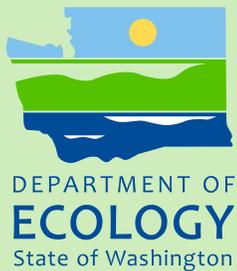




Sumas-Blaine Aquifer Long-Term Groundwater Quality Monitoring, 2009-2016



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Sumas-Blaine Aquifer Long-Term Groundwater Quality Monitoring, 2009-2016

by

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Water Resource Inventory Area (WRIA) and 8-digit Hydrologic Unit Code (HUC) numbers for the study area:

WRIA

- 01

HUC numbers

- 17110001
- 17110004

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Abstract

During 2009-2016, groundwater sampling was conducted annually at 16-25 water supply wells in the Sumas-Blaine aquifer in Whatcom County. Samples were collected during the spring of each year and were analyzed for nitrate, chloride, and bromide.

This study is part of a long-term groundwater monitoring program that began in 1997 in response to elevated nitrate concentrations in the area. The objective of monitoring has been to measure broad-scale changes in groundwater nitrate over time.

Statistically significant decreasing trends for nitrate were detected in 9 of 25 wells sampled in 2003-2016. Fifteen wells showed no significant nitrate trend, while one well had an upward trend. The percent of samples that exceeded 10 mg/L nitrate-nitrogen (nitrate-N) decreased from 48%-63% in 2003-2005 to 15%-32% in 2013-2016. Trends were similar when 1997 data were included in the analysis. Despite decreasing or stable nitrate-N concentrations in the majority of wells, 24% of 25 wells continued to exceed (not meet) the drinking water standard in 2016.

Annual average and median nitrate-N concentrations likewise trended downward in 11 wells that were consistently sampled during 2003-2016. Chloride concentrations trended downward in 6 wells and increased in one well during 2009-2016.

Several aspects of the study limit broad-scale inferences about nitrate trends in the Sumas-Blaine area as a whole. These include the small number of wells relative to the size of the aquifer, representativeness of samples from private water supply wells, unreliable ongoing access to wells, and potential long-term climate influences on groundwater nitrate concentrations.

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- Lynden-area homeowners who participated in the study.
- Whatcom County Health Department.
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Introduction

The Sumas-Blaine aquifer (SBA) is part of the transboundary Abbotsford-Sumas aquifer that extends from northern Whatcom County, Washington, into southern British Columbia, Canada (Figure 1). The SBA is the main drinking water source for rural residents of the area. Groundwater nitrate concentrations above (not meeting) the U.S. drinking water standard of 10 mg/L-N have been documented across the SBA during various sampling efforts over the past 40 years¹.

Nitrate in groundwater is a human health concern because of the risk of methemoglobinemia, or blue-baby syndrome. Water with elevated nitrate concentrations can result in nitrate molecules replacing oxygen in the hemoglobin, depriving an infant of oxygen. Other conditions also linked with the intake of high nitrate water include specific cancers and birth defects (Jones et al., 2016; Inoue-Choi et al., 2015; Brender et al., 2013; and Ward et al., 2010).

In addition to potential human health impacts, elevated nitrate in groundwater presents significant environmental concerns. Groundwater contributes a substantial portion of the total flow to surface waters in the Nooksack River basin. During the summer months, groundwater baseflow is estimated to contribute 72-86% of the flow in the Nooksack River at Ferndale (Sinclair and Pitz, 1999). At least a portion of the nitrate in area groundwater is transported to streams, rivers, and eventually marine water.

Trend analysis of ambient surface water data for the Nooksack River for the 1995-2013 period indicates the river has (1) the highest total nitrogen and nitrite+nitrate-nitrogen (nitrate-N) loading to Puget Sound of any monitored river and (2) the highest annual nitrogen contribution per unit area of watershed for rivers in the basin (Von Prause, 2014). The potential impacts of elevated nitrate in surface water and marine water include increased algal production and depressed dissolved oxygen concentrations. These conditions can harm fish and other aquatic organisms (Durand et al., 2011).

Recent Ecology investigations

In 1997, the Washington State Department of Ecology (Ecology) conducted an aquifer-wide survey of nitrate in 248 wells and 2 springs across the SBA (Erickson, 1998). Twenty-one percent of wells had nitrate-N concentrations above 10 mg/L. Nitrate concentrations appeared to be highest in the central and northeast parts of the SBA. Therefore, a subset of 35 wells in that area was chosen for ongoing monitoring (Erickson, 1998; Redding, 2008).

¹ Nitrate results from 19% of the 100 SBA wells sampled from 1970-1973 exceeded 10 mg/L-N (Obert, 1973). Erickson and Norton (1990) sampled 27 wells in the Bertrand Creek area and found that 7 wells exceeded 10 mg/L-N. Samples collected from 248 wells in the spring 1997 indicated 21% exceeded 10 mg/L-N (Erickson, 1998). Cox and Kahle (1999) likewise found 21% of nitrate samples from 230 wells sampled during 1990-1992 in the eastern SBA had levels exceeding 10 mg/L-N. Mitchell et al (2005) found that 64% of nitrate samples from 26 wells in the Judson Lake area in 2002-2004 were above 10 mg/L-N. Redding (2008) evaluated seasonal variation from 2003-2005 in 35 wells across the SBA sampled by Erickson (1998) and found that 26% of these wells consistently had nitrate-N concentrations above 10 mg/L.

The ongoing monitoring initially consisted of quarterly sampling at 35 mostly private water supply wells for 3 years (2003-2005). Most of the wells sampled during this period were also sampled during the 1997 aquifer-wide sampling (Erickson, 1998). The 2003-2005 study included analysis of nitrate seasonal variations and short-term trends over time.

The combined results of previous monitoring by the U.S. Geological Survey (USGS) and Ecology between 1981 and 2010 indicate that approximately 29% of sampled wells have exceeded (not met) the 10 mg/L-N drinking water standard for nitrate-N, during at least one sampling event (Carey and Cummings, 2012). Several public drinking water systems that rely on groundwater in the Lynden area have also reported exceedances of the nitrate standard, affecting over 1,000 residents (Hulsman, 2016).

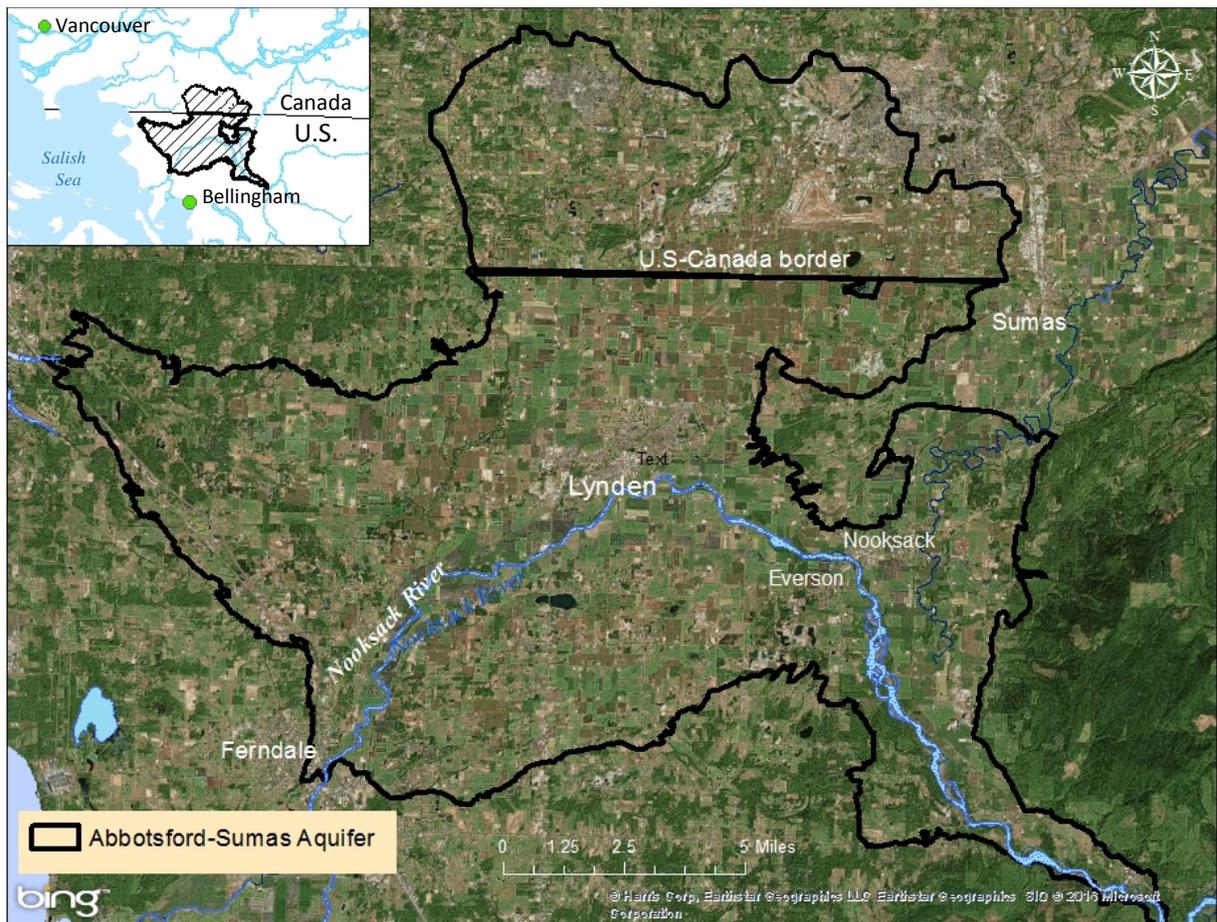


Figure 1. The Abbotsford-Sumas aquifer boundary.

The study area is south of the Canada-U.S. border.

The aquifer boundary is from Tooley and Erickson (1996) and Graham (2008).

Purpose and objectives

The purpose of this study was to continue annual monitoring at the network of water supply wells that were sampled in 2003-2005. The main objective of ongoing sampling, which began in 2009, is to provide up-to-date information to evaluate long-term trends in groundwater nitrate and chloride concentrations. Additionally, bromide samples have been collected since 2009 as part of a larger effort to test the use of chloride/bromide (Cl/Br) mass ratios as an indicator of nitrate sources (Redding, 2008, 2009).

Samples for this study were collected each year in March to limit seasonal variations observed during quarterly sampling in 2003-2005². Twenty-two of the 35 wells originally sampled in 2003 were still available for sampling in 2016.

The objectives of the current study are to:

- Collect nitrate, chloride, and bromide samples as well as standard water quality field measurements, in March of each year, 2009-2016, in wells sampled during 2003-2005 (Redding, 2008).
- Analyze nitrate and chloride results for significant trends using the Mann-Kendall statistical test.
- Compare nitrate results with Washington State's groundwater quality standards (Chapter 173-200 WAC).
- Prepare a report (this report) to document and interpret the results of groundwater quality sampling for 2009-2016 and associated nitrate and chloride trends for 1997-2016.

² Samples collected in 2014 were not included in the statistical analyses because they were not collected in March.

Background

The main sources of information on the geology and hydrogeology of the study area are an extensive range of maps, summaries, and interpretations compiled by Cox and Kahle (1999). Unless otherwise referenced, the following hydrogeologic framework is based on their work.

Geology

The Abbotsford-Sumas aquifer is located in the Fraser-Whatcom Lowlands. This area was influenced and shaped by repeated glacial advances and retreats during the Pleistocene epoch. The Fraser Glaciation smoothed the bedrock surface before depositing unconsolidated material over the Puget Sound Lowland. The SBA study area experienced 3 main glacial stages with the most recent advance roughly 11,000 to 10,000 years ago. Meltwater streams from the last glaciation carried material toward the mouth of the Nooksack River. Outwash from the melting glacier deposited gravel and cobbles near the international border grading to sand and clay lenses near Lynden.

Over the last 10,000 years, the Nooksack River has eroded and cut through the upper glacial deposits forming the Nooksack Valley Floodplain. In some areas, depressions in the glacial deposits are filled with deposits of peat up to 30 feet thick (Easterbrook, 1971). These bog areas usually have saturated soils, are high in organic carbon, and have reducing conditions. Together, these conditions can provide a favorable environment for biological and chemical conversion of nitrate to nitrogen gas (Redding, 2008).

Hydrogeology

The study area contains 4 main hydrogeologic units: the Sumas surficial aquifer, the Everson-Vashon semi-confining unit, the Vashon semi-confining unit, and the bedrock semi-confining unit. Figure 2 shows the main surficial hydrogeologic units and a vertical cross-section across the northern portion of the study area. The two glacial semi-confining units are combined into a single hydrogeologic unit in the cross-section shown in Figure 2.

The SBA is the uppermost aquifer in the area and is the sole drinking water source for the area's rural residents. The aquifer is unconfined and covers an area of about 150 square miles. Groundwater within the aquifer naturally discharges to local streams and the Nooksack River (Tooley and Erickson, 1996) (Figure 2).

The highly productive SBA consists mainly of stratified sand, silt, and gravel outwash deposits with minor clay lenses, especially in the Lynden area. The aquifer also contains alluvial deposits from the Nooksack and Sumas river systems, including lenses of till and fine-grained lacustrine and peat deposits. The area is fairly flat with gradients of about 15 feet per mile, or 0.0028, toward the Nooksack River. The hydraulic conductivity of the SBA varies greatly due to extreme heterogeneity. Cox and Kahle (1999) found a median hydraulic conductivity of 270 feet/day and a range of 7 to 7,800 feet/day.

The SBA is vulnerable to contamination due to its shallow depth to water, heavy seasonal rainfall, and intensive overlying agricultural production. The depth to groundwater is less than 10 feet across most of the aquifer (Tooley and Ericson, 1996). The SBA is relatively thin with most areas less than 50 feet thick except for thicker portions in the Sumas area. It is underlain by low permeability deposits of the Everson-Vashon semi-confining layer (Tooley and Erickson, 1996).

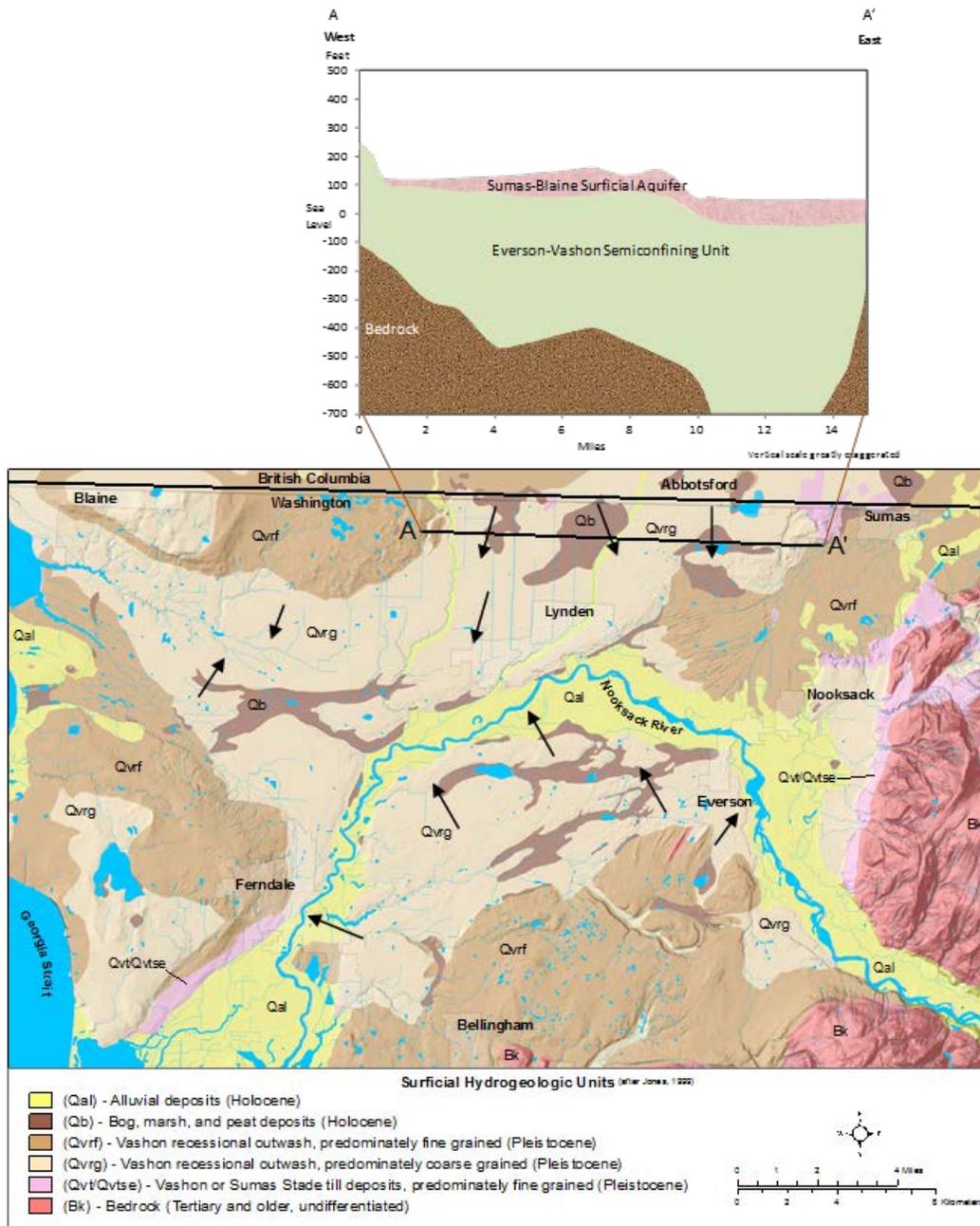


Figure 2. Surfacial hydrogeologic units in the Sumas-Blaine aquifer area and cross-section A-A' (Jones, 1999; Cox and Kahle, 1999). Arrows indicate the general direction of groundwater flow (Tooley and Ericson, 1996).

Recharge to the SBA is mainly from precipitation. Annual rainfall over the SBA ranges from about 32 inches in the southwest to 50 inches on the eastern edge. About 67% of annual precipitation falls from October through March, when crop uptake is lowest (Cox and Kahle, 1999). Low rainfall intensity and the flat topography of the area allow much of the rainfall that occurs in the non-growing season to percolate through the soil and into groundwater or into the drainage systems found in many low-lying agricultural fields.

Land use

Dairy farms and berry production are the main agricultural activities overlying the aquifer. Residential homes outside of the small cities of Lynden, Everson, and Nooksack rely on on-site sewage systems for wastewater disposal. Manure from dairies is used on forage crops for fertilizer and as needed for raspberry production. Inorganic fertilizer is used on berry and other crops. An estimated 16-18 million pounds of nitrogen are applied to land over the SBA from all land uses annually (Almasri and Kaluarachchi, 2004; Carey and Cummings, 2012).

In recent years, many fields formerly in dairy production (grass and corn) have been converted to berry production. Raspberries have been the primary berry crop, but blueberries make up a significant share of recently planted acreage. In 2015, grass and corn were grown on 45,219 acres and berries on 15,029 acres in Whatcom County (Washington State Department of Agriculture, 2017, <http://agr.wa.gov/pestfert/natresources/aglanduse.aspx>).

Land use adjacent to sampled wells included agricultural and rural residential. We were not able to measure the depth to groundwater in many of the sampled wells due to well construction or access considerations. Determining groundwater flow rate and direction in the immediate vicinity of the sampled wells would require additional data from appropriately designed monitoring wells. Consequently, the water quality results obtained during the study cannot be conclusively associated with particular land uses.

Methods

The sampling and analysis methods for this project are described in the Quality Assurance Project Plan (QAPP) (Redding, 2009), and addendum (Redding, 2012), as well as Ecology’s Standard Operating Procedure EAP096 (Carey, 2016). The spatial distribution of sampled wells is shown in Figure 3. Construction information for the wells is provided in Appendix A and at <http://www.ecy.wa.gov/eim/index.htm>.

