



Comparative Transboundary Nitrogen Budget of the Abbotsford – Sumas Aquifer

A project submitted in partial fulfillment of the requirements of the

Master of Land and Water Systems (MLWS)

Faculty of Land and Food Systems

University of British Columbia

Kamal Kakish

August 2018

Table of Contents

Abstract.....	3
Introduction	4
Facts and Figures from the Abbotsford – Sumas Aquifer	9
Site description.....	9
Nitrate contamination and groundwater flows	11
Agricultural land use and transboundary sources of nitrate.....	11
Long-term groundwater nitrate monitoring	12
Methodology	16
Balance Equation	16
Comparative Nitrogen Budget at the Abbotsford – Sumas Aquifer.....	16
Data requirement and data sources.....	17
Data Analysis	21
Data Analysis on the Abbotsford Sumas Aquifer Southwest BC, Canada.....	21
Total number of poultry at the ASA	21
Poultry manure -N production and application at the ASA.....	23
Atmospheric N losses from manure	25
Analysis of crop production	25
Fertilizer application on the ASA SWBC.....	26
Nitrogen Uptake by crops.....	27
Atmospheric N deposition at the ASA SWBC.....	27
Data Analysis on Abbotsford – Sumas aquifer Northwestern Washington State, US	27
Analysis of dairy animal numbers.....	28
Dairy manure- N production and application at the ASA.....	28
Atmospheric N losses from manure	29
Analysis of crop production	30
Fertilizer application on the ASA NWWS.....	30
Nitrogen Uptake by crops on ASA NWWS	31
Atmospheric N deposition at the ASA NWWS.....	31
Summary of major agricultural nitrogen flows and N- Surplus calculations.....	32
Total nitrogen surplus on the total area of the Abbotsford-Sumas aquifer.....	32
Total nitrogen surplus on the ASA SWBC	32
Total nitrogen surplus on the ASA NWWS	32
Total nitrogen surplus per hectare	33

Data limitations.....	34
Conclusion	35
Bibliography	37

List of Tables

Table 1: Components of the ASA nitrogen budget analysis.....	17
Table 2: Average per farm poultry number variation based on geographic zone (2016).....	22
Table 3: Summary of Poultry numbers per category over the ASA SWBC	23
Table 4: Manure and manure-N excretion rates and coefficients per poultry category.....	24
Table 5: Atmospheric Nitrogen loss from manure and ammonia losses as % total-N	25
Table 6: manure and manure- N production at the ASA NWWS	29
Table 7: Manure nitrogen losses on the ASA NWWS.....	30
Table 8: changes in total nitrogen surplus at the ASA based on a level of uncertainty of 15% ..	32

List of Figures

Figure 1: simplified illustration of the nitrogen cycle	5
Figure 2: Boundaries of the Abbotsford – Sumas Aquifer.....	10
Figure 3: Nitrate – N concentration from 12 wells over the ASA SWBC	14
Figure 4: Long term Nitrate - N concentration from 15 wells over the ASA NWWS	15
Figure 5: Distribution of estimated annual nitrogen inputs to the land and subsurface of the Sumas-Blain Aquifer, NWWS.....	16
Figure 6: Modelled annual total nitrogen deposition over the Georgia Basin/Puget Sound.....	18
Figure 7: Total poultry population in the city of Abbotsford (1996 – 2016)	21
Figure 8: Census of agriculture information coverage	22
Figure 9: Annual poultry manure and manure -N application on the ASA SWBC based on the two application scenarios	24
Figure 10: Nitrogen Uptake by crops on ASA SWBC (kg/year)	27
Figure 11: Total Dairy cattle numbers over the ASA based on WSDE geodatabase	28
Figure 12: Area of crop field coverage of major crops at the ASA NWWS.....	30
Figure 13: Summary of major agricultural nitrogen flows kg- N/year over the ASA.....	33

Abstract

Transboundary groundwater issues are of significant importance. These issues are gaining attention for two reasons: the depletion of aquifers is adding pressure to growing water scarcity in many parts of the world; and groundwater quality is being reduced as a consequence of several sources of anthropogenic pollution, which eventually restricts its uses in certain applications.

Achieving sustainable management of shared resources will require a shift towards holistic cooperation, while strengthening the scientific knowledge available, in order to effectively inform policy actions. This is particularly important within the Abbotsford – Sumas Aquifer, a Transboundary Aquifer (TBA) system shared by British Columbia, Canada and Washington State, US. This aquifer is characterized by an elevated nitrate concentration that exceeds drinking water standards on both sides of the international border. Its contamination has been linked to land use, specifically the extensive agricultural practices in the area.

