475 millimeters. For mean annual precipitation greater than 475 millimeters (covering about the eastern 1/3 of the State), modeled sulfate concentration did not vary with mean annual precipitation. Each of the coefficients for the explanatory variables was highly significant (p-values less than 0.001) and the direction of the relations between modeled sulfate concentration and each of the explanatory variables was consistent with physical expectations. Because none of the variables in the regression model were transformed, modeled sulfate concentration for a particular basin consisting of one or more hydrologic units was equivalent to the weighted average of the modeled sulfate concentrations for each of the hydrologic units in the basin.

Modeled sulfate concentrations generally were highest (greater than 750 milligrams per liter) for basins in western North Dakota and lowest (less than 250 milligrams per liter) for basins in the upper Sheyenne River and upper James River. Area-weighted means for the basin characteristics also were computed for 10-digit and 8-digit hydrologic units for streams in North Dakota and sulfate concentrations were estimated from the characteristics. The resulting distribution of modeled sulfate concentrations was similar to the distribution of estimates for the 12-digit hydrologic units, but less variable because the basin characteristics were averaged over larger areas.

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