The original QAPP specified annual sampling each year in the month of March at 24 private domestic wells and one small public water supply well that were sampled in 2003-2005. However, several wells could not be accessed every year, and three wells were later added to this group to replace wells that were no longer accessible.

Wells were sampled for nitrite+nitrate-N, chloride, bromide, and field parameters (temperature, pH, conductivity, and dissolved oxygen). “Nitrite+nitrate-N” is referred to as “nitrate-N” in this report, because nitrite-N is typically negligible in surface water and groundwater (Sawyer and McCarty, 1978). Ammonium-N was also analyzed in 2015 and 2016.

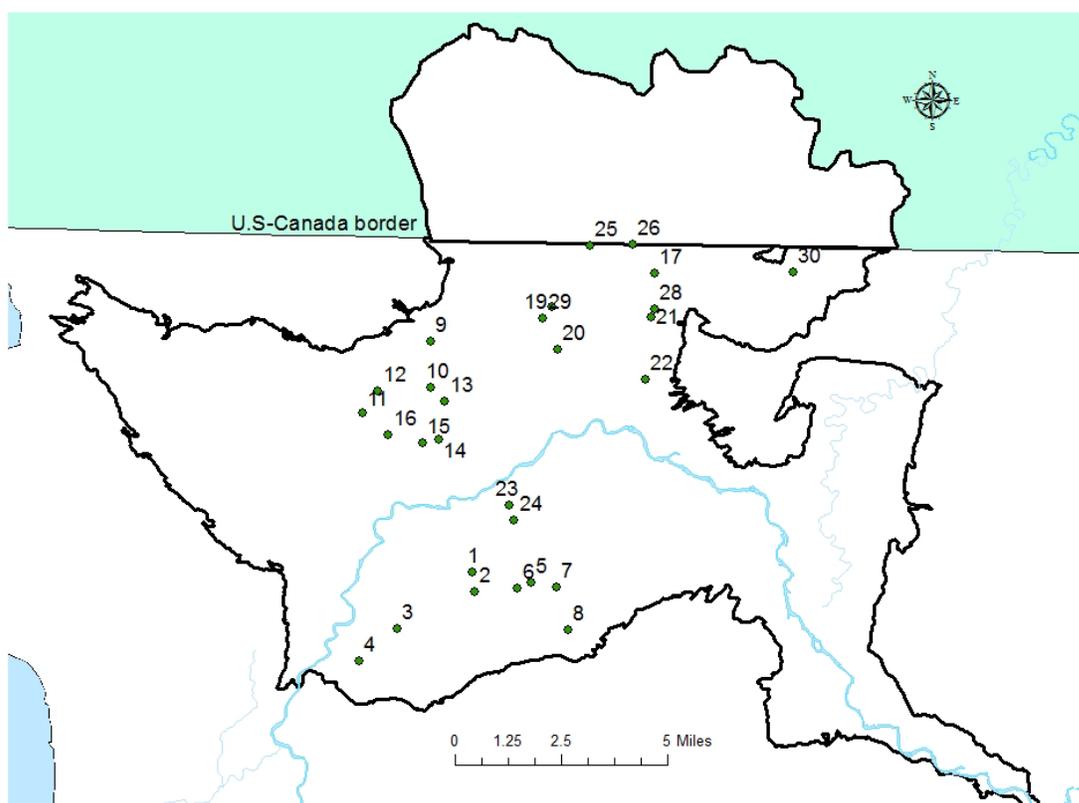


Figure 3. Locations of sampled wells with map ID.

EPA's ProUCL software package³ was used to evaluate nitrate-N and chloride results for statistical trends using the Mann-Kendall non-parametric analysis method (USEPA, 2009). Nitrate trends were analyzed for the period 2003-2016 for all wells with 6 or more results. Long-term nitrate trends for 1997-2016 were also evaluated for those wells sampled in March 1997. Analysis of chloride trends was limited to the 2009-2016 period because chloride was not sampled for in 2003-2005. All trends and statistical analyses were conducted at the 95% confidence level ($p < 0.05$).

³ https://www.epa.gov/sites/production/files/2015-03/documents/proucl_one_page_fact_sheet.final_.pdf

Results

Results of water quality sampling conducted at 28 wells in 2009-2016 are described below and in Appendix B. The corresponding data quality assessment is described in Appendix C.

Nitrate

Nitrate-N concentrations in the 28 wells sampled during 2009-2016 ranged from 0.96 to 28.4 mg/L. The annual percentage of wells that exceeded 10 mg/L-N ranged from 15% to 44% (Table 1).

Table 1. Nitrate-N results and summary statistics for the current study (2009-2016) as well as two previous Ecology studies.

Map ID locations are shown in Figure 3. Shaded values are greater than 10 mg/L-N.

			Erickson (1998)	Redding (2008)				Current study						
Map ID	Location Name	Well Tag ID	1997	2003	2004	2005	2009	2010	2011	2012	2013	2014	2015	2016
1	39212C1	AGF141	8.08	9.00	10.6	8.93	9.19	12.1	8.76	8.71	8.85	9.95	11.3	9.20
2	39317H1	BCS951	6.32	8.26	10.7	12.5	7.25	7.48	7.84	6.62	7.44	7.34	8.81	6.99
3	39307K2	BCS952	18.6	19.6	19.4	19.4	12.9	13.0	11.2	14.2				
4	39307H1	BCS953	53.0	33.9	32.4	33.9	27.3	23.5	24.5	22.6	22.9	16.6	23.3	24.0
5	39212K2	BCS954	5.86	3.58	4.95	4.06	2.07	2.27	1.77	1.37		2.17	2.47	2.13
6	39215J1	BCS955	15.8	2.36	1.96	2.52	2.18	2.80	2.58	4.35			3.04	2.79
7	39221H1	BCS956	5.37	10.8	6.96	6.43	3.38	4.08	2.80	3.41	2.37		3.87	2.86
8	40211P1	BCS957	4.72	2.67		2.40	0.96	3.97		7.81	6.31			
9	40223A3	BCS958	6.65	12.7	8.23	10.7	2.43	1.36	2.77	4.83	4.55			1.53
10	40226B1	BCS959	7.05	10.2	15.0	9.68	5.41	4.70	4.03	5.77	5.93	7.01	5.75	6.65
11	40226D2	BCS960	3.23	8.37	43.1	18.7	14.6	14.2	11.0				11.9	13.2
12	40221J5	BCS961	10.4	10.8	6.22	5.13	4.85	7.88	8.37	5.72	1.82	4.98	4.31	2.25
13	40214P1	BCS962	28.6	17.6	18.3	16.3	16.1	14.9	17.3	25.3	16.3	25.1	12.7	9.76
14	40222D1	BCS963	3.11	1.6	5.67	2.65	5.52	7.36	6.62	6.19	2.36	2.66	1.68	4.35
15	40305N3	BCS964	1.61	5.52	6.31	20.2	24.1	12.8	5.64	4.45	2.30		5.31	9.05
16	40308P1	BCS965				13.2	14.2	12.1	12.6	10.2	6.77	11.8	21.7	
17	40331P3	BCS966	5.61	5.66	9.88	22.4	5.18	8.23	4.21	8.10	7.15	4.28	6.93	7.99
18	40331L1	BCS967	3.36	7.06	6.35	7.79	8.49	5.35	5.85	5.80	5.21	4.18	4.50	5.51
19	40310F1	BCS968	12.4	13.0	12.7	13.1	13.4	16.5	13.9	13.5		11.1	10.1	28.4
20	40227C1	BCS969	8.78		23.7	19.4	5.63	6.22	6.02	11.5	8.28	4.42	10.9	14.4
21	41333M1	BCS970	5.97	33.9	15.9	15.4	12.5	14.7	17.7	12.5	9.08	8.06	9.47	6.91
22	41334E1	BCS971	14.3	8.82	12.4	13.4	9.41	8.55	10.8		7.52			
23	40303B1	BCS972	11.6	8.60	6.30	20.2	8.82	9.12	13.7	7.96	8.44	8.77	9.16	9.92
24	40315L1	BCS973	24.4	13.9	12.6	15.0	11.9	14.2	9.83	11.9	10.5	10.7	9.85	11.4
25	N41431Q1	ABO112	10.8				13.8	10.4	12.6	8.66	8.52		8.06	4.55
26	40303Q1	AGT433	15.1											6.32
27	40307H1		13.1										14.3	8.10
28	N39308F2		21.8	13.8										7.53
Annual statistics			1997	2003	2004	2005	2009	2010	2011	2012	2013	2014	2015	2016
Average			12.1	11.38	13.2	13.1	9.66	9.51	9.27	9.19	7.63	8.70	9.06	8.57
Median			8.78	9.00	10.7	13.2	8.82	8.55	8.57	7.96	7.30	7.70	8.99	7.26
Maximum			53.0	33.9	43.1	33.9	27.3	23.5	24.5	25.3	22.9	25.1	23.3	28.4
Minimum			1.61	1.60	1.96	2.40	0.96	1.36	1.77	1.37	1.82	2.17	1.68	1.53
Standard deviation			10.6	8.47	9.71	7.63	6.60	5.29	5.61	5.73	4.92	5.82	5.59	6.44
Number of wells			27	23	22	24	25	25	24	23	20	16	22	24
% exceeding 10 mg/L			48	48	55	63	40	44	42	35	15	31	32	21

Nitrate results for each well were divided into the 3 sub-areas shown in Figure 4.

Figures 5-7 display nitrate-N concentration in wells from 1997-2016:

- Figure 5 – Northeast
- Figure 6 – Northwest
- Figure 7 – South

Figures 8-10 show the distribution of nitrate concentrations in sampled wells by year.

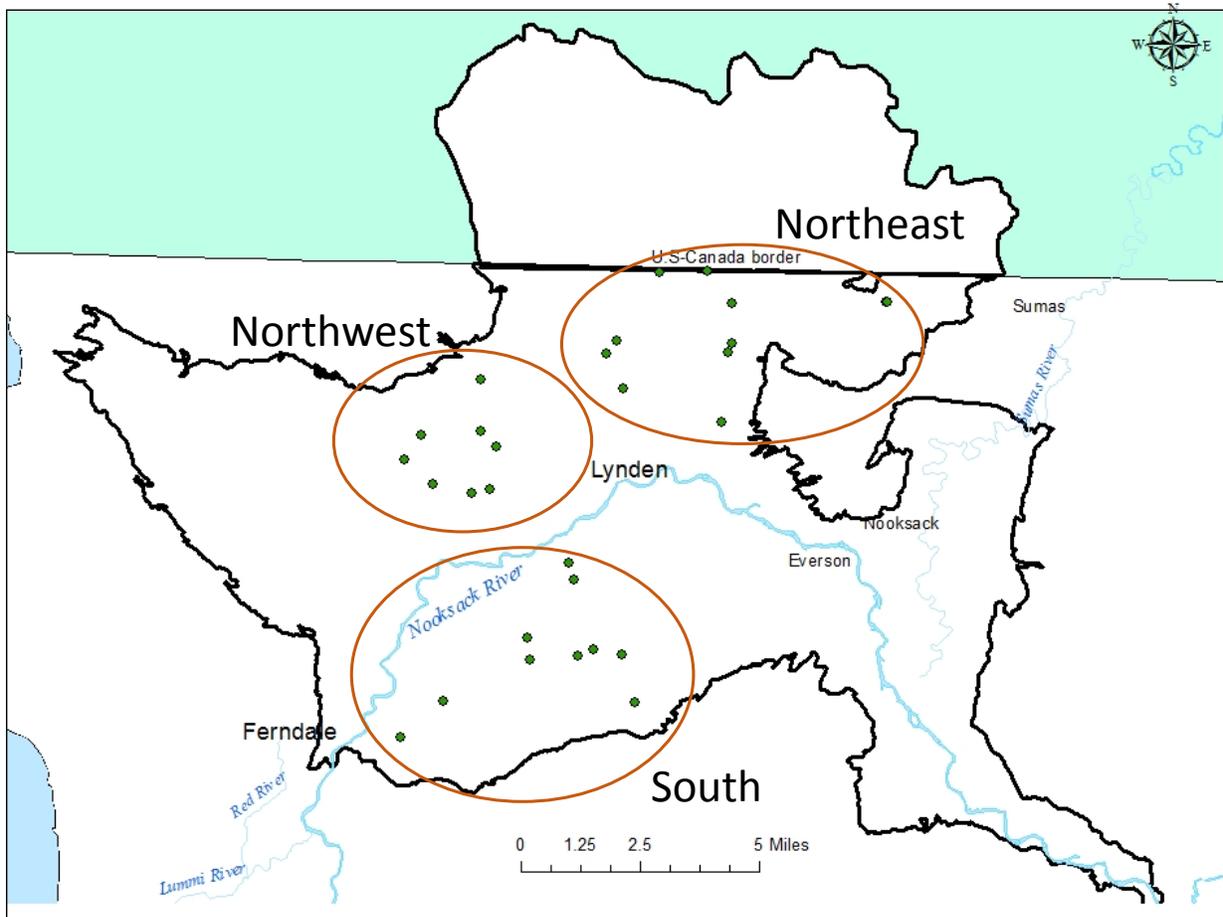


Figure 4. Groupings of wells sampled.

Nitrate results for grouped wells are shown in Figures 5-7.

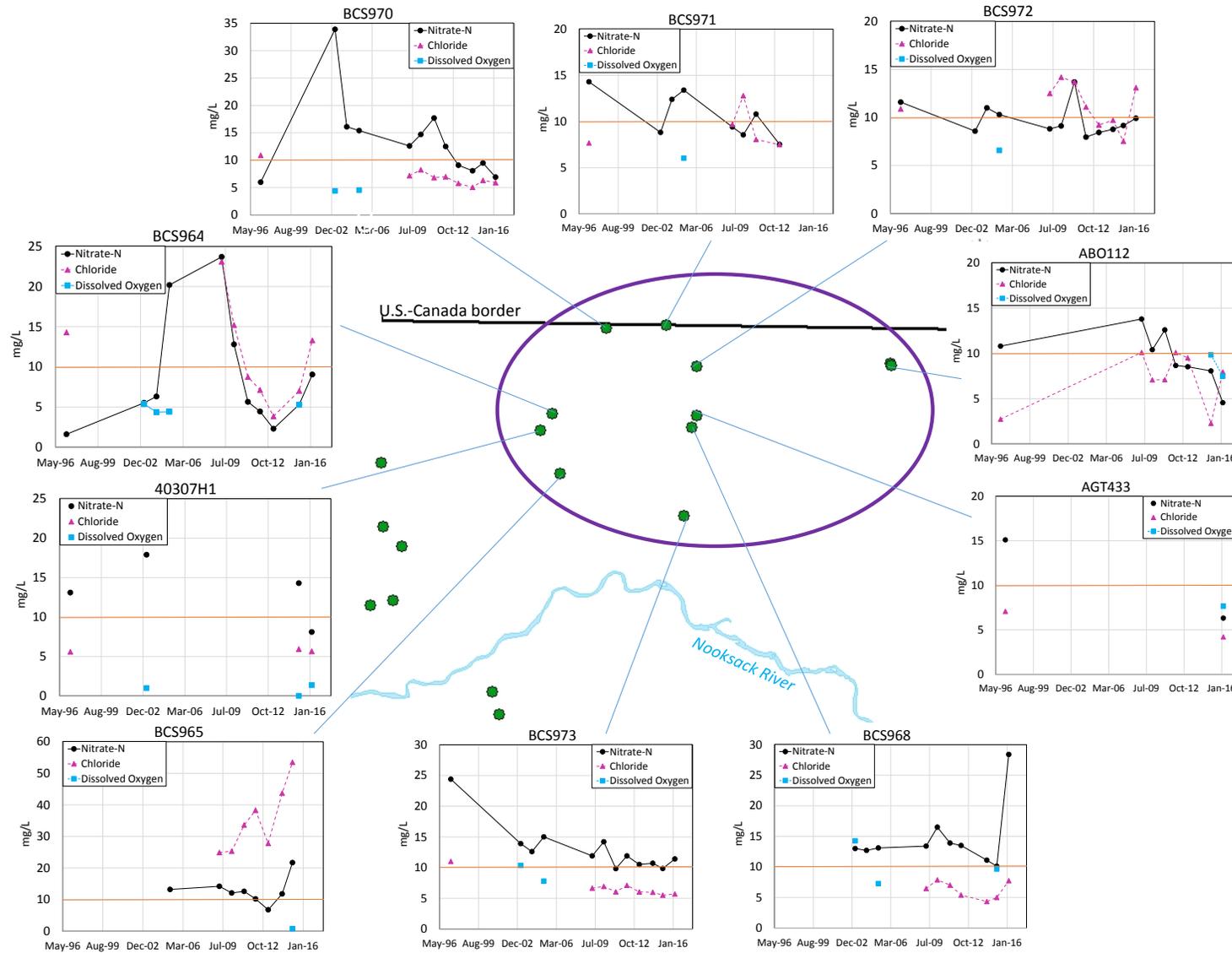


Figure 5. Nitrate-N, chloride, and dissolved oxygen results from wells in the northeast portion of the study area, 1997-2016. The orange line indicates the groundwater and drinking water standard for nitrate-N (10 mg/L).

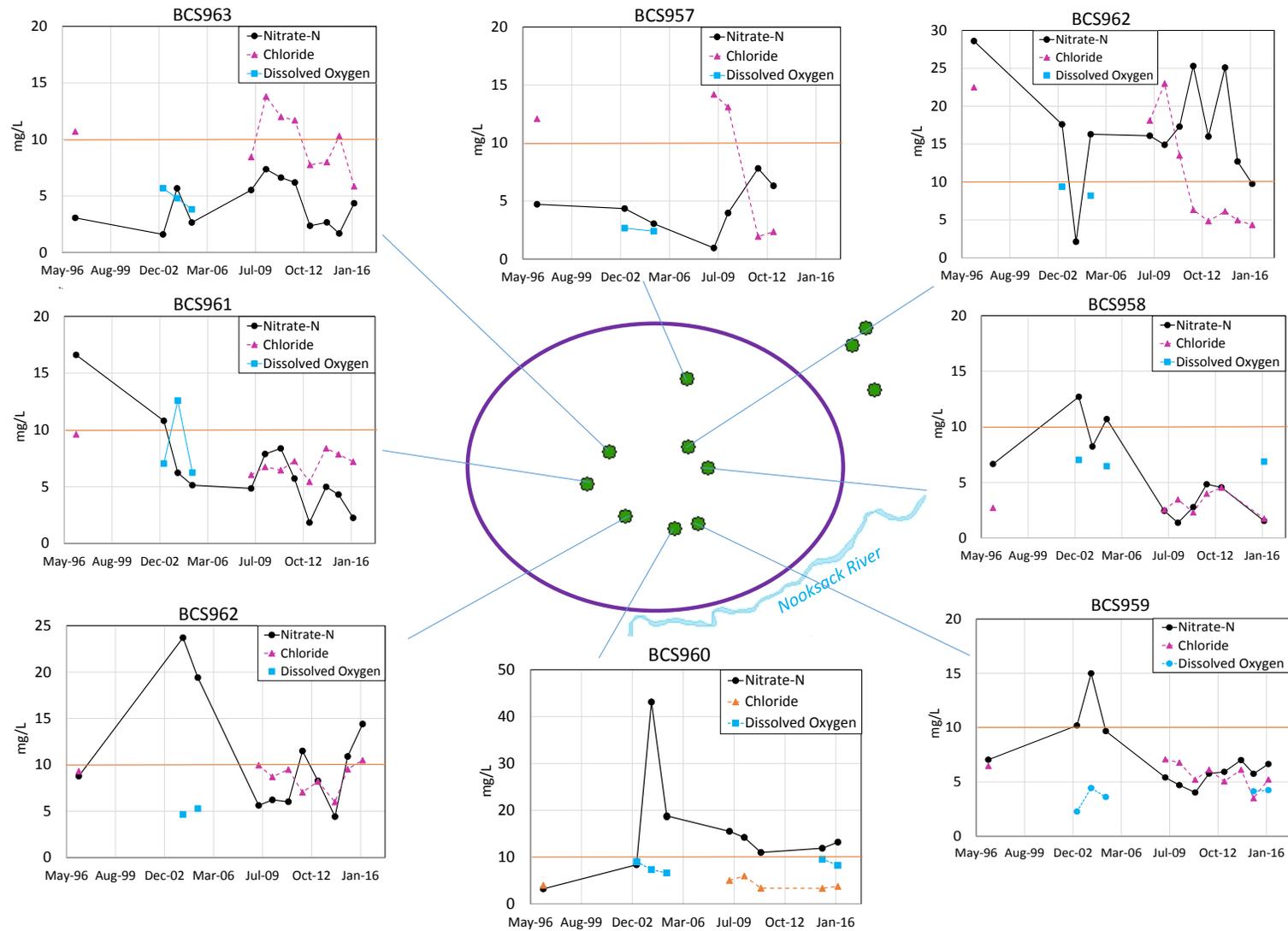


Figure 6. Nitrate-N, chloride, and dissolved oxygen results from wells in the northwest portion of the study area, 1997-2016. The orange line indicates the groundwater and drinking water standard for nitrate-N (10 mg/L).