In this paper, a comparative nitrogen budget analysis is conducted on the Abbotsford – Sumas aquifer (ASA) that includes all major agricultural nitrogen flows. The study compares nitrogen surplus amounts on both sides of the Canada - US. border. This provides an indicator of excess nitrogen that could be leaked into the environment and eventually contribute to the contamination of the aquifer. Further, conceptualising nitrogen flows at the regional scale within the extent of the aquifer can promote effective design of intervention measures and conjunctive policy creation for the sustainable management of the transboundary Abbotsford – Sumas aquifer.

The results of this study indicate a higher nitrogen surplus on the Canadian portion of the aquifer than the portion in the US. This assumes poultry manure application on berry farms within the Canadian portion of the aquifer. The surplus nitrogen is estimated to range from 610 – 749 kg- N/ ha. On the US portion of the aquifer, the total nitrogen surplus is around 353 kg- N/ha assuming dairy manure application on dairy farms' forage and grain crops within the extent of the aquifer.

Introduction

Transboundary groundwater issues are of significant importance, and remains a focal topic in a range of water literature.^{1,2,3,4} Amidst growing global water scarcity, and factors such as population growth and climate change that can contribute toward conflict and increased competition, there is a need for enhanced management of transboundary water resources.

The United Nations draft article on the Law of Transboundary Aquifers defines a transboundary aquifer as “an aquifer or aquifer system, parts of which are situated in different States”.⁵ Transboundary groundwater is a natural subsurface path of groundwater flow, intersected by an international boundary.⁶

Worldwide, there are 276 transboundary basins, shared by 148 countries and 270 transboundary aquifers that have long supported the livelihoods of millions around the world.^{7,8} Additionally, a wide range of habitat relies on groundwater flows to surface water bodies for their survival.⁹

Issues pertaining to transboundary aquifers are complex in nature. Several challenges are distinct to groundwater systems and in many cases could complicate management and protection strategies. The first challenge lies in the need for a better understanding of the interactions between groundwater and surface water systems. Nearly all groundwater features interact with surface water such as streams, lakes, reservoirs, and wetlands.¹⁰ Secondly, despite the advancement of studies and regional investigations on groundwater recharge processes, recharge evaluation and recharge zones identification remain challenging and uncertain.¹¹ In contrast to surface water, quality and quantity alterations of groundwater are often a slow process. Such dynamics require an elaborate and complex monitoring network and data interpretation which can be both expensive and time-consuming.¹²

¹ Naho Mirumachi, “Transboundary Water Security: Reviewing the Importance of National Regulatory and Accountability Capacities in International Transboundary River Basins,” *Department of Geography, King's College London*, 2013.

² Enamul Choudhury¹ and Shafiqul Islam², “Nature of Transboundary Water Conflicts: Issues of Complexity and the Enabling Conditions for Negotiated Cooperation,” *Journal of Contemporary Water Research & Education, Universities Council on Water Resources*, no. 155 (2015): 43–52.

³ Asit K. Biswas, “Indus Water Treaty: The Negotiating Process,” *Water International* 17, no. 4 (1992), <https://doi.org/10.1080/02508069208686140>.

⁴ Shira Yoffe et al., “Geography of International Water Conflict and Cooperation: Data Sets and Applications,” *Water Resources Research* 40, no. 5 (May 1, 2004), <https://doi.org/10.1029/2003WR002530>.

⁵ “Draft Articles on the Law of Transboundary Aquifers (2008),” *United Nations*, adopted by the International Law Commission at its sixtieth session (2008).

⁶ “Atlas of Transboundary Aquifers: Global Maps, Regional Cooperation and Local Inventories; 2009,” *UNESCO*, 2009.; Cited in Alfonso Rivera, “Transboundary Aquifers along the Canada–USA Border: Science, Policy and Social Issues,” *Journal of Hydrology: Regional Studies* 4 (September 2015), <https://doi.org/10.1016/j.ejrh.2015.09.006>.

⁷ “Water Resources Management Overview,” accessed July 31, 2018, <http://www.worldbank.org/en/topic/waterresourcesmanagement>.

⁸ Rivera, “Transboundary Aquifers along the Canada–USA Border.”

⁹ Rivera.

¹⁰ See generally; Thomas C. Winter et al., “Ground Water and Surface Water; a Single Resource,” USGS Numbered Series, Circular (U.S. Geological Survey, 1998), <http://pubs.er.usgs.gov/publication/cir1139>.

¹¹ Jacobus J. de Vries and Ian Simmers, “Groundwater Recharge: An Overview of Processes and Challenges,” *Hydrogeology Journal* 10, no. 1 (February 1, 2002), <https://doi.org/10.1007/s10040-001-0171-7>.