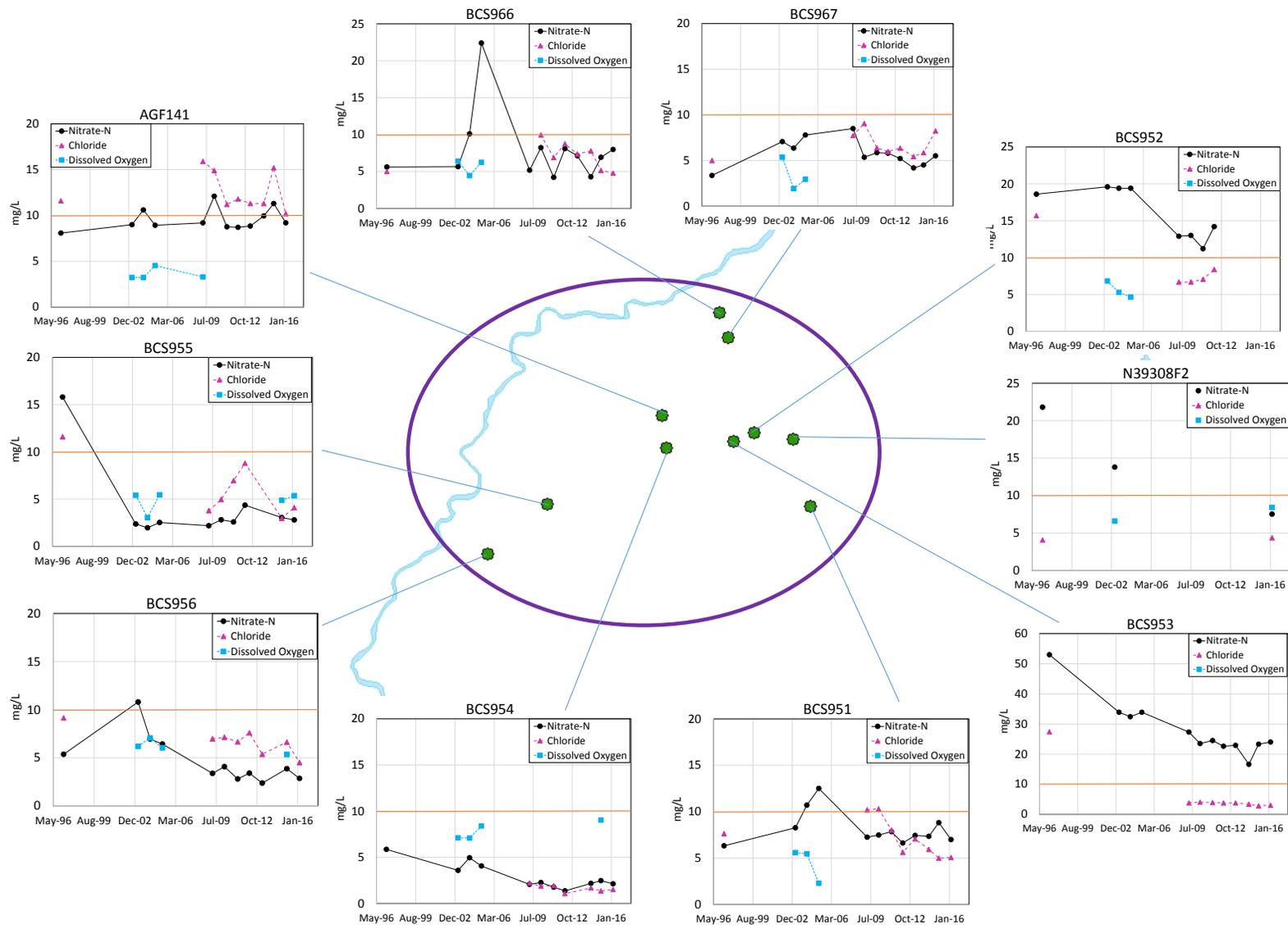


Figure 7. Nitrate-N, chloride, and dissolved oxygen results from wells in the area south of the Nooksack River, 1997-2016. *The orange line indicates the groundwater and drinking water standard for nitrate-N (10 mg/L).*

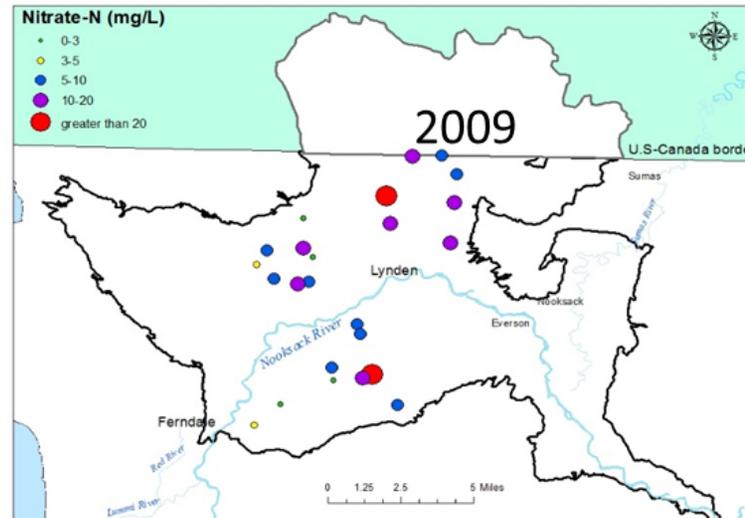
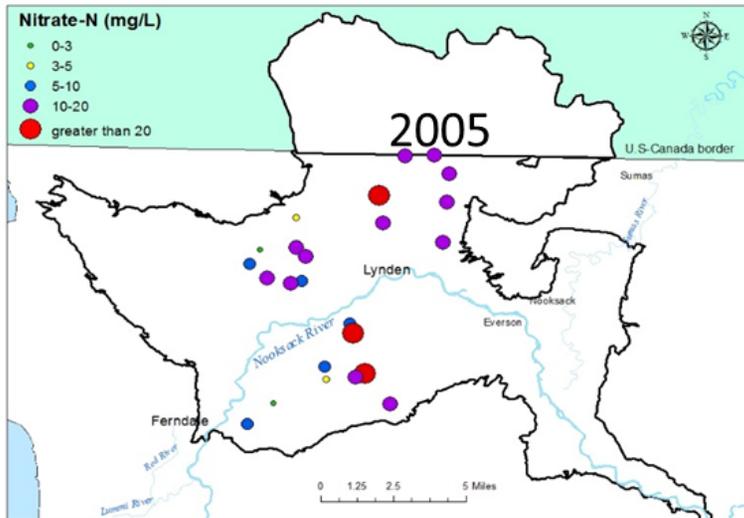
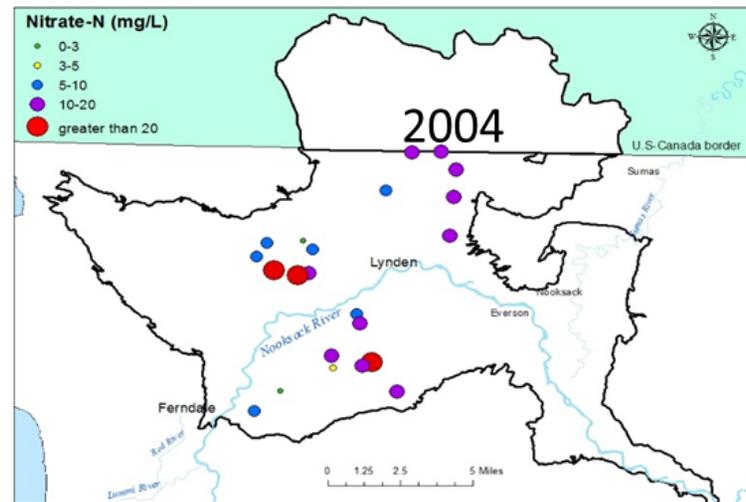
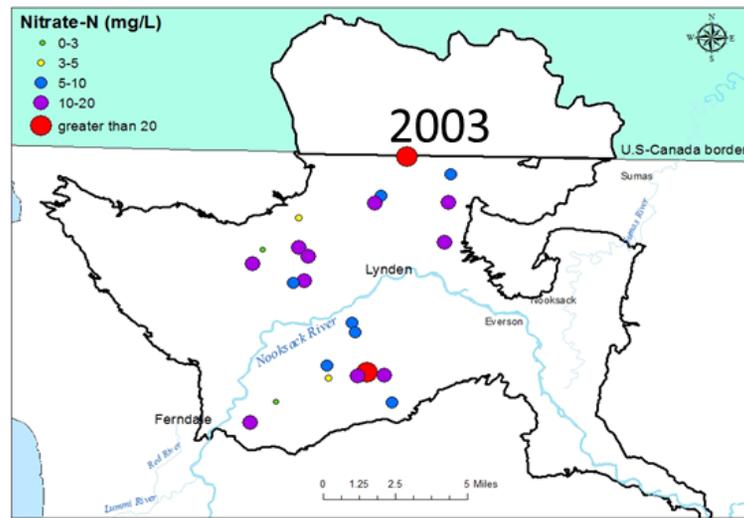


Figure 8. Nitrate-N concentrations (mg/L) for wells sampled in 2003, 2004, 2005, and 2009.

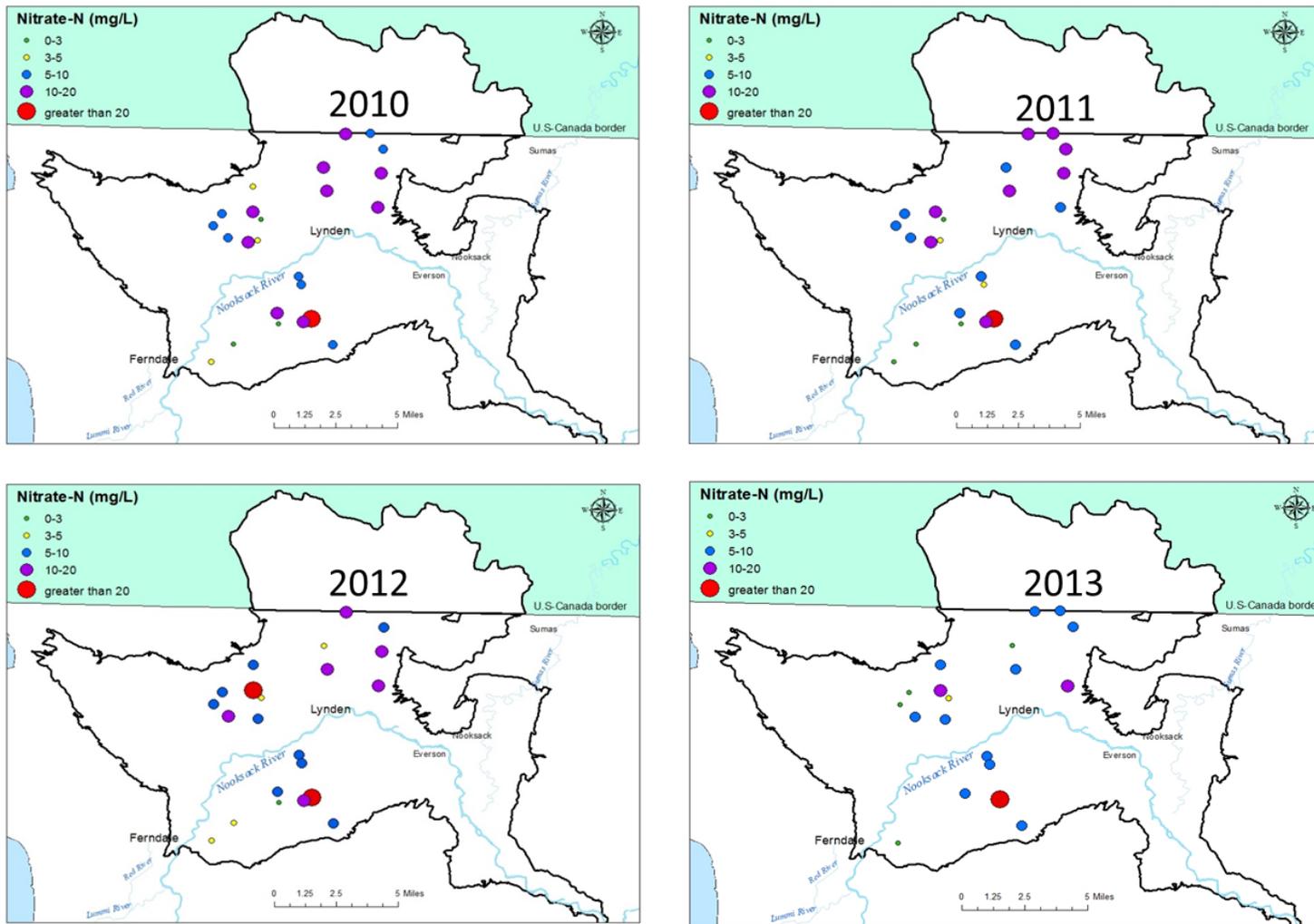


Figure 9. Nitrate-N concentrations (mg/L) for wells sampled in 2010-2013.

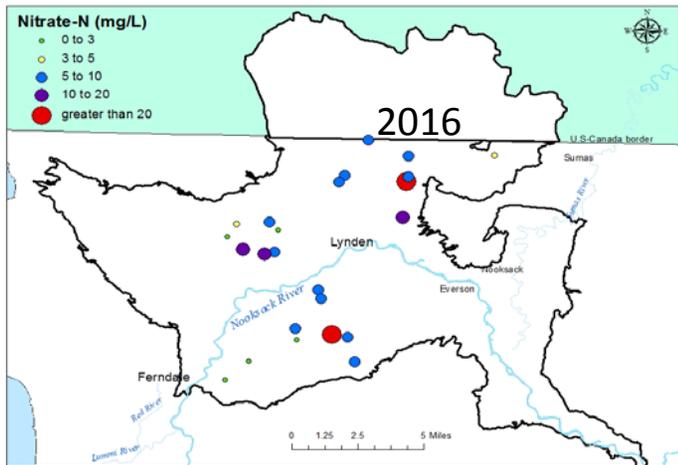
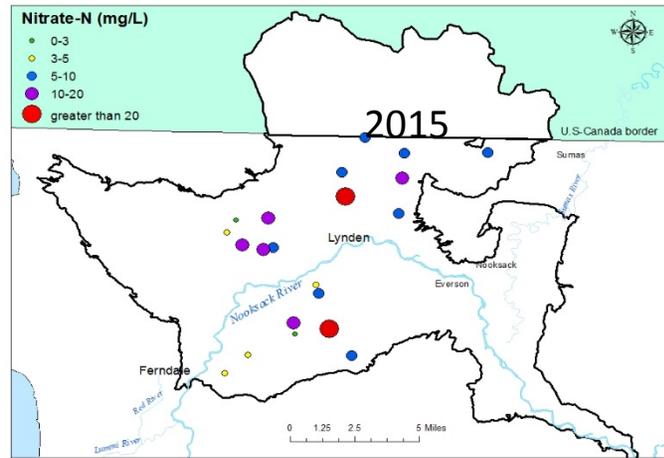
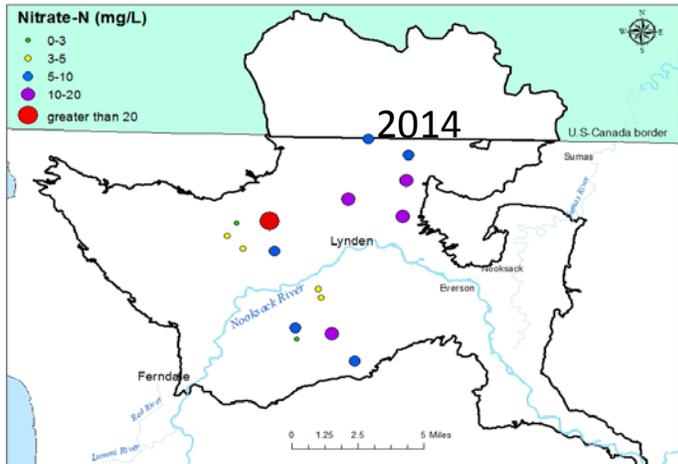


Figure 10. Nitrate-N concentrations (mg/L) for wells sampled in 2014-2016.

Ammonium

Ammonium-nitrogen (ammonium-N) was detected in 4 wells at concentrations ranging from less than 0.010 to 0.155 mg/L (Table 2). Ammonium-N is typically oxidized to nitrate before reaching groundwater unless there is insufficient oxygen for bacterial conversion. The U.S. Environmental Protection Agency (USEPA) has not established a maximum contaminant level (MCL) for ammonium in drinking water.

Table 2. Ammonium-N results for wells where detected in 2015 and 2016.

EIM Location ID	Well Tag ID	Sample Date	Ammonium-N (mg/L)
39307H1	BCS953	3/16/2015	0.010
39307H1	BCS953	3/23/2016	0.010 U
40305N3	BCS964	3/18/2015	0.046
40305N3	BCS964	3/22/2016	0.041
40308P1	BCS965	3/17/2015	0.155
40303Q1	AGT433	3/22/2016	0.014

U: Below the specified detection limit.

Chloride

Chloride concentrations for sampled wells are shown graphically in Figures 5-7 and in tabular form in Appendix B. Chloride concentrations ranged from 1.07 to 53.5 mg/L and averaged 8.34 mg/L. These levels are well below the 250 mg/L public water supply secondary MCL for chloride (Chapter 246-290 WAC). This standard is not health-based.

Bromide

Bromide was detected in 16 wells (Appendix B). The maximum concentration observed was 2.98 mg/L. Bromide was detected in 2 wells between 2009 and 2011, when the laboratory detection limit was 0.2 mg/L. When the detection limit was lowered to 0.025 mg/L in 2012, five wells where bromide previously had not been detected had concentrations above the 0.025 mg/L threshold.

Field parameters

Results for temperature, pH, conductivity, and dissolved oxygen are listed in Appendix B. pH ranged from 4.27 to 7.65. Conductivity ranged from 61 to 583 umhos/cm. Dissolved oxygen concentrations ranged from 0.0 to 10.0 mg/L and are shown in Figures 5-7. There are no MCLs for these parameters.

Discussion

The Sumas-Blaine aquifer ambient groundwater monitoring network was designed to provide a broad-scale assessment of trends in nitrate concentrations over time in drinking water wells that had been previously sampled in 1997 and 2003-2005⁴.