¹² Tuinhof Albert et al., “Groundwater Monitoring Requirements for Managing Aquifer Response and Quality Threats” (The World Bank, January 1, 2004), <http://documents.worldbank.org/curated/en/334871468143053052/Groundwater-monitoring-requirements-for-managing-aquifer-response-and-quality-threats>.

Nitrogen is an essential plant nutrient that is vital for plant growth. Nevertheless, excess nitrogen can negatively affect the environment and human health. For instance, nitrogen as nitrate or ammonium is highly soluble and can contribute to water and air pollution, respectively.¹³ Nitrate contamination of groundwater is a challenging and widespread concern. Nitrate “NO₃-” is the most common form of nitrogen found in water. Major anthropogenic sources of nitrate in groundwater include the leaching of chemical fertilizers, intensive animal operations, over application of animal manure, and on-site sewage systems.¹⁴

The maximum Acceptable Concentration (MAC) for nitrate in drinking water in British Columbia and Washington State is 45 mg/l, or 10mg/l when reported as nitrate-nitrogen (NO₃- N).¹⁵ The primary adverse health effect associated with human exposure to nitrate is Methemoglobinemia, commonly called “blue-baby syndrome”, which can harm infants by reducing the ability of blood to transport oxygen.¹⁶ Any concentration greater than 3 mg/L indicates that the groundwater system has been affected by anthropogenic activities.¹⁸

In the environment, natural nitrogen flux begins through the biological fixation of atmospheric N₂ by specialized bacteria, or directly during lightning. In the atmosphere and the soil, nitrogen goes through a biochemical cycle in which it is converted into multiple forms, see Figure 1.¹⁹ Through the cycle, nitrogen is combined into both living and nonliving material and exchanged between the soil and air repeatedly. The main natural processes involved in the nitrogen

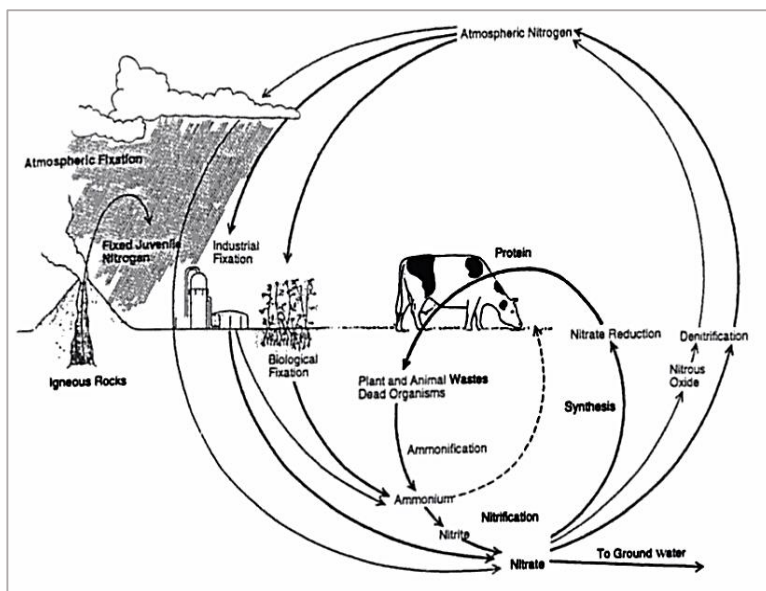


Figure 1: simplified illustration of the nitrogen cycle; source: US. EPA, in *Nitrogen Control*, Technomic Publishing, Lancaster (1994).
Obtained from Canter Larry, “Nitrates in Groundwater,” (1994)

¹³ “Manure Chemistry – Nitrogen, Phosphorus, & Carbon” (Natural Resources Conservation Services, USDA 2007), https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_043440.pdf.

¹⁴ Larry W. Canter, *Nitrates in Groundwater* (CRC Press, 1996).

¹⁵ “Nitrate in Groundwater” (British Columbia Ilbc, 2002), http://www.ilbc.leg.bc.ca/public/pubdocs/bcdocs/358316/nitrate_2002.pdf.

¹⁶ National Research Council (US) Subcommittee on Nitrate and Nitrite in Drinking Water, *Nitrate and Nitrite in Drinking Water* (Washington (DC): National Academies Press (US), 1995), <http://www.ncbi.nlm.nih.gov/books/NBK231046/>.

¹⁷ “Nitrate in Groundwater.”

¹⁸ “Nitrate in Groundwater.”