Nitrate

Evaluation of nitrate trends

The Mann-Kendall non-parametric test⁵ was used to assess trends in individual well nitrate-N concentrations over two periods: 2003-2016 and 1997-2016. The nitrate-N data for 1997 were collected by Ecology during a large-scale evaluation of ambient groundwater quality conditions in the SBA as a whole (Erickson, 1998). The 2003-2005 data were collected during an earlier phase of the current study (Redding, 2008). Trend statistics are reported at the 95% confidence level ($P < 0.05$).

Nine wells showed statistically significant decreasing trends in nitrate-N concentration during 2003-2016, while one well showed an increasing trend (Table 3 and Figure 11). The remaining 15 wells showed no statistically significant trend in nitrate-N concentrations.

Long-term nitrate trends for 1997-2016 were similar to those observed for 2003-2016. Seven of the 24 wells sampled during both periods showed significant decreases in nitrate-N concentration (Table 3).

⁴ Eleven wells have a complete set of nitrate data for the 2003-2005 and 2009-2016 monitoring periods. The remaining 14 wells have at least one missing sample due to varying accessibility. Three wells were added in 2015 and 2016 to replace wells that were no longer accessible. The new wells had been previously sampled in either 1997 or 2003-2005 but had not been sampled since 2005.

⁵ The Mann-Kendall test does not require that the data fit a particular distribution (EPA Unified Guidance, 2009). The test is also not sensitive to breaks in data over time: for example, if a sample could not be collected every year (Karmeshu, 2012).

Table 3. Results of Mann-Kendall trend tests for nitrate-N (2003-2016 and 1997-2016) and chloride (2009-2016) concentrations.

Blank cells indicate no statistically significant trend ($p < 0.05$).

Well ID	Nitrate-N (2003-2016) ¹		Nitrate-N (1997-2016) ^{1,2}		Chloride (2009-2016)	
	n	Increase/ Decrease	n	Increase/ Decrease	n	Increase/ Decrease
ABO112 ^	7	Decrease	8	Decrease	7	
AGF141	10		11		8	
BCS951 **+	10		11		8	Decrease
BCS952 +	7	Decrease	8		4	
BCS953 ***+	10	Decrease	11	Decrease	8	Decrease
BCS954 *~	9		10	Decrease	7	
BCS955 ~	9	Increase	10		6	
BCS956 *^	10	Decrease	11	Decrease	7	
BCS957	6		7		4	
BCS958	9		10		6	
BCS959	10		11		8	Decrease
BCS960	8		9		5	
BCS961 ^	10	Decrease	11	Decrease	8	
BCS962	10	Decrease	11	Decrease	8	Decrease
BCS963	10		11		8	
BCS964	10		11		7	
BCS965	7		7	NA	7	Increase
BCS966	10		11		7	Decrease
BCS967 ~	10	Decrease	11		8	
BCS968	9		10	Increase	7	
BCS969	9		10		8	
BCS970 **^	10	Decrease	11	Decrease	8	Decrease
BCS971	7		8		4	
BCS972	10		11		8	
BCS973 +	10	Decrease	11	Decrease	8	

¹ From Redding (2008)

² From Erickson (1998)

Bold: Wells with a complete data set (2003-2005 and 2009-2016)

n: Number of samples

** Both nitrate-N and chloride decreased during 2009-2016

^ Nitrate-N decreased from greater than 10 mg/L to less than 10 mg/L during 2009-2016

+ Nitrate-N was still greater than 10 mg/L in 2016

~ Nitrate-N has not exceeded 10 mg/L

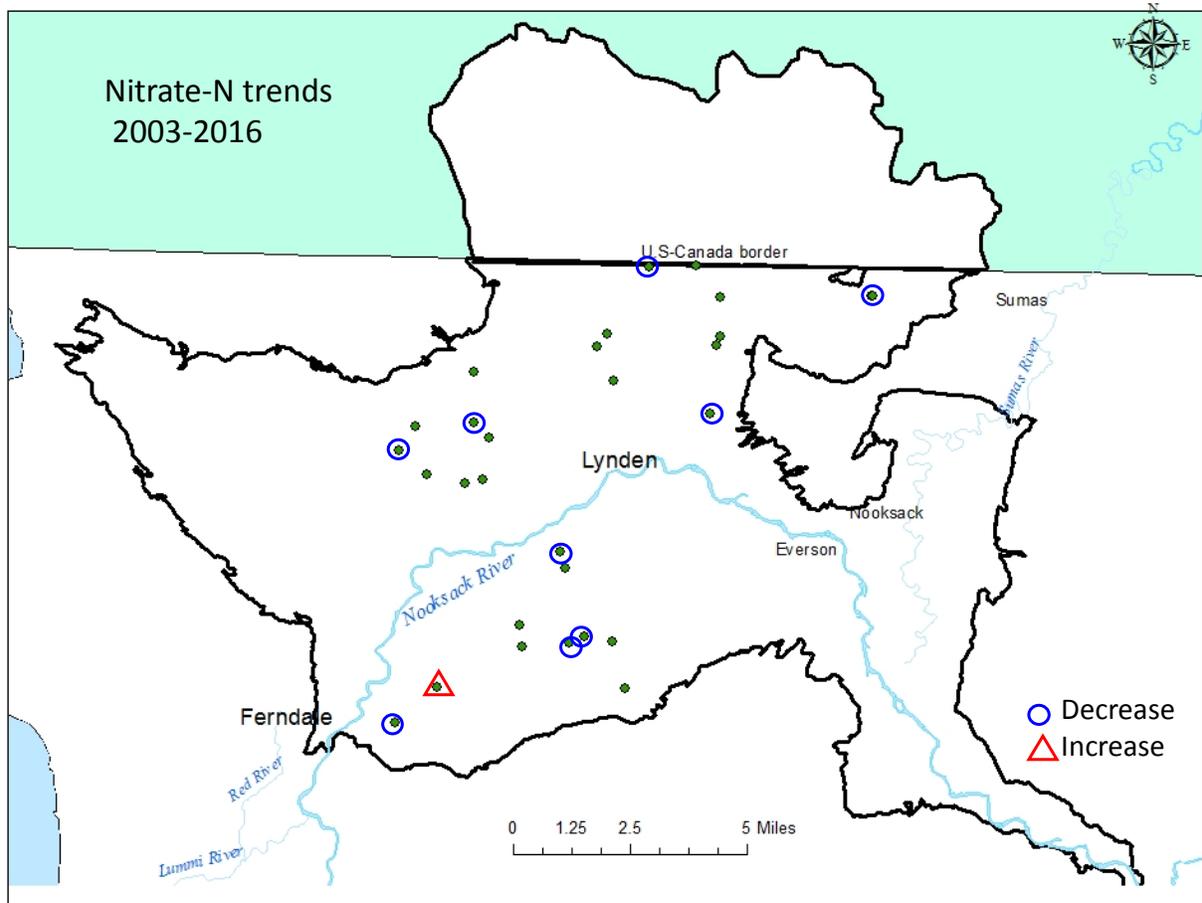


Figure 11. Wells with significant trends in nitrate-N concentration for 2003-2016 using the Mann-Kendall test at the 95% confidence level.

The concentration of nitrate-N in 5 wells with significant downward trends also decreased from above 10 mg/L to below 10 mg/L over the period 2003-2016 (Table 4). Nitrate-N concentrations remained above 10 mg/L in 3 wells despite decreasing trends. Nitrate-N concentrations were consistently less than 10 mg/L in the remaining well.

Table 4. Status of wells with statistically significant decreasing trends from 2003 to 2016 based on the Mann-Kendall test ($p < 0.05$).

Nitrate-N concentration relative to 10 mg/L groundwater standard ¹	Number of wells	Well tag IDs
Nitrate-N has been greater than 10 mg/L, and was less than 10 mg/L in 2016	5	ABO112, BCS956, BCS961, BCS962, BCS970
Nitrate-N has been greater than 10 mg/L, and was still greater than 10 mg/L in 2016	3	BCS952, BCS953, BCS973
Nitrate-N has been less than 10 mg/L in all years	1	BCS967

¹Chapter 173-200 WAC Water quality standards for groundwaters of Washington.

<http://apps.leg.wa.gov/WAC/default.aspx?cite=173-200>

In addition to trends in individual wells, we also used the Mann-Kendall method to assess potential trends in the annual average and median nitrate concentrations for 11 wells that were consistently sampled during 2003-2016 (Figure 12). Data for 2014 were not included because they were collected after the spring season.

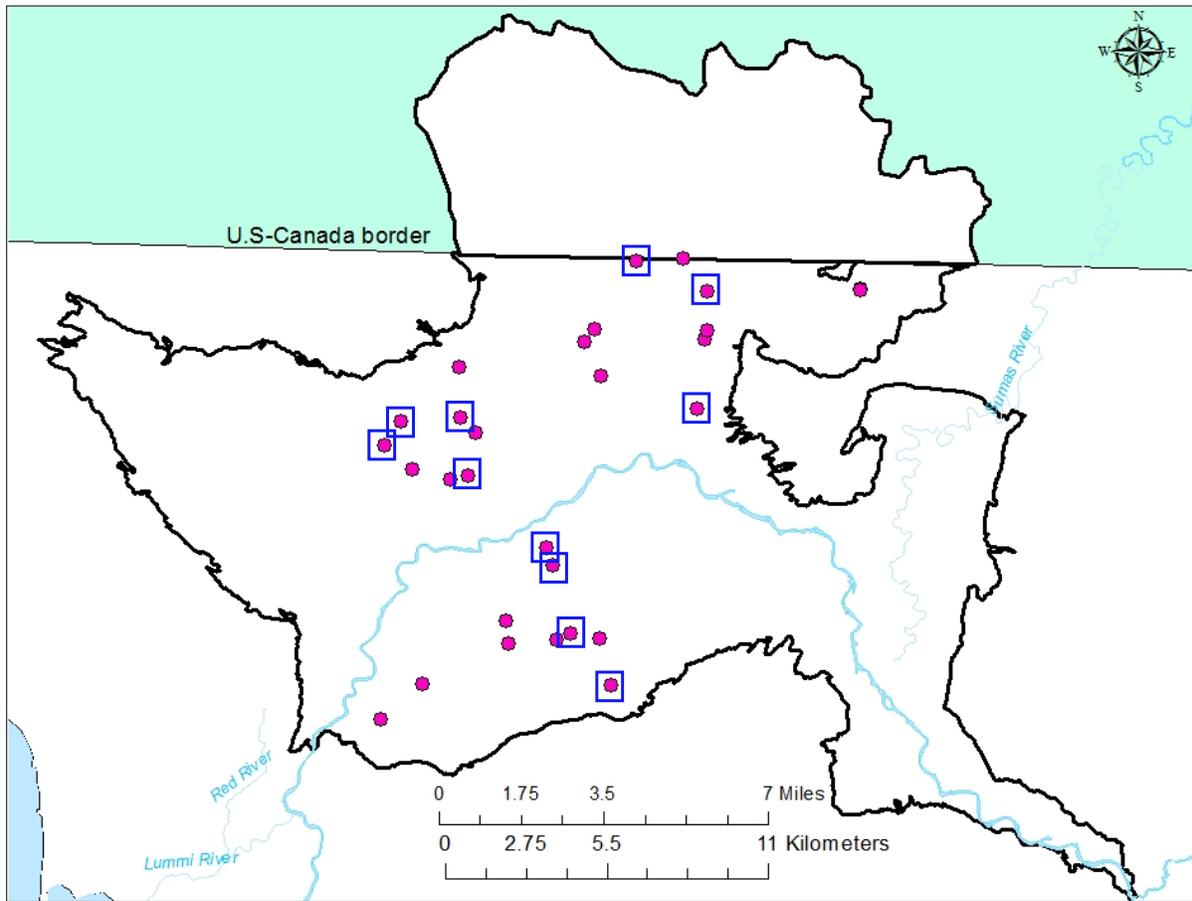


Figure 12. Sampled wells with complete nitrate data for 2003-2005 and 2009-2016.

Pink dots indicate all wells sampled in 2009-2016.

Blue squares indicate wells with a complete nitrate record for spring 2003-2005 and 2009-2016.

The annual average nitrate-N concentration in wells with complete data sets showed a statistically significant decreasing trend from 13.8 mg/L in 2003 to 8.70 mg/L in 2016 (Figure 13). The annual median nitrate-N concentration also showed a statistically significant decrease from 10.2 to 6.99 mg/L. The percent of samples that exceeded 10 mg/L nitrate-N in the complete data set also decreased from 55%-64% in 2003-2005 to 18%-27% in 2013-2016 (Table 5).

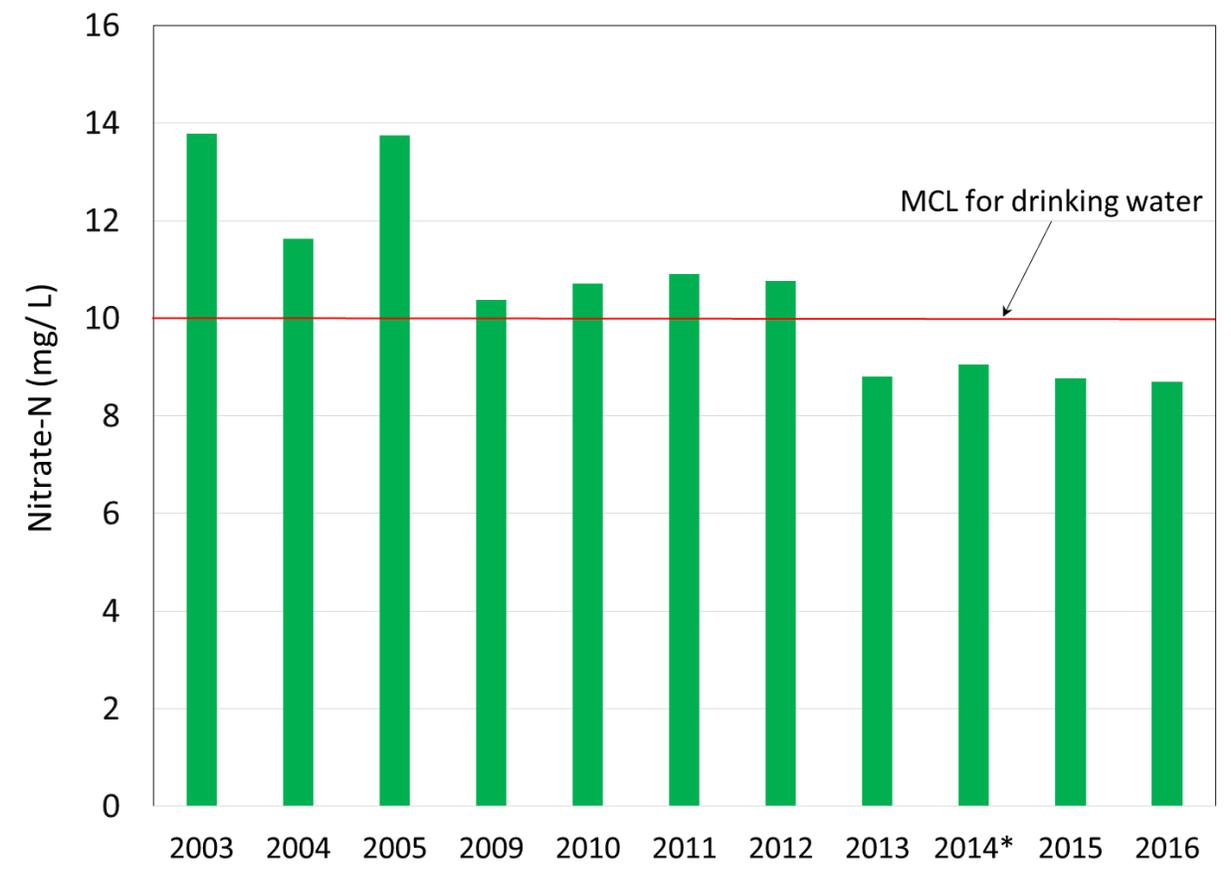


Figure 13. Annual average nitrate-N concentrations for 11 wells with complete records.

Table 5. Descriptive statistics for nitrate-N concentrations in 11 wells with complete records for 2003-2005 and 2009-2016 and the percentage of wells exceeding 10 mg/L nitrate-N.

	2003	2004	2005	2009	2010	2011	2012	2013	2014*	2015	2016
Average	13.8	11.6	13.7	10.4	10.7	10.9	10.8	8.80	9.06	8.77	8.70
Median	10.2	10.7	12.5	8.49	8.23	8.37	7.96	7.44	7.34	8.81	6.99
Maximum	34.0	32.0	34.0	28.0	24.0	24.5	25.3	22.9	25.1	23.3	24.0
Minimum	1.60	2.12	2.65	4.85	4.70	4.03	5.72	1.84	2.66	1.68	2.25
Standard Deviation	10.8	8.0	8.7	6.9	5.7	6.6	7.0	6.1	6.6	5.7	5.7
% wells exceeding 10 mg/L	55	64	64	36	27	27	36	18	27	18	18

*Samples were collected in May.

The annual average and median nitrate-N concentrations in all sampled wells, including those with incomplete records, also showed a statistically significant decreasing trend from 2003 to 2016 (Table 3). The percent of samples that exceeded 10 mg/L nitrate-N also decreased from 48-63% in 2003-2005 to 15-32% in 2013-2016 (Table 3).

Annual snapshot maps of nitrate-N concentrations shown in Figures 8-10 indicate fewer nitrate-N results in the 10-30 mg/L category in recent years than in earlier years. Likewise, there were more results in the 5-10 mg/L category in recent years than in earlier years.

Nitrate-N concentrations still did not meet the 10 mg/L drinking water standard in 24% of the wells sampled in 2016 that had sufficient data for trend analysis. Four of the 25 trend wells were not accessible for sampling in 2016.

Precipitation influence on nitrate concentrations

The available period of record for nitrate sampling is relatively short compared to long-term climate cycles. However, there appears to be a correlation between median nitrate-N concentrations in groundwater from the SBA and wintertime precipitation based on records from the Abbotsford, British Columbia, Airport (September-March) (Figure 14).

Winter precipitation during the 6 winter months preceding groundwater sampling was used for the precipitation indicator, because nearly all annual recharge to the aquifer occurs during the winter. Local field studies have documented very rapid movement of recharge to the shallow water table (Cox, 2016; Carey et al., 2014; Carey, 2002). The fall/winter period was therefore considered the most important season for nitrate mobilization.

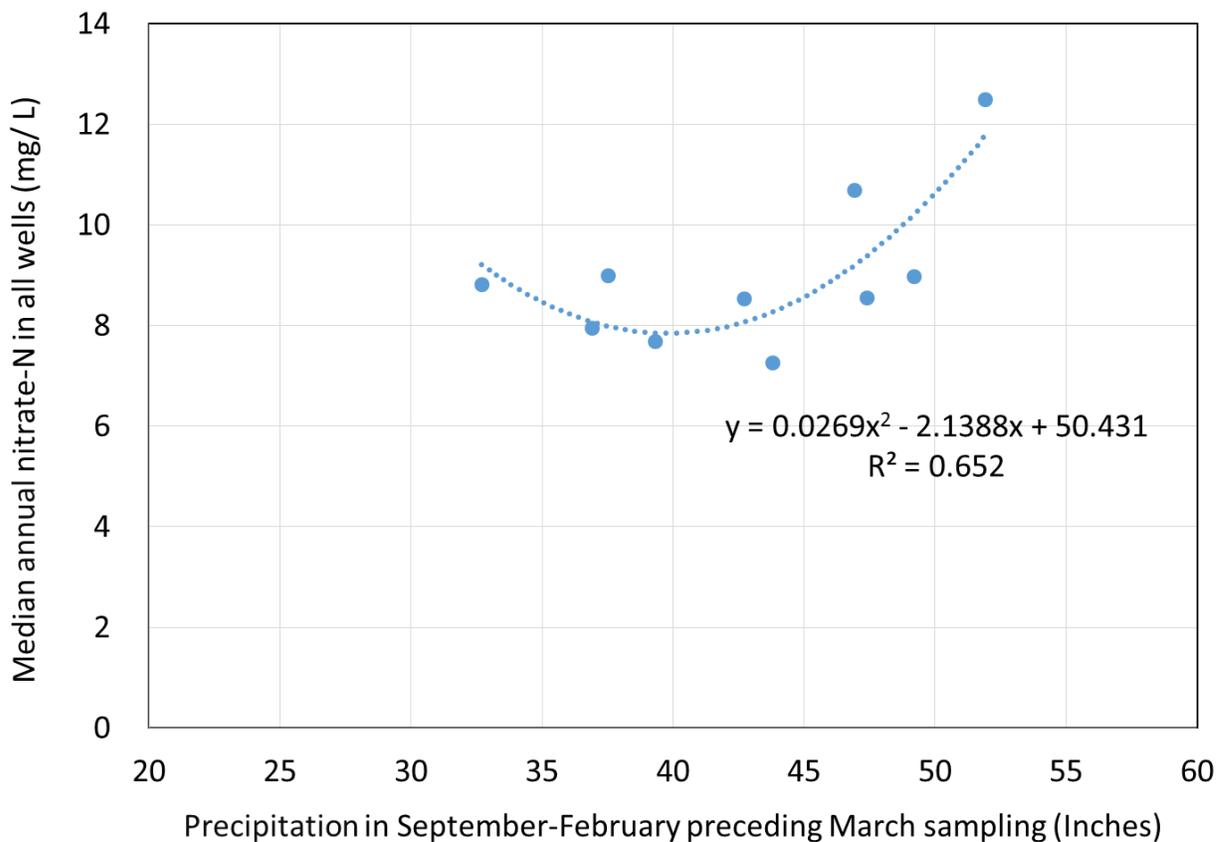


Figure 14. Trend line for correlation between annual median groundwater nitrate-N concentration and winter precipitation (September-March) at Abbotsford, B.C. Airport for 2003-2005 and 2009-2016.

2013 is excluded due to gaps in the precipitation record for 2013.

http://climate.weather.gc.ca/historical_data/search_historic_data_e.html

The correlation between precipitation and groundwater nitrate-N concentration is similar to findings in the northern portion of the Abbotsford-Sumas aquifer. Graham et al. (2015) found that warmer, drier El Nino winters with less recharge resulted in less nitrate leaching than cooler, wetter winters. Wick et al. (2012) and Fraters et al. (2015) found higher nitrate mass leaching, yet lower leachate nitrate concentrations, in wetter years due to dilution. However, Graham et al. (2015) and Owens et al. (2012) reported both higher nitrate mass leaching and higher nitrate concentrations in groundwater. The latter two studies may indicate that dilution from higher recharge in these settings did not overcome the effects of greater nitrate mass leaching.

Ammonium

Ammonium-N was detected in 4 of 23 wells sampled in 2015 and 2016 at relatively low concentrations (Table 2). Reducing conditions (low dissolved oxygen) were also found in samples from wells with ammonium-N. This is consistent with results from Cox and Kahle (1999), where few of the 182 ammonia samples they collected across the SBA contained more than 0.01 mg/L ammonium-N. Ammonium-N is typically converted to nitrate when sufficient oxygen and carbon are adequate for the bacterial reaction.

Conductivity measurements in 2 wells with ammonium detections (BCS953 and BCS965) were 100-200 umhos/cm higher than the area average conductivity of 223 umhos/cm. This may indicate a nearby source of organic nitrogen and/or leakage along the well's annular space.

Chloride

Chloride is a good tracer for animal and human waste because it is relatively non-reactive chemically and biologically. Chloride is also typically not found in significant concentrations in geologic materials or in fertilizers. Cox and Kahle (1999) categorized naturally occurring chloride concentrations in local groundwater resulting from infiltrating precipitation as less than 4 mg/L. Concentrations of chloride greater than 4 mg/L and less than 40 mg/L were considered likely indicators of contamination from animal or human waste (Erickson, 1998; Cox and Kahle, 1999).

Erickson (1994) evaluated leakage from two local dairy lagoons and reported chloride concentrations in lagoon wastewater of 139-962 mg/L. Chloride concentrations in liquid samples collected from a manure gun at a grass field in the area averaged 340 mg/L and ranged from 153 to 652 mg/L (Carey, 2002).

The annual mean and median chloride concentrations in samples collected during this study during 2009-2016 were lower than those reported by Erickson (1998). Erickson (1998) found a mean chloride concentration of 13.7 mg/L and a median of 8.3 mg/L based on 248 area wells (Table 6). The mean annual chloride concentrations observed during the current study ranged from 6.2 to 9.9 mg/L. The annual median chloride concentration ranged from 5.4 to 8.2 mg/L.

Table 6. Annual mean, median, maximum, and minimum chloride values for 2009-2016 and number of wells sampled (mg/L).

	2009	2010	2011	2012	2013	2014*	2015	2016
Mean	9.55	9.92	8.43	8.36	7.45	8.68	8.07	6.16
Median	7.45	8.24	6.99	7.11	6.19	6.06	5.69	5.44
Maximum	24.9	25.3	33.6	38.3	27.8	43.7	53.5	13.3
Minimum	2.21	1.88	1.94	1.07	2.36	1.68	1.36	1.52
n	24	25	24	23	20	16	21	21

*Samples were collected in May.

n: Number of samples.

Statistically significant downward trends were detected in chloride concentrations at 6 wells during this study, while one well showed an upward trend (Table 3 and Figure 15). The remaining 18 wells showed no statistically significant trend in chloride concentration.

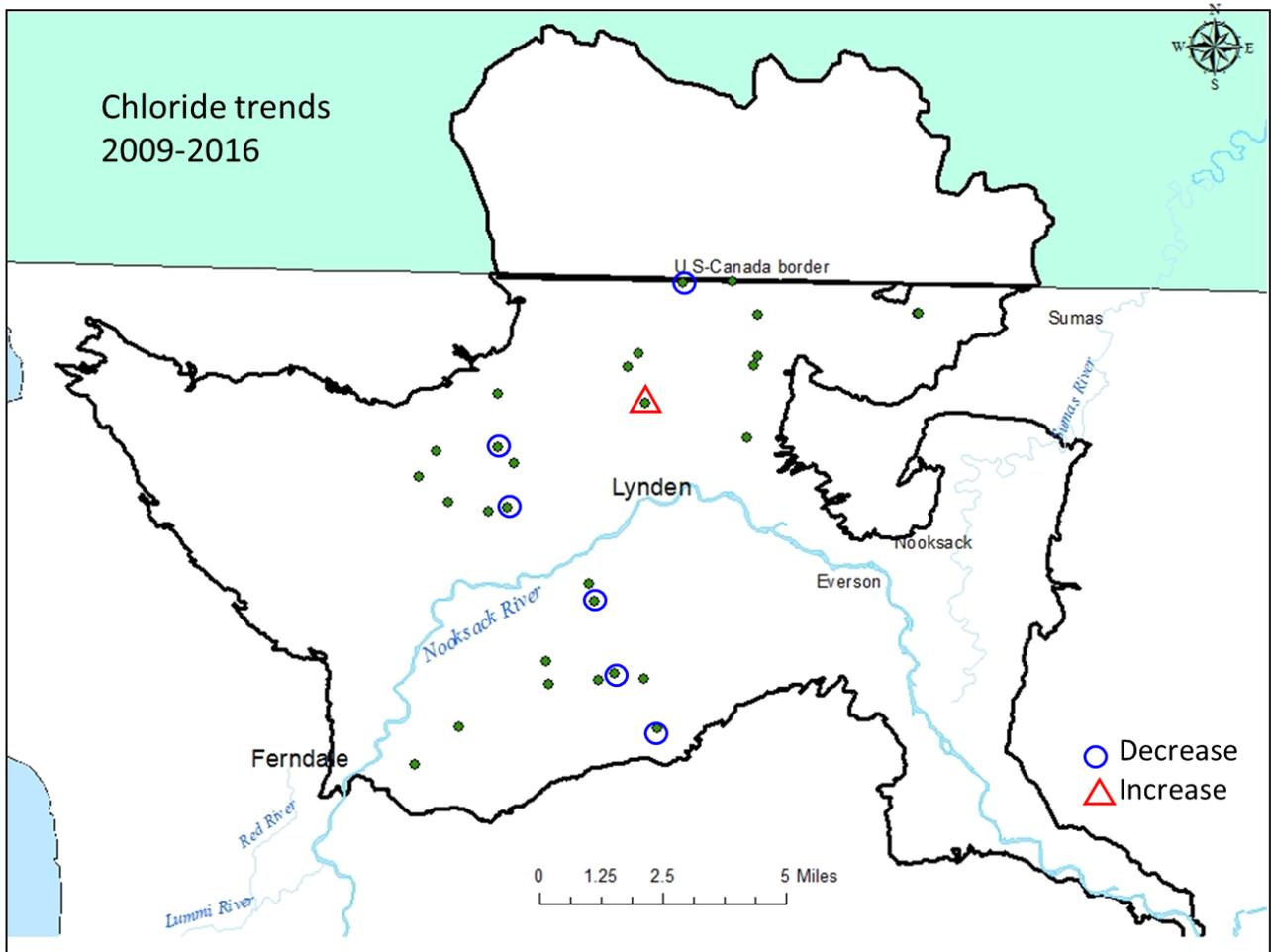


Figure 15. Wells with statistically significant trends in chloride concentration for 2009-2016 using the Mann-Kendall test at the 95% confidence level.

Three wells with statistically significant decreasing chloride trends also had decreasing nitrate trends (Table 3). Chemical and biological reactions such as denitrification and crop uptake affect nitrate, but not chloride, and may help explain the differences between trends in the 2 ions in some locations. The difference between the trends may also be related to the source of nitrate, whether animal/human, chemical fertilizer, or both.

The annual average and median chloride concentrations for the wells as a whole showed significant downward trends during 2009 to 2016 (Table 6). The annual average chloride concentration was 9.55 mg/L in 2009 and 6.16 mg/L in 2016. The median concentration was 7.45 mg/L in 2009 and 5.44 mg/L in 2016.

Nitrate, chloride, and dissolved oxygen

Time series plots of nitrate, chloride and dissolved oxygen illustrate that in some wells nitrate and chloride followed similar patterns (Figures 5-7). Correlation coefficients (r^2) for nitrate and chloride concentrations were greater than 0.70 in 6 wells (BCS958, BCS960, BCS964, BCS968, BCS970, and BCS973), indicating a possible relationship between sources. Nitrate-N concentrations in 5 of the 6 wells were greater than 10 mg/L.

Although nitrate at a particular location can originate from a combination of sources, similar upward and downward changes in nitrate and chloride concentrations over time likely suggest manure and/or human waste as a primary source. Wells where nitrate and chloride did not track closely could indicate influence from inorganic fertilizer or manure/animal waste where proportionately more nitrogen has been lost to volatilization, denitrification, or crop removal than at other locations. The shorter period of record for chloride (8 years) compared to nitrate (11 years) may have prevented detection of tandem trends with nitrate. The stringent 95% trend confidence level likewise may have prevented detection of changes that might be evident if less stringent confidence levels were used.

Chloride/bromide ratio

Bromide, like chloride, is a conservative element in the environment. When used in combination with other evidence and indicators, the chloride/bromide (Cl/Br) mass ratio can potentially be used as a tracer to distinguish among sources of groundwater contamination, especially domestic sewage, stormwater, and agriculture (Davis et al., 1998; Katz et al., 2011; Pasten-Zapata, 2014). Much of the chloride and bromide in groundwater comes from atmospheric deposition, especially near salt water (Davis et al., 1998). Further from the coast, other sources of chloride and bromide, such as on-site sewage systems, seawater intrusion, agricultural activities, and dissolution of minerals in soil, become more influential.

Chlorine and bromine have similar properties, including high solubility, low adsorption in solution, and low concentration in rock minerals. The main difference between the ions is that chlorine is about 40 to 8,000 times more prevalent than bromine in the environment. Therefore, if chlorine is relatively stable, small changes in bromine can help indicate a source of contamination (Davis et al., 1998). The Cl/Br ratio has mainly been found to be effective in helping evaluate contaminant sources when the chloride concentration in groundwater is greater than 20 mg/L (Katz et al., 2011). Chloride concentrations in wells where bromide was detected during this study, 1.7-13.3 mg/L, were below 20 mg/L. Therefore the method may not be appropriate for this setting.

The Cl/Br ratio is also not well suited for detecting on-site sewage contamination in areas with a low density of on-site systems such as the SBA area (Katz et al., 2011). The method is more applicable to areas where lot sizes are 1 acre or less.

Pesticides containing bromine have also been shown to affect Cl/Br ratios in urban runoff (Davis et al., 1998). Groundwater contamination from ethylene dibromide (EDB) and 1,2-dichloropropane (1,2-DCP) has been documented in the SBA study area (Redding, 2011b;

Ecology, 1999). In 2007, EDB and breakdown products were detected in some of the wells shown in Figure 16. Davis et al. (1998) reported Cl/Br ratios of 10 to 100 in urban runoff containing EDB in the 1980s, when EDB was still being used as a gasoline additive.

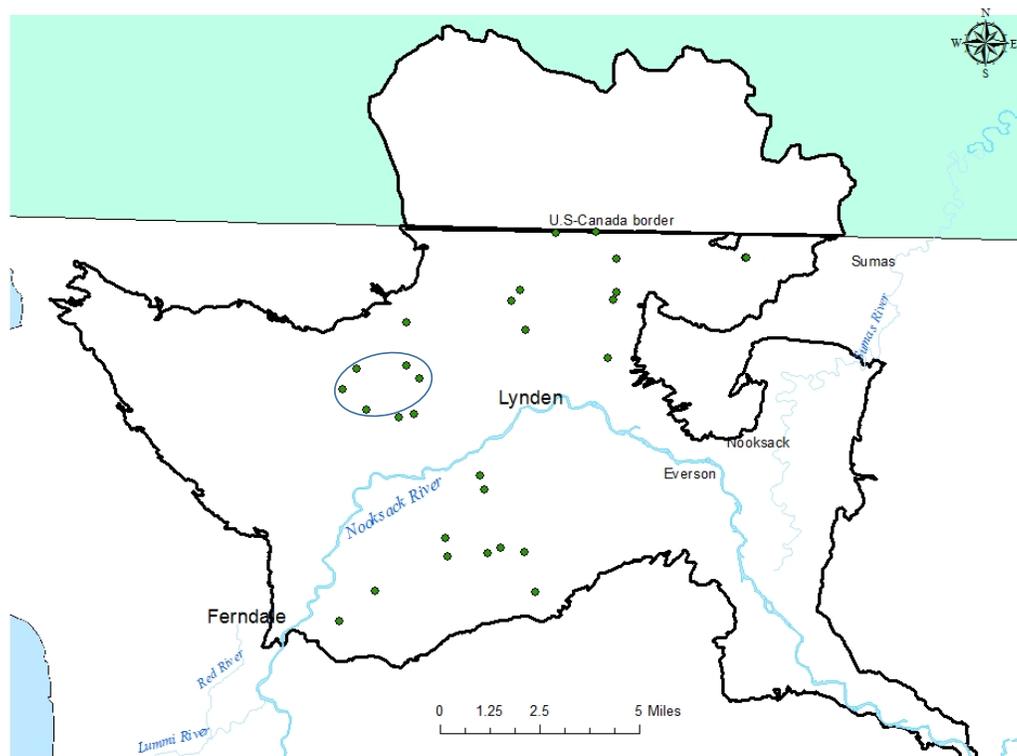


Figure 16. The area (ring) where EDB and breakdown products, 1,2-DCP and DBCP, were detected in water supply wells in 2007 (Redding, 2011b).

Circles indicate wells sampled as part of the current study.

The following general ranges of Cl/Br mass ratios have been suggested for possible source screening in conjunction with other information:

- 400-1,100 – On-site sewage (Katz et al., 2011)
- 100-1,200 – Agrochemicals (Pasten-Zapata et al., 2014)
- 10-100 – Brominated pesticides such as EDB (Davis et al., 1998)

Overlap in Cl/Br ranges associated with different sources prevents clear distinctions between sources except for the low EDB ratios.

Figure 17 shows the Cl/Br ratios for wells where bromide was detected. Three wells with Cl/Br ratios less than or equal to 100, indicative of brominated pesticides, are located in the area where EDB contamination occurred and was detected most recently in 2007 (Redding, 2011b).

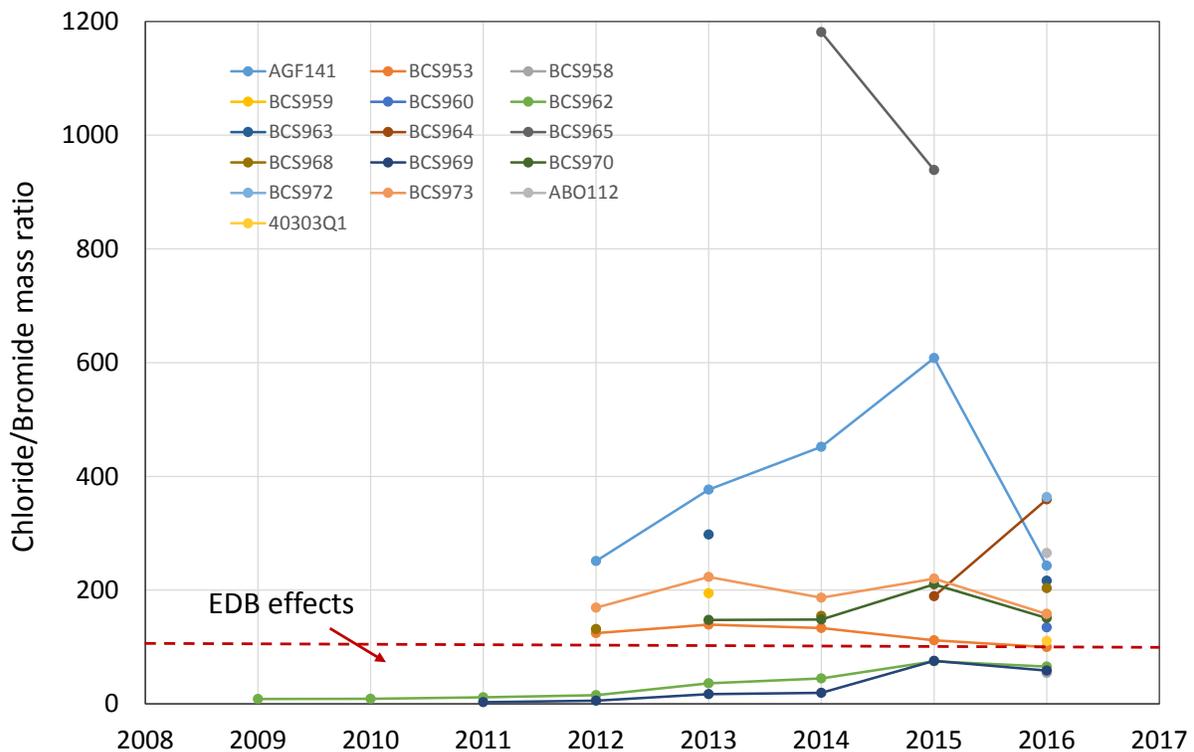


Figure 17. Chloride/bromide mass ratios in wells where bromide was detected. Ratios below 100 may indicate influence from EDB and/or EDB breakdown products.

Limitations of the current study

The current SBA ambient groundwater monitoring network has several limitations for assessing nitrate trends. These limitations include: the scale of the study, unreliable access to wells, sample representativeness of aquifer quality, uncertain local groundwater flow direction, and the potential impacts of long-term climate oscillations.

Study scale and unreliable access to wells

The scale of the study is relatively small for the 150-square-mile aquifer area. Each of the 25 wells analyzed represents only a limited area upgradient of the well. Groundwater quality can be extremely variable over short distances, because land use overlying the SBA is so variable. In addition, slow groundwater movement (on the order of feet/year) limits the representativeness of the 25-well data set for the SBA as a whole.

The number of consistently sampled wells has decreased since 2009 due to changes in land ownership or owners opting out of the study. Five wells that are no longer accessible had nitrate-N results greater than 10 mg/L, indicative of a contaminant source.

Representativeness

Samples from private drinking water wells may not be representative of recently recharged (younger) groundwater. The top of the open interval of wells, where groundwater enters the well, was an average of 11 feet below the top of the water table and ranged from 3 to 36 feet (Appendix A). Water levels in most wells were at least 10 feet below the top of the water table based on drilling logs. Because sample water intake was probably below the top of the water table during most sampling events, results may not represent water that recently reached the water table.

Figure 18 illustrates that generally groundwater at deeper depths in a surficial aquifer originates at some distance upgradient of the well. Deeper water represents older groundwater than groundwater at shallow depths. Well water at deeper depths typically entered the aquifer over an unknown period of time and represents a mixture of water of different ages.

At least 12 wells sampled in the study are shallow, dug wells sealed with concrete. Such wells are susceptible to leaking between tile curbs, which may allow leaching of surface water along the well casing, especially during the rainy winter season. Drilling logs are not available for an additional 5 older shallow wells that may be similarly constructed.

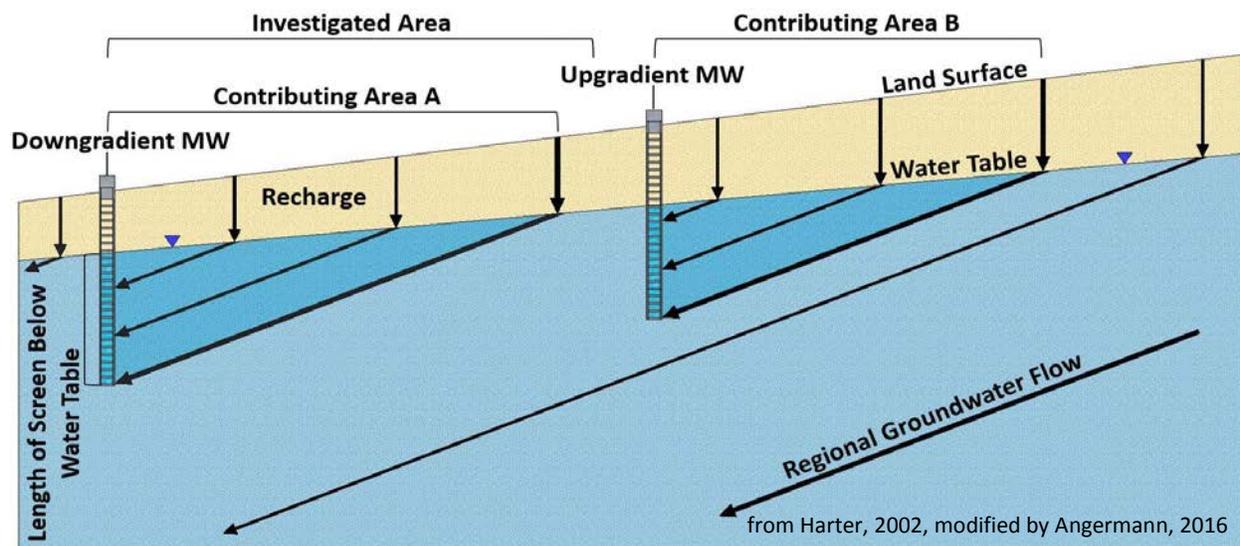


Figure 18. Generalized groundwater flow diagram showing that water near the top of the water table represents the most recent recharge from above-land uses.

Water deeper in the aquifer represents water recharged further upgradient and longer ago than shallow groundwater. Vertical tubes with horizontal lines represent wells. MW = Monitoring well.

Flow direction

Another limitation of the current network is the lack of information on the local groundwater flow direction in the vicinity of individual wells. Without information on nearby flow direction, it is difficult to determine land use impacts on individual wells. Assessing land use impacts at individual wells was not the intent of the study and would require a more intensive monitoring program.

Climate influences

The period of record for this study is short compared with climatic cycles shown to affect groundwater nitrate-N concentrations. The 17-year nitrate record for the Environment Canada groundwater monitoring network in the nearby northern portion of the Abbotsford-Sumas aquifer provided evidence of seasonal influences due to cycles in precipitation (1 year) as well as longer-period cycles (~5 years) (Graham et al., 2015). These cycles may be due to ENSO (El Niño Southern Oscillation) or the PNA (Pacific North American) pattern.

Nitrate-N variations of up to ± 3 mg/L may be explained simply by climate variability. Graham et al. (2015) caution that a sufficiently long period of record is needed to include climate oscillations in trend analyses in this location. They advise that attributing short-term trends in groundwater nitrate concentration to land use or management practices without taking long-term climate variability into account can be misleading.

Conclusions

The Sumas-Blaine aquifer (SBA) ambient groundwater monitoring network provides information to evaluate trends over time for nitrate and chloride in drinking water wells at roughly 25 locations. Nitrate trend analysis for individual wells indicated statistically significant decreases in 9 of 25 wells (36%) at the 95% confidence level ($p < 0.05$) for 2009-2016. No statistically significant nitrate trends were observed in 15 wells (56%), and one well showed a significant increase (4%). Trend results for 1997-2016 in 19 wells were consistent with results for 2003-2016.

Nitrate-nitrogen (nitrate-N) concentrations in 5 wells with statistically significant decreasing trends that had been greater than 10 mg/L in earlier years were below 10 mg/L in the most recent samples. In 3 wells with statistically significant decreasing trends, the latest nitrate-N concentrations were still above 10 mg/L.

The average and median annual nitrate-N concentrations trended downward in 11 wells with a complete nitrate record. The percentage of wells exceeding (not meeting) the 10 mg/L standard for drinking water and groundwater likewise trended downward in the group with complete data. Exceedances of the nitrate groundwater standard were lower for the most part in recent years (15-32% in 2013-2016) than in 2003-2005 (48-63%). Despite decreasing or stable nitrate-N concentrations in the majority of wells, 24% of 25 wells analyzed for trends continued to exceed (not meet) the drinking water standard in 2016.

Annual median nitrate-N concentrations were correlated with precipitation during the 6 months preceding sampling (September-March). Long-term climate cycles may influence groundwater nitrate concentrations, but the current period of record is too short to determine their importance.

Chloride trends for 2009-2016 were significantly downward in 6 wells (24%), were not significant in 18 (72%), and increased in 1 (4%). In 3 wells, both nitrate and chloride results showed a statistically decreasing trend. Corresponding changes in nitrate and chloride concentrations suggest animal/human sources in some wells. A somewhat shorter period of record for chloride than nitrate and the stringent 95% confidence limit may have obscured similarities in nitrate and chloride trends. In some cases, differences in nitrate and chloride trends may be related to inorganic nitrogen fertilizer sources or to animal/human sources, where nitrate losses vary from year to year due to chemical and biological processes in the environment.

The chloride/bromide mass ratio was not a useful indicator of nutrient sources locally due to overlap in the signals for different land uses and to generally low chloride concentrations.

The current SBA groundwater monitoring network provides a broad-scale assessment of changes in nitrate and related constituents over time, with limitations. Samples from drinking water wells may not be representative of recently recharged water. The network does not address groundwater flow direction and related cause-and-effect relationships. Unreliable access to the network's domestic wells, and the small number of wells sampled relative to the spatial extent of the aquifer, limit the ability to draw conclusions about changes in nitrate concentrations over time in the SBA as a whole.

Recommendations

The following recommendations are intended to improve our understanding of nitrate conditions in the Sumas-Blaine aquifer (SBA):

- Conduct a follow-up, large-scale, spring-season well sampling for nitrate and chloride across the SBA to compare current conditions with those observed in 1997.
- Assemble interested local and regional stakeholders, including farmers and local residents, to evaluate and revise the monitoring network goals and objectives for the SBA. Possible goals for the next stage of monitoring could include:
 - Characterize the groundwater flow system in more detail, including groundwater/surface water interactions and building on the U.S. Geological Survey (USGS) and Environment Canada monitoring efforts.
 - Monitor the most recently recharged groundwater representative of recent activities.
 - Determine the impact of various land uses and management practices on groundwater.
 - Investigate climate influences on groundwater nitrate concentration.
 - Characterize concentrations of other chemicals of concern (e.g., pesticides, herbicides, pharmaceuticals).
- Propose a re-designed, long-term monitoring study based on the revised recommended goals and objectives.
- Continue sampling wells in the current network to provide a long-term record of nitrate concentrations until revisions to the program are finalized.
- Test age-dating methods and additional tracers to identify nitrate sources.

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Appendices

Appendix A. Well construction information from drilling logs

Additional details for each well are available in the EIM database: <http://www.ecy.wa.gov/eim/groundwaterInt.htm>

Well Tag	Location	Site Latitude (Decimal degrees	Site Longitude (Decimal degrees	Water Use ¹	Land surface altitude (feet-- NAVD88)	Well depth (feet) ²	Casing diameter (inches)	Completion type and open interval (feet) ³	Drawdown test method and duration (hours) ⁵	Drawdown level from driller's log (feet) ⁶	Static water level from driller's log (feet) ⁶	Distance from top of screen or open interval to water table (feet) ⁶	Length of screen or perforations (feet)	Seal material		
ID	Local number	NAD83 HARN)	NAD83 HARN)													
AGF141	39N/02E-12C1	39212C1	48.8892175	-122.4970834	P	84	37	36	O	1	P4	Yes	12	25	27	Concrete
BCS951	39N/03E-17H1	39317H1	48.87019572	-122.4469225	D	99	118	18	P (21-23)	A	A1	Yes	flowing	NA	2	Bentonite
BCS952	39N/03E-07K2	39307K2	48.88399788	-122.473273	D	86	24	36	P (18-24)			Yes	10	8	6	Concrete
BCS953	39N/03E-07H1	39307H1	48.88593598	-122.4664953	D	89	29	6	S (24-29)			Yes	10	14	5	Bentonite
BCS954	39N/02E-12K2	39212K2	48.8822871	-122.495604	D	86	20	12	P (19.5-20.0)	1	P1	Yes	5	14.5	1.5	Concrete
BCS955	39N/02E-15J1	39215J1	48.86915645	-122.5346919	D	67	22	12	P (21.5-22.0)	5	B4	Yes	10	11.5	0.5	Concrete
BCS956	39N/02E-21H1	39221H1	48.85789579	-122.5538999	D	67	29	6	S (24-29)	8	B1	Yes	8	16	5	Bentonite
BCS957	40N/02E-11P1	40211P1	48.96708772	-122.5215007	D	111	31	8	S (21-31)	7	A1	Yes	5	16	10	Bentonite
BCS958	40N/02E-23A3	40223A3	48.94682067	-122.5133205	D	94	23	6	P (18-23)	2	P4	Yes	3	15	5	Bentonite & cement
BCS959	40N/02E-26B1	40226B1	48.93368898	-122.5161679	D	84	34	36	O			Yes	16	18		Concrete
BCS960	40N/02E-26D2	40226D2	48.93241888	-122.524424	D	75	15 R					No		5		No log
BCS961	40N/02E-21J5	40221J5	48.94233000	-122.55557	D	89	17	18				No		7		No log
BCS962	40N/02E-14P1	40214P1	48.95154878	-122.5205087	D	98	43	36	S (29-39)	6	P1	Yes	22	7	10	Bentonite
BCS963	40N/02E-22D1	40222D1	48.94972619	-122.5479615	D	96		18				No				No log
BCS964	40N/03E-05N3	40305N3	48.97979626	-122.459263	D	130	29	36	O			Yes	6	23	10.3	Concrete
BCS965	40N/03E-08P1	40308P1	48.96550568	-122.4557403	D	117	15 R	36	O			No		5		No log
BCS966	40N/03E-31P3	40331P3	48.90690342	-122.4758653	D	83	36	18	P (30-36)	4	P2	Yes	24	6	6	Concrete
BCS967	40N/03E-31L1	40331L1	48.91228517	-122.4787826	D	70	30	18	P (24-30)			Yes		14	6	Concrete
BCS968	40N/03E-10F1	40310F1	48.97739921	-122.4078477	D	136	21	36	P (6-21)			Yes		0	15	Concrete
BCS969	40N/02E-27C1	40227C1	48.93517030	-122.542019	D	78	32 R	18				No		22		No log
BCS970	41N/03E-33M1	41333M1	49.00092099	-122.4403481	D	150	43	6	S (38-43)	3	B1	Yes	17	21	5	Bentonite
BCS971	41N/03E-34E1	41334E1	49.00199364	-122.4182973	D	150	20	36	P (12-20)			Yes	4	8	8	Concrete
BCS972	40N/03E-03B1	40303B1	48.99214286	-122.4066568	D	136	29	6	S (24-29)			Yes	10	19	5	Bentonite
BCS973	40N/03E-15L1	40315L1	48.95604514	-122.4100942	D	103	20 R					No		10		No log
ABO112	41N/04E-31Q1	N41431Q1	48.99358178	-122.3353541	D	170	50	6	S (42-50)	8	B4	Yes	36	6	8	Bentonite
AGT433	40N/03E-03Q1	N41431Q1	48.98015933	-122.406256	D	138	30	6	O	2	B4	Yes	8	22		Bentonite
	39N/03E-08F2	39308F2	48.88459809	-122.4563028	D	90	20	12	P (19.5-20.0)	1	P4	Yes	7	12.5	0.5	Concrete
	40N/03E-07H1	40307H1	48.97588306	-122.4636143	D	123	21	36	O	7	B1	Yes	4	17		Concrete

¹ P-Public water supply, D-Private domestic water supply, I-Irrigation

² R-Reported well depth, no driller's log available

³ P-Casing with perforations, O-Open ended casing, S-Well screen

⁴ A-Artesian

⁵ P-Pumped, B-Bailer test, A-Air test

⁶ Depth relative to land surface

⁷ Based on drilling log

Appendix B. Water quality results

EIM Location ID	Well Tag ID	Sample Date	Field Measurements						Lab Results								
			Temperature (C°)	pH (Standard Units)		Conductivity (umhos/cm)		Dissolved Oxygen (mg/L)		Ammonia-N (mg/L)		Nitrite+Nitrate-N (mg/L)		Chloride (mg/L)		Bromide (mg/L)	
41431Q1	ABO112	4/1/2009	9.7									13.8		10.1	J	0.2	U
41431Q1	ABO112	3/4/2010	9.9	7.50	J	215	J					10.4	J	7.07		0.2	U
41431Q1	ABO112	3/30/2011	10.1	5.96	J	231	J	8.96	J			12.6		7.09		0.2	U
41431Q1	ABO112	3/7/2012	9.0	5.73	J	222	J	5.96	J			8.66		10.1		0.025	U
41431Q1	ABO112	3/19/2013	9.12	4.88	J			7.66	J			8.52		9.50		0.025	U
41431Q1	ABO112	3/17/2015	17.0	6.01		176		9.83		0.01	U	8.06		2.27		0.025	U
41431Q1	ABO112	3/22/2016	17.0	6.19		222		7.48		0.01	U	4.55		7.96		0.03	
39212C1	AGF141	3/18/2009	12.3	5.81	J			5.25	J			9.19		15.9	J	0.2	U
39212C1	AGF141	3/3/2010	12.3	6.42	J	249	J	5.03	J			12.1		14.9		0.2	U
39212C1	AGF141	3/30/2011	11.6	6.01	J	209	J	6.95	J			8.76		11.2		0.2	U
39212C1	AGF141	3/8/2012	11.8	5.56	J	210	J	6.77	J			8.71		11.8		0.047	
39212C1	AGF141	3/22/2013	11.6	5.63	J			7.11	J			8.85		11.3		0.03	
39212C1	AGF141	5/14/2014	12.1	6.54		202						9.95		11.3		0.025	
39212C1	AGF141	3/16/2015	12.4	5.99		240		4.98		0.01	U	11.3		15.2		0.025	
39212C1	AGF141	3/23/2016	12.5	6.09		187		5.55		0.01	U	9.20		10.2		0.042	
39317H1	BCS951	3/18/2009	13.3	6.08	J	167	J	5.02	J			7.25		10.2	J	0.2	U
39317H1	BCS951	3/3/2010	10.6	6.09	J	209	J	3.18	J			7.48		10.3		0.2	U
39317H1	BCS951	3/30/2011	10.7	6.04	J	206	J					7.84		8.01		0.2	U
39317H1	BCS951	3/8/2012	9.7	5.73	J	186	J	3.80	J			6.62		5.62		0.025	U
39317H1	BCS951	3/20/2013	10.2	4.96	J			3.23	J			7.44		7.06		0.025	U
39317H1	BCS951	5/14/2014	12.0	6.38		194						7.34		5.93		0.025	U
39317H1	BCS951	3/16/2015	11.2	6.16		178		3.41		0.01	U	8.81		5.00		0.025	U
39317H1	BCS951	3/23/2016	11.1	6.19		169		3.34		0.01	U	6.99		5.06		0.025	U
39307K2	BCS952	3/18/2009	12.1	6.58	J	269	J	5.80	J			12.9		6.68	J	0.2	U

EIM Location ID	Well Tag ID	Sample Date	Field Measurements						Lab Results								
			Temperature (C°)	pH (Standard Units)		Conductivity (umhos/cm)		Dissolved Oxygen (mg/L)		Ammonia-N (mg/L)		Nitrite+Nitrate-N (mg/L)		Chloride (mg/L)		Bromide (mg/L)	
39307K2	BCS952	3/24/2010	10.5	5.37	J	282	J					13.0		6.68		0.2	U
39307K2	BCS952	3/30/2011	10.3	6.31	J	273	J	6.78	J			11.2		7.05		0.2	U
39307K2	BCS952	3/8/2012	10.2	5.88	J	313	J	5.92	J			14.2		8.39		0.2	U
39307H1	BCS953	3/18/2009	11.4	6.21	J			6.67	J			27.3		3.76	J	0.2	U
39307H1	BCS953	3/3/2010	10.2			395	J	6.92	J			23.5		4.02		0.2	U
39307H1	BCS953	3/30/2011	10.3	6.44	J	368	J	8.10	J			24.5		3.91		0.2	U
39307H1	BCS953	3/8/2012	10.3	6.12	J	368	J	7.43	J			22.6		3.73		0.03	
39307H1	BCS953	3/22/2013	9.68					7.27	J			22.9		3.76		0.027	
39307H1	BCS953	5/14/2014	10.7	6.85		370						16.6		3.34		0.025	
39307H1	BCS953	3/16/2015	10.6	6.55		345		7.82		0.01		23.3		2.80		0.025	U
39307H1	BCS953	3/23/2016	10.7	6.57		349		6.15		0.01	U	24.0		3.00		0.03	
39212K2	BCS954	3/18/2009	10.4	6.25	J			8.66				2.07		2.21	J	0.2	U
39212K2	BCS954	3/4/2010	9.70	6.36	J	72	J	9.98				2.27	J	1.88		0.2	U
39212K2	BCS954	3/31/2011	9.66	6.43	J	80	J					1.77		1.94		0.2	U
39212K2	BCS954	3/8/2012	9.5	6.09	J	61	J					1.37		1.07		0.025	U
39212K2	BCS954	5/14/2014	10.5	6.75		76						2.17		1.68		0.025	U
39212K2	BCS954	3/16/2015	10.8	6.52		76		9.03		0.01	U	2.47		1.36		0.025	U
39212K2	BCS954	3/23/2016	10.2	6.58		68		8.71		0.01	U	2.13		1.52		0.025	U
39215J1	BCS955	3/18/2009	10.4	6.49	J			5.08	J			2.18		3.77	J	0.2	U
39215J1	BCS955	3/24/2010	10.1	5.01	J	124	J					2.80		4.96		0.2	U
39215J1	BCS955	3/31/2011	10.2	6.3	J	128	J	6.78	J			2.58		6.96		0.2	U
39215J1	BCS955	3/8/2012	10.2	5.92	J	151	J	5.64	J			4.35		8.80		0.025	U
39215J1	BCS955	3/16/2015	10.8	6.28		118		4.87		0.01	U	3.04		2.96		0.025	U
39215J1	BCS955	3/23/2016	10.7	6.37		118		5.35		0.01	U	2.79		4.10		0.025	U
39221H1	BCS956	3/18/2009	10.1	6.42	J	141	J	7.17	J			3.38		6.98	J	0.2	U
39221H1	BCS956	3/3/2010	10.1	8.27	J	165	J	6.43	J			4.08		7.14		0.2	U
39221H1	BCS956	3/31/2011	10.1	6.34	J	152	J	7.61	J			2.80		6.66		0.2	U

EIM Location ID	Well Tag ID	Sample Date	Field Measurements						Lab Results								
			Temperature (C°)	pH (Standard Units)		Conductivity (umhos/cm)		Dissolved Oxygen (mg/L)		Ammonia-N (mg/L)		Nitrite+Nitrate-N (mg/L)		Chloride (mg/L)		Bromide (mg/L)	
39221H1	BCS956	3/8/2012	10.0	6.03	J	159	J	7.09	J			3.41		7.6		0.025	U
39221H1	BCS956	3/22/2013	9.87	5.39	J							2.37		5.38		0.025	U
39221H1	BCS956	3/16/2015	10.4	6.33		160		7.06		0.01	U	3.87		6.64		0.025	U
39221H1	BCS956	3/23/2016	10.4	6.44		139		5.77		0.01	U	2.86		4.51		0.025	U
40211P1	BCS957	3/19/2009	9.1	6.43		318	J					0.956		14.2	J	0.2	U
40211P1	BCS957	3/4/2010	9.4	6.52		271	J	3.96	J			3.97	J	13.1		0.2	U
40211P1	BCS957	3/8/2012										7.81		1.94		0.025	U
40211P1	BCS957	3/22/2013	7.7	5.05	J			6.37	J			6.31		2.36		0.025	U
40223A3	BCS958	3/19/2009	8.7	5.81	J	81	J	6.56	J			2.43		2.54	J	0.2	U
40223A3	BCS958	3/4/2010	9.6	7.26	J	82	J	7.78	J			1.36	J	3.46		0.2	U
40223A3	BCS958	3/31/2011	9.2	5.77	J	70	J	9.86	J			2.77		2.30		0.025	U
40223A3	BCS958	3/8/2012	9.6	5.39	J	106	J	7.27	J			4.83		3.98		0.025	U
40223A3	BCS958	3/22/2013	10.2	6.16	J			5.11	J			4.55		4.52		0.025	U
40223A3	BCS958	3/21/2016	9.7	5.85		65		6.87		0.01	U	1.53		1.74		0.032	
40226B1	BCS959	3/19/2009	11.1	6.21	J	186	J	3.54	J			5.41		7.08	J	0.2	U
40226B1	BCS959	3/4/2010	11.3	6.96	J	173	J	3.82	J			4.70	J	6.78		0.2	U
40226B1	BCS959	3/31/2011	11.3	6.2	J	154	J	6.19	J			4.03		5.21		0.2	U
40226B1	BCS959	3/8/2012	11.2	5.9	J	168	J	4.53	J			5.77		6.13		0.025	U
40226B1	BCS959	3/22/2013	11.2	5.2	J							5.93		5.06		0.026	
40226B1	BCS959	5/12/2014	11.9	5.82		193						7.01		6.12		0.025	U
40226B1	BCS959	3/18/2015	11.9	5.82		193		4.14		0.01	U	5.75		3.51		0.025	U
40226B1	BCS959	3/21/2016	11.8	6.23		171		4.24		0.01	U	6.65		5.23		0.033	
40226D2	BCS960	3/19/2009	9.3	5.94	J	243	J	8.12	J			15.5		5.04	J	0.2	U
40226D2	BCS960	3/4/2010	10.1	6.24	J	228	J	8.97	J			14.2	J	5.98		0.2	U
40226D2	BCS960	3/31/2011	9.54	5.89	J	203	J					11.0		3.37		0.2	U
40226D2	BCS960	3/18/2015	10.9	5.91		202		9.56		0.01	U	11.9		3.34		0.025	U
40226D2	BCS960	3/21/2016	10.7	5.93		220		8.24		0.01	U	13.2		3.77		0.028	

EIM Location ID	Well Tag ID	Sample Date	Field Measurements						Lab Results								
			Temperature (C°)	pH (Standard Units)		Conductivity (umhos/cm)		Dissolved Oxygen (mg/L)		Ammonia-N (mg/L)		Nitrite+Nitrate-N (mg/L)		Chloride (mg/L)		Bromide (mg/L)	
40221J5	BCS961	3/19/2009	8.0	5.91	J	133	J	6.63	J			4.85		6.04	J	0.2	U
40221J5	BCS961	3/4/2010	10.3	6.34	J	135	J	4.43	J			7.88	J	6.75		0.2	U
40221J5	BCS961	3/31/2011	8.2	7.65	J	148	J	7.65	J			8.37		6.46		0.2	U
40221J5	BCS961	3/8/2012	8.7	5.31	J	139	J	6.87	J			5.72		7.25		0.025	U
40221J5	BCS961	3/20/2013	8.5	5.07	J			6.11	J			1.84		5.43		0.025	U
40221J5	BCS961	5/12/2014	9.2	5.22		109						4.98		8.38		0.025	U
40221J5	BCS961	3/18/2015	9.8	6.19		145		7.83		0.01	U	4.31		7.85		0.025	U
40221J5	BCS961	3/21/2016	9.9	5.86		127		5.06		0.01	U	2.25		7.20		0.025	U
40214P1	BCS962	3/19/2009	9.9	7.04	J	357	J	9.88	J			16.1		18.1	J	2.13	
40214P1	BCS962	3/24/2010	10	4.92	J	397	J					14.9		23.0		2.61	
40214P1	BCS962	3/31/2011	10.3	6.05	J	370	J	10.0	J			17.3		13.5		1.17	
40214P1	BCS962	3/8/2012	9.18	5.43	J	373	J	8.73	J			25.3		6.33		0.418	
40214P1	BCS962	3/22/2013	9.39	5.56	J			9.37	J			16		4.83		0.134	
40214P1	BCS962	5/12/2014	11.1	5.54		310						25.1		6.14		0.137	
40214P1	BCS962	3/18/2015	10.4	6.16		266		8.33		0.01	U	12.7		4.95		0.066	
40214P1	BCS962	3/21/2016	10.6	5.99		254		7.35		0.01	U	9.76		4.34		0.066	
40222D1	BCS963	3/19/2009	9.7	5.9	J	216	J	4.16	J			5.52		8.44	J	0.2	U
40222D1	BCS963	3/24/2010	10.4	4.76	J			4.49	J			7.36		13.8		0.2	U
40222D1	BCS963	3/31/2011	10.1	5.86	J	252	J	6.28	J			6.62		12.0		0.2	U
40222D1	BCS963	3/8/2012	10.1	5.44	J	241	J	4.33	J			6.19		11.7		0.025	U
40222D1	BCS963	3/20/2013	10.2	6.16	J			5.11	J			2.36		7.74		0.026	
40222D1	BCS963	5/13/2014	11.5	5.69		208						2.66		8.00		0.025	U
40222D1	BCS963	3/17/2015	11.1	6.22		182		5.57		0.01	U	1.68		10.3		0.025	U
40222D1	BCS963	3/21/2016	11.2	5.96		248		4.99		0.01	U	4.35		5.85		0.027	
40305N3	BCS964	3/19/2009	9.0	5.82	J	422	J	6.36	J			23.7		23.1	J	0.2	U
40305N3	BCS964	3/4/2010	9.5	7.45	J	276	J	5.53	J			12.8	J	15.2		0.2	U
40305N3	BCS964	3/31/2011	9.3	5.88	J	232	J	6.77	J			5.64		8.75		0.2	U

EIM Location ID	Well Tag ID	Sample Date	Field Measurements							Lab Results							
			Temperature (C°)	pH (Standard Units)		Conductivity (umhos/cm)		Dissolved Oxygen (mg/L)		Ammonia-N (mg/L)		Nitrite+Nitrate-N (mg/L)		Chloride (mg/L)		Bromide (mg/L)	
40305N3	BCS964	3/7/2012	9.3	5.64	J	211	J	5.92	J			4.45		7.12		0.038	
40305N3	BCS964	3/22/2013	9.18	4.27	J							2.30		3.84		0.025	U
40305N3	BCS964	3/18/2015	10.4	6.12		212		5.29		0.046		5.31		7.01		0.037	
40305N3	BCS964	3/22/2016	10.6	5.91		279		3.63		0.041		9.05		13.3		0.037	
40308P1	BCS965	3/19/2009	9.7	5.88	J	441	J					14.2		24.9	J	0.2	U
40308P1	BCS965	3/24/2010	10.9	4.72	J	288	J	2.27	J			12.1		25.3		0.2	U
40308P1	BCS965	3/31/2011	10.2	5.82	J	432	J	0.66	J			12.6		33.6		0.2	U
40308P1	BCS965	3/7/2012	9.8	5.39	J	476	J	1.45	J			10.2		38.3		0.025	U
40308P1	BCS965	3/20/2013	10.1	5.88	J		J	2.57	J			6.77		27.8		0.025	U
40308P1	BCS965	5/13/2014	12.0	5.58		503						11.8		43.7		0.037	
40308P1	BCS965	3/17/2015	10.5	6.01		583		0.78		0.155		21.7		53.5		0.057	
40331P3	BCS966	3/20/2009	11.0	6.27	J	249	J	5.50	J			5.18		6.98	J	0.2	U
40331P3	BCS966	3/3/2010	10.9	6.42	J	243	J	6.62	J			8.23		9.95		0.2	U
40331P3	BCS966	3/30/2011	11.2	6.1	J	200	J	7.28	J			4.21		6.9		0.2	U
40331P3	BCS966	3/8/2012	11.2	5.78	J	241		6.32	J			8.1		8.75		0.025	U
40331P3	BCS966	3/22/2013	10.9	4.46	J			7.58	J			7.15		7.38		0.025	U
40331P3	BCS966	5/13/2014	11.4	5.96		209						4.28		7.79		0.025	U
40331P3	BCS966	3/18/2015	11.2	6.32		212		5.91		0.01	U	6.93		5.16		0.025	U
40331P3	BCS966	3/24/2016	11.2	6.39		204		3.60		0.01	U	7.99		4.79		0.025	U
40331L1	BCS967	3/20/2009	9.6	6.97	J	212	J	5.00	J			8.49		7.73	J	0.2	U
40331L1	BCS967	3/3/2010	9.7	6.97	J	193	J	3.28	J			5.35		9.05		0.2	U
40331L1	BCS967	3/30/2011	9.8	6.64	J	173	J	5.68	J			5.85		6.38		0.2	U
40331L1	BCS967	3/8/2012	9.7	6.33	J	185	J	3.74	J			5.8		5.98		0.025	U
40331L1	BCS967	3/20/2013	9.7	5.82	J			3.80	J			5.21		6.35		0.025	U
40331L1	BCS967	5/13/2014	9.8	6.23		155						4.18		5.43		0.025	U
40331L1	BCS967	3/18/2015	9.9	6.67		152		5.56		0.01	U	4.5		5.86		0.025	U
40331L1	BCS967	3/24/2016	10.0	6.62		168		2.87		0.01	U	5.51		8.23		0.025	U

EIM Location ID	Well Tag ID	Sample Date	Field Measurements						Lab Results								
			Temperature (C°)	pH (Standard Units)		Conductivity (umhos/cm)		Dissolved Oxygen (mg/L)		Ammonia-N (mg/L)		Nitrite+Nitrate-N (mg/L)		Chloride (mg/L)		Bromide (mg/L)	
40310F1	BCS968	3/20/2009	9.6	6.52	J	239	J					13.4		6.46	J	0.2	U
40310F1	BCS968	3/4/2010	9.7	6.49	J	258	J	9.10	J			16.5	J	7.87		0.2	U
40310F1	BCS968	3/31/2011	9.6	6.05	J	240	J	10.3	J			13.9		7.02		0.2	U
40310F1	BCS968	3/7/2012	9.7	5.75	J	248	J	8.47	J			13.5		5.39		0.041	
40310F1	BCS968	5/13/2014	10.9	5.79		206						11.1		4.33		0.028	
40310F1	BCS968	3/17/2015	11.6	6.09		201		9.64		0.01	U	10.1		4.99		0.025	U
40310F1	BCS968	3/22/2016	10.8	5.96		328		8.51		0.01	U	28.4		7.73		0.038	
40227C1	BCS969	4/1/2009	10.0					8.52	J			5.63		9.96	J	0.2	U
40227C1	BCS969	3/3/2010	11.2			206	J	7.76	J			6.22		8.71		0.2	U
40227C1	BCS969	3/30/2011	10.8	5.97	J	246	J	6.82	J			6.02		9.5		2.98	
40227C1	BCS969	3/8/2012										11.5		7.04		1.242	
40227C1	BCS969	3/20/2013										8.28		8.21		0.483	
40227C1	BCS969	5/13/2014										4.42		5.99		0.309	
40227C1	BCS969	3/18/2015	11.0	5.94		261		7.05		0.01	U	10.9		9.54		0.126	
40227C1	BCS969	3/21/2016	10.9	5.92		280		4.39		0.01	U	14.4		10.5		0.179	
41333M1	BCS970	4/1/2009	10.4					8.54	J			12.6		7.16	J	0.2	U
41333M1	BCS970	3/4/2010	10.9	7.03	J	307	J	6.00	J			14.7	J	8.24		0.2	U
41333M1	BCS970	3/31/2011	10.5	6.10	J	307	J	7.82	J			17.7		6.81		0.2	U
41333M1	BCS970	3/7/2012	10.6	5.77	J	296	J	8.02	J			12.5		6.96		0.025	U
41333M1	BCS970	3/19/2013	10.1	7.31	J			6.60	J			9.08		5.76		0.039	
41333M1	BCS970	5/13/2014	11.1	5.85		216						8.06		5.04		0.034	
41333M1	BCS970	3/17/2015	11.1	6.15		236		5.08		0.01	U	9.47		6.31		0.030	
41333M1	BCS970	3/22/2016	11.3	6.16		239		6.46		0.01	U	6.91		5.89		0.039	
41334E1	BCS971	4/1/2009	9.3									9.41		9.68	J	0.2	U
41334E1	BCS971	3/4/2010	10.6	6.20	J	192	J	7.17	J			8.55	J	12.8		0.2	U
41334E1	BCS971	3/31/2011	10.4	5.75	J	200	J	8.51	J			10.8		8.05		0.2	U
41334E1	BCS971	3/22/2013	8.9	4.51	J							7.52		7.49		0.025	U

EIM Location ID	Well Tag ID	Sample Date	Field Measurements						Lab Results								
			Temperature (C°)	pH (Standard Units)		Conductivity (umhos/cm)		Dissolved Oxygen (mg/L)		Ammonia-N (mg/L)		Nitrite+Nitrate-N (mg/L)		Chloride (mg/L)		Bromide (mg/L)	
40303B1	BCS972	4/1/2009	9.9									8.82		12.5	J	0.2	U
40303B1	BCS972	3/4/2010	9.8	6.39	J	204	J	7.30	J			9.12	J	14.2		0.2	U
40303B1	BCS972	3/31/2011	10.6	5.92	J	249	J	9.10	J			13.7		13.7		0.2	U
40303B1	BCS972	3/7/2012	9.3	5.66	J	197	J	7.49	J			7.96		11.1		0.025	U
40303B1	BCS972	3/22/2013	9.9	3.99	J							8.44		9.23		0.025	U
40303B1	BCS972	5/13/2014	10.2	5.80		192						8.77		9.71		0.025	U
40303B1	BCS972	3/17/2015	10.8	6.03		194		8.41		0.01	U	9.16		7.52		0.025	U
40303B1	BCS972	3/22/2016	11.3	5.97		204		6.61		0.01	U	9.92		13.1		0.036	
40315L1	BCS973	4/1/2009	13.2									11.9		6.64	J	0.2	U
40315L1	BCS973	3/24/2010	16.5	5.31	J							14.2		6.93		0.2	U
40315L1	BCS973	3/31/2011	11.3	6.16	J	223	J					9.83		6.05		0.2	U
40315L1	BCS973	3/7/2012										11.9		7.11		0.042	
40315L1	BCS973	3/22/2013										10.5		6.03		0.027	
40315L1	BCS973	5/13/2014	11.1	5.73		221						10.7		5.97		0.032	
40315L1	BCS973	3/16/2015	10.6	6.03		210		9.75		0.01	U	9.85		5.51		0.025	U
40315L1	BCS973	3/24/2016	10.7	6.08		202		8.19		0.01	U	11.4		5.69		0.036	
39308F2		3/23/2016	10.5	6.03		202		8.41		0.01	U	7.53		4.37		0.025	U
40307H1		3/17/2015	10.4	5.98		293		0.00									
40307H1		3/22/2016	10.7	5.79		293		1.37									
40303Q1	AGT433	3/22/2016	11.2	6.14		257		7.65		0.014		6.32		4.2		0.038	

J: the analyte was positively identified; the reported result is an estimate

U: the analyte was not detected at or above the reported value

Appendix C. Quality assurance results

Field meter calibration and verification

A Hydrolab MS-5 mini-sonde for measuring temperature, pH, conductivity, and dissolved oxygen was calibrated before each field event and post-calibrated at the end of the event per SOP EAP033 (Swanson, 2007). Calibration results were recorded only during 2014-2016.

Fresh commercially-prepared buffer solutions and reference standards were used to calibrate the mini-sonde for pH and specific conductance. The dissolved oxygen sensor was calibrated against theoretical water-saturated air using the manufacturer-supplied calibration chamber. The initial pH and specific conductance calibrations were checked by placing the probes in pH buffer solutions and reference standards, respectively, and evaluating the difference between the standard and the meter values (Table C-1). The pH calibration was accepted if the metered values differed by less than ± 0.05 pH units from the buffer value. The specific conductance calibration was accepted if the meter values deviated by no more than $\pm 5\%$ from the specific conductance check standards.

After each sampling event, the mini-sonde was rechecked against reference standards to confirm it had not drifted unacceptably since the initial calibration. Results were either accepted, qualified as estimates, or rejected as unusable based on the post-use acceptance criteria listed in Table C-1.

Field measurements collected before field calibrations were recorded in 2009-2013 and are flagged as estimates (J). Pre-calibration in 2014 also met acceptance standards; however, post-calibration was not conducted in 2014. Therefore, field measurements for 2014 are also J-qualified.

Calibration acceptance standards were met for pH, conductivity, and dissolved oxygen and were accepted without qualification (Table C-1).

Water quality data

Private drinking water wells were purged and sampled according to SOP EAP096 (Carey, 2016). Field measurements were made using an in-line flow cell. Samples were collected using disposable in-line filters as shown in Figure C-1.

Samples were collected in clean bottles supplied by Manchester Environmental Laboratory (MEL). Pre-acidified bottles were used for nitrate and ammonia samples. Filled sample bottles were labeled, bagged, and stored in clean, ice-filled coolers until their arrival at MEL for analysis. Chain-of-custody procedures were followed throughout the project.

Table C-1. Hydrolab mini-sonde calibration records for 2014-2016.

Date	Status	pH				Specific conductance				Dissolved oxygen			
		Reference standard (pH)	Meter reading (pH)	Deviation from standard (pH units)	Accept or reject calibration /result ^{1,2}	Reference standard (uS/cm)	Meter reading (uS/cm)	Deviation from standard (%)	Accept or reject calibration /result ^{1,2}	Meter reading (mg/L)	Saturation (%)	Deviation from saturation (%)	Accept or reject calibration /result ^{1,2}
5/9/2014	Pre-sampling	7.00	7.00	0.0	Accept	0.0	0.0	0.0	Accept				
		4.01	4.01	0.0	Accept	1413	1413	0	Accept	8.68	100.0	0.0	Accept
3/12/2015	Pre-Sampling	7.00	7.00	0.0	Accept	0.0	0.0	0.0	Accept	8.60	99.9	0.1	Accept
		4.01	4.00	0.01	Accept	100.0	100.9	0.9	Accept				
3/20/2015	Post-Sampling	7.00	7.00	0.0	Accept	1412	1412	0.0	Accept				
		4.01	4.03	0.02	Accept	0.0	0.0	0.0	Accept	8.81	97.4	2.6	Accept
3/17/2016	Pre-Sampling	7.00	7.00	0.0	Accept	100.0	99.3	0.7	Accept				
		4.01	4.06	0.05	Accept	1412	1408	4.0	Accept	8.54	99.9	0.1	Accept
3/28/2016	Post-Sampling	7.00	6.96	0.04	Accept	1413	1406	7.0	Accept				
		4.01	3.93	0.08	Accept	0.0	0.0	0.0	Accept	8.56	97.0	3.0	Accept
						100.3	99.4	0.9	Accept				
						1413	1392	21	Accept				

¹Pre-sampling calibration acceptance criteria

²Post-sampling acceptance criteria-deviation from check standards

pH

Deviation from check standards following initial calibration:
 ≤± 0.05 pH deviation from all standards = Accept calibration
 >± 0.05 pH deviation from any standard = Reject calibration

pH

Deviation from check standards following post-calibration:
 ≤± 0.15 pH deviation from all standards = Accept results
 >± 0.15 pH and ≤± 0.5 pH deviation from any standard = Reject results
 ± 0.5 pH deviation from any standard = Reject results

Specific conductance

≤± 5% deviation from all standards = Accept calibration
 >± 5% deviation from any standard = Reject calibration

Specific conductance

≤± 5% deviation from all standards = Accept results
 >± 5% and ≤± 10% deviation from any standard = Qualify results as estimates ("J" code)
 > 10% deviation from any standard = Reject results

Dissolved oxygen

≥ 99.7% saturation and ≤ 100.3% = Accept calibration
 < 99.7% saturation or > 100.3% = Reject calibration

Dissolved oxygen

≤ ±5% saturation = Accept results
 ≥ ± 5% saturation and ≤ ± 10% = Qualify results as estimates ("J" code)
 ≥ ± 10% = Reject results

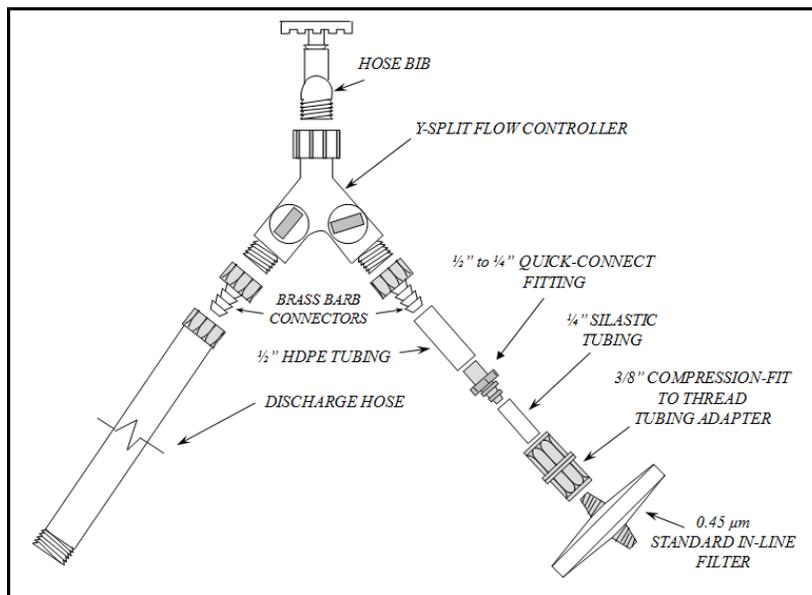


Figure C-1. Sample collection using y-split flow controller and disposable 0.45 um in-line filter. (from Carey, 2016—SOP EAP096)

Table C-2 lists the measurement quality objectives for the study.

Table C-2. Measurement quality objectives.

Parameter	Accuracy	Field Replicate Precision (% RPD)	Laboratory duplicates (% RPD)	Matrix spikes (% recovery limits)	Matrix spike duplicates (RPD)
Field Parameters					
Temperature	± 0.1 °C	NA	NA	NA	NA
pH	± 0.15 SU	± 10%	NA	NA	NA
Specific conductance	± 10 uS/cm	± 10 %	NA	NA	NA
Dissolved oxygen	± 0.2 mg/L	± 20 %	NA	NA	NA
Laboratory Analyses					
Nitrate+Nitrite-N	± 20%	± 7%	± 15%	75-125%	± 20%
Chloride	± 25%	± 5%	± 15%	75-125%	± 20%
Bromide	± 25%	± 5%	± 15%	75-125%	± 20%

RPD = relative percent difference

Laboratory quality assurance

MEL follows strict protocols to ensure and evaluate the quality of analytical results (Ecology, 2008). Instrument calibration was performed by laboratory staff before each analytical run and checked against verification standards and blank samples. Calibration standards and blanks were analyzed at a frequency of 10% during the analysis and at the end of the analytical run. The laboratory also evaluates procedural blanks, spiked samples, and laboratory control samples (LCS) as additional quality checks. Results of these analyses were summarized in a case narrative and submitted to the author along with each result package.

The laboratory quality assurance (QA) narrative and supporting data indicate that all samples arrived at the laboratory in good condition. Table C-3 lists the laboratory QA results. All samples were processed and analyzed within acceptable holding times. Two samples did not meet the applicable acceptance criteria: the chloride matrix spike analyzed on 4/9/2009, and one of the bromide lab duplicates on 4/9/2009. All other QA samples met the applicable acceptance criteria (Table C-2). Chloride samples from the 2009 sampling event that were associated with the chloride matrix spike sample that did not meet the acceptance standard are qualified as estimates (J) in Appendix B. Bromide samples associated with the 4/9/2009 sample are considered acceptable without qualification, because the concentrations were less than 5 times the reporting limit, the guideline suggested by MEL.

Table C-3. Laboratory quality assurance results.

Date	Parameter	Laboratory Duplicate Results					Laboratory Control Samples (LCS)	Matrix Spike	Blank	
		mg/L		mg/L		RPD				
3/30/2015	Ammonia-N	0.010	U	0.010	U	NA	102	99	0.010	U
3/30/2015		0.010	U	0.010	U	NA	102	100	0.010	U
3/30/2016		0.010	U	0.010	U	NA	100	96	0.010	U
3/30/2016		0.010	U	0.010	U	NA	99	99	0.010	U
4/9/2009	Nitrate+ Nitrite-N	1.74		1.74		0.03	99	102	0.010	U
4/9/2009		4.84		4.85		0.20	99	91	0.010	U
4/9/2009		0.465		0.464		0.07	102	99	0.010	U
4/9/2009		3.5		3.5		0.06	101	102	0.010	U
3/15/2010		7.19		7.48		3.95	99	101	0.010	U
3/15/2010		0.575		0.562		2.29	112	110	0.010	U
3/26/2010		0.010	U	0.010	U	NA	102	95	0.010	U
4/6/2011		6.09		5.85		4.02	101	89	0.010	U
4/6/2011		10.6		10.8		1.87	102	92	0.010	U
4/11/2011		0.757		0.758		0.13	106	95	0.010	U
3/14/2012		8.27		8.33		0.72	98	94	0.010	U
3/14/2012		2.45		2.50		2.02	101	94	0.010	U
3/22/2013		9.11		9.08		0.33	105	93	0.010	U
3/27/2013		0.035		0.034		2.90	105	105	0.010	U
3/27/2013		0.111		0.117		5.26	107	107	0.010	U
5/23/2014		0.189		0.188		0.53	101	91	0.010	U
5/23/2014		9.95		9.95		0.00	104	94	0.010	U
3/20/2015		11.2		11.3		0.89	105	92	0.010	U
3/30/2015		9.47		9.80		3.43	108	90	0.010	U
4/26/2016		2.12		2.13		0.47	109	95	0.010	U
4/26/2016	0.038		0.036		5.41	106	103	0.010	U	

U: the analyte was not detected at or above the reported value.

Table C-3 (continued). Laboratory quality assurance results.

Date	Parameter	Laboratory Duplicate Results			Laboratory Control Samples (LCS)	Matrix Spike	Blank	
		mg/L	mg/L	RPD				
4/9/2009	Chloride	16.3	14.3	14	96	72	0.10	U
4/9/2009						77		
4/9/2009		5.10	5.09	0.20	96	96	0.10	U
4/9/2009						96		
4/9/2009		9.95	9.96	0.06	97	95	0.10	U
4/9/2009						98		
4/9/2009		9.69	9.68	0.10	97	96	0.10	U
4/9/2009						93		
3/9/2010		10.3	10.3	0.04	102	101	0.10	U
3/9/2010						106		
3/31/2010		6.70	6.71	0.15	99	105	0.10	U
4/8/2010		213	214	0.47	100	99	0.10	U
4/5/2011		7.90	8.01	1.38	100	102	0.10	U
4/5/2011		9.42	9.50	0.85	96	105	0.10	U
4/6/2011		7.95	8.05	1.25	104	102	0.10	U
4/6/2011		1.95	1.94	0.51	103	103	0.10	U
3/28/2012		38.3	38.3	0.00	101	100	0.10	U
3/28/2012						101		
3/28/2012		6.01	5.98	0.50	101	98	0.10	U
3/28/2012						101		
3/25/2013		4.88	4.88	0.02	97	100	0.10	U
3/25/2013						98		
3/26/2013		2.34	2.36	0.85	97	99	0.10	U
5/23/2014		11.3	11.3	0.20	100	100	0.10	U
5/23/2014						96		
3/23/2015		2.95	2.95	0.00	101	99	0.10	U
3/23/2015	7.52	7.51	0.13		97			
4/4/2016	10.3	10.2	1.00	103	104	0.10	U	
4/4/2016					104			

U: the analyte was not detected at or above the reported value.
 Gray shading: The result did not meet data quality objectives.

Table C-3 (continued). Laboratory quality assurance results.

Date	Parameter	Laboratory Duplicate Results					Laboratory Control Samples (LCS)	Matrix Spike	Blank	
		mg/L		mg/L		RPD	90-110%	75-125%	mg/L	
4/9/2009	Bromide	0.2	U	0.2	U	NA	98	102	0.2	U
4/9/2009								102		
4/9/2009		0.2	U	0.27		29.8	99	98	0.2	U
4/9/2009								102		
4/9/2009		0.2	U	0.2	U	NA	95	100	0.2	U
4/9/2009								99		
4/9/2009							97	99	0.2	U
4/9/2009								100		
3/9/2010		0.2	U	0.2	U	NA	101	106	0.2	U
3/9/2010								107		
3/31/2010		0.2	U	0.2	U	NA	99	100	0.2	U
3/31/2010								101		
4/5/2011		0.2	U	0.2	U	NA	100	105	0.2	U
4/5/2011		3.00		2.98		0.67	99	104	0.2	U
4/6/2011		0.2	U	0.2	U	NA	104	104	0.2	U
4/6/2011		0.2	U	0.2	U	NA	105	104	0.2	U
3/13/2012		0.025	U	0.025	U	NA	102	111	0.025	U
3/13/2012								120		
3/13/2012		0.025	U	0.025	U	NA	103	114	0.025	U
3/26/2013		0.050	U	0.033			96	100	0.050	U
3/26/2013								108		
3/26/2013		0.050	U	0.025	U	NA	96	111	0.050	U
5/23/2014		0.050	U	0.025	U	NA	102	105	0.050	U
5/23/2014								109		
3/23/2015		0.025		0.025	U	0.0	96	94	0.025	U
3/23/2015								91		
3/31/2015	0.025	U	0.025	U	NA	96	87	0.025	U	
4/4/2016	0.043		0.042		0.5	101	101	0.025	U	
4/4/2016	0.025	U	0.025	U	NA		100	0.025	U	

U: the analyte was not detected at or above the reported value.
 Gray shading: The result did not meet data quality objectives.

Field quality assurance

One field transfer blank was collected during each sampling event from 2014 to 2016 by pouring unfiltered laboratory grade de-ionized water from MEL into sample bottles in the field. An equipment blank was collected in 2014 from sample tubing after rinsing with MEL de-ionized water. The field blanks were below detection for all parameters (Table C-4). Field blanks were not collected prior to 2014⁶.

Table C-4. Results of blind field blank and equipment blank samples.

Field transport blanks

Date	Nitrate+ Nitrite-N	Chloride	Bromide ¹	Ammonium- N
	mg L ⁻¹ -N			
5/13/2014	<0.010	<0.10	<0.025	
3/19/2015	<0.010	<0.10	<0.025	<0.010
3/21/2016	<0.010	<0.10	<0.025	<0.010

Field equipment blank

Date	Nitrate+ Nitrite-N	Chloride	Bromide ¹
	mg/L-N	mg/L-N	mg/L-N
5/13/2014	<0.010	<0.10	<0.025

¹ The detection limit decreased from 0.2 to 0.025 mg/L in 2012.

⁶ Because consistent field methods were used throughout this study, we've assumed here that samples collected before 2014 would also have shown no contamination resulting from the project field procedures.

All but 2 field duplicates met the project measurement quality objective of +/-15% RPD (relative percent difference) established for precision (Redding, 2009) (Table C-5). The RPD for nitrate-N on March 4, 2010 was 25.1%. The results for that date were qualified as estimates (“J coded”) (Appendix B). The RPD for bromide on March 19, 2013 was 16.7%. However, the bromide concentrations, 0.033 and 0.039 mg/L, were less than 5 times the method detection limit of 0.025 mg/L. This level of difference is acceptable at such low concentrations (MEL 2008).

Table C-5. Relative percent differences¹ between blind field duplicate samples.

Date	Well ID	Nitrate+Nitrite-N			Chloride			Bromide ²			Ammonium-N		
		mg/L-N	mg/L-N	RPD	mg/L	mg/L	RPD	mg/L	mg/L	RPD	mg/L-N	mg/L-N	RPD
3/18/2009	BCS953	27.3	28.8	5.35	3.76	3.89	3.40	<0.2	<0.2	NA			
3/19/2009	BCS964	23.7	24.1	1.67	23.1	23.0	0.43	<0.2	<0.2	NA			
3/19/2009	BCS960	14.6	14.7	0.68	5.07	5.09	0.39	<0.2	<0.2	NA			
4/1/2009	BCS970	11.5	11.9	3.42	7.16	7.16	0.00	<0.2	<0.2	NA			
3/3/2010	BCS953	23.5	23.7	0.85	4.02	4.13	2.70	<0.2	<0.2	NA			
3/4/2010	BCS970	12.8	9.95	25.1	8.24	8.26	0.24	<0.2	<0.2	NA			
3/24/2010	BCS965	12.1	12.1	0.00	25.3	25.1	0.79	<0.2	<0.2	NA			
3/30/2011	BCS953	24.5	24.5	0.00	3.91	3.87	1.03	<0.2	<0.2	NA			
3/30/2011	BCS963	6.62	6.45	2.60	12.0	12.2	1.65	<0.2	<0.2	NA			
3/31/2011	BCS965	12.6	12.5	0.80	33.6	33.4	0.60	<0.2	<0.2	NA			
3/7/2012	BCS970	12.5	12.5	0.00	6.96	6.93	0.43	<0.025	0.029	NA			
3/8/2012	BCS954	1.37	1.37	0.00	1.07	1.05	1.89	<0.025	<0.025	NA			
3/8/2012	BCS966	8.10	8.33	2.80	8.75	8.69	0.69	<0.025	<0.025	NA			
3/19/2013	BCS970	9.08	9.08	0.00	5.76	5.78	0.35	0.033	0.039	16.7			
3/20/2013	BCS961	1.84	1.82	1.09	5.43	5.42	0.18	<0.025	<0.025	NA			
3/22/2013	BCS962	16.0	16.3	1.86	4.83	4.79	0.83	0.122	0.134	9.38			
5/13/2014	BCS970	8.06	8.02	0.50	5.04	5.05	0.20	0.034	0.035	2.90			
3/17/2015	BCS972	9.16	9.12	0.44	7.52	7.51	0.13	<0.025	<0.025	NA	<0.010	<0.010	NA
3/18/2015	BCS966	6.93	6.60	4.88	5.16	5.20	0.77	<0.025	<0.025	NA	<0.010	<0.010	NA
3/21/2016	BCS960	13.1	13.2	0.76	3.77	3.96	4.92	0.028	0.028	0.00	<0.010	<0.010	NA

¹ RPD = (Difference between Result 1 and Result 2)/(Average of the duplicate results) x 100.

² The detection limit decreased from 0.2 to 0.025 mg/L in 2012.

Yellow-shaded results did not meet the data quality objective.

Except as noted above, results from the laboratory and field QA reviews indicate that the water quality data generated during this study are of high quality and can be used as intended without further qualification.

Appendix D. Glossary, acronyms, and abbreviations

Glossary

Aquifer: An underground bed of saturated material.

Conductivity: A measure of water's ability to conduct an electrical current. Conductivity is related to the concentration and charge of dissolved ions in water.

Dissolved oxygen: A measure of the amount of oxygen dissolved in water.

Groundwater: Subsurface water in the saturated zone that is under pressure that is equal to or greater than atmospheric pressure.

Maximum Contaminant Level (MCL): A standard that is set by the U.S. Environmental Protection Agency (EPA) for drinking water quality. An MCL is the legal threshold limit on the amount of a substance that is allowed in public water systems under the Safe Drinking Water Act.

Parameter: Water quality constituent being measured (analyte). A physical, chemical, or biological property whose values determine environmental characteristics or behavior.

pH: A measure of the acidity or alkalinity of water. A low pH value (0 to 7) indicates that an acidic condition is present, while a high pH (7 to 14) indicates a basic or alkaline condition. A pH of 7 is considered to be neutral. Since the pH scale is logarithmic, a water sample with a pH of 8 is ten times more basic than one with a pH of 7.

Recharge (noun): Water entering the saturated zone at the water-table surface over a period of time, usually from precipitation or irrigation.

Water table: The top of the saturated zone of an unconfined aquifer.

Acronyms and Abbreviations

Ecology	Washington State Department of Ecology
EDB	Ethylene dibromide
EIM	Environmental Information Management database
EPA	U.S. Environmental Protection Agency
MCL	Maximum contaminant level
MEL	Manchester Environmental Laboratory
Nitrate-N	Nitrate-nitrogen
QA	Quality assurance
QAPP	Quality Assurance Project Plan
RPD	Relative percent difference
SBA	Sumas-Blaine aquifer
SOP	Standard operating procedures
USGS	U.S. Geological Survey

WAC Washington Administrative Code

Units of Measurement

°C	degrees centigrade
ft	feet
km	kilometer, a unit of length equal to 1,000 meters
lbs	pounds
mg	milligram
mg/L	milligrams per liter (parts per million)
mL	milliliters
s.u.	standard units
umhos/cm	micromhos per centimeter
uS/cm	microsiemens per centimeter, a unit of conductivity