¹⁹ Lidia Razowska-Jaworek and Andrzej Sadurski, eds., “Nitrates in Groundwater: IAH Selected Papers on Hydrogeology 5,” in *CRC Press* (the European meeting of the International Association of Hydrogeologists, Wisla, Poland, June 2002, Routledge, 2014), <https://www.crcpress.com/Nitrates-in-Groundwater-IAH-Selected-Papers-on-Hydrogeology-5/Razowska-Jaworek-Sadurski/p/book/9789058096647>.

cycle are, nitrogen fixation, ammonification, nitrification, uptake by plants, and denitrification.²⁰

Human activities support new sources of fixed nitrogen through agricultural practices such as increasing the area of nitrogen-fixing legume crops, using synthesis ammonia, and manure.²¹ High nitrogen amounts are then removed from the ecosystem through crop uptake. In the past, agricultural production was limited, until the introduction of mineral N-fertilizers through the Haber – Bush process. This anthropogenic means of fixing nitrogen is responsible for the immense growth of agricultural production and the support of nearly 40% of the world's population.²²

Nevertheless, excessive use of manure and inorganic fertilizers as well as high-density animal farming have contributed toward changing the natural nitrogen balances, and to a high N- surplus in the environment. High N amounts in the soil increase the potential for nitrate leaching and ammonia NH₃, nitric oxide NO, and nitrous oxide N₂O volatilization. Leaching into nearby groundwater bodies is influenced by a range of factors, including the amount of N- surplus in the soil, climate, and the use and transformations of nitrate-N by animals and plants.²³

High levels of nitrate in the Abbotsford-Sumas aquifer (ASA) have persisted over the past few decades and have been linked to land use; specifically, the intensive agricultural practices that will be illustrated further in this paper.²⁴ Amid a growing population, and an increasing demand for agricultural products and water resources, the most important, yet challenging question is how to balance these needs while protecting the health of the aquifer.

The transboundary nature of the ASA introduces further complexity to its management. A major impediment to effective management of transboundary aquifer systems internationally is the lack of effective legal instruments. Even though 60% of globally available freshwater is contained in cross-border basins, only 40% is governed by a basin agreement.^{25,26} Globally, regulatory frameworks for TAS have been characterized by slow development and immaturity. For instance, it took more than 44 years for the United Nations Convention (UNWC, 2014) on the Law of Non-Navigational Uses of International Watercourses to be drafted. It became enforced only recently, in August 2014.²⁷ Nonetheless, no resolution or convention had been adopted on transboundary aquifers

²⁰ Anne Miek Kremer, "Methodology and Handbook Eurostat/ OECD: Nutrient Budget," *European Commission Eurostat*, no. Version 1.02. Eurostat and OECD, Luxembourg (2013).

²¹ Razowska-Jaworek and Sadurski, "Nitrates in Groundwater."

²² Kremer, "Methodology and Handbook Eurostat/ OECD: Nutrient Budget."

²³ Kremer.

²⁴ Robert J. Mitchell et al., "Nitrate Distributions and Source Identification in the Abbotsford-Sumas Aquifer, Northwestern Washington State," *Journal of Environmental Quality* 32, no. 3 (June 2003).

²⁵ "Water Resources Management Overview."

²⁶ Rivera, "Transboundary Aquifers along the Canada–USA Border."

²⁷ "Convention on the Law of the Non-Navigational Uses of International Watercourses, 1997" (United Nations, 2014). ;Cited in Rivera, "Transboundary Aquifers along the Canada–USA Border."

until late 2008, via the adoption of the UN general assembly of the Law of Transboundary Aquifers.^{28,29}

The UN International Watercourse Convention (UNWC) remains the most important global instrument on transboundary waters.³⁰ It provides a useful framework for reviewing state practice and a reference point indicating states' rights and obligations towards the management of transboundary water resources.³¹

The UNWC applies to many of the world's groundwater resources. However, some are excluded as the language used for the word "watercourse" emphasizes a physical relationship and unitary whole of the system. Therefore, for an aquifer to be considered within the UNWC, it has to be part of a "system of surface waters and groundwater".³² Confined transboundary aquifers are an example of aquifers that are not included in the UNWC. While the UN International Law Commission (ILC) has submitted a resolution on confined (independent and hydraulically unrelated transboundary groundwater resources), it has not yet been incorporated in the UNWC.³³

Other important instruments in international transboundary law are treaties and state agreements. When these exist, they provide states that share water bodies and drainage basins with an operational framework for inter-state cooperation.³⁴ Treaties and agreements usually account for the locality of each international water body.

In Canada, the process of identification of transboundary aquifer systems (TAS) had not started until recently.³⁵ Transboundary rivers and watersheds have received more attention and have been identified for a longer time.³⁶ Recent efforts for TAS identification are a result of the Internationally Shared Aquifer Resource Management Initiative (ISARM). According to ISARM, ten TAS were identified along the border between Canada and USA.³⁷ Tensions over groundwater resources between Canada and the USA have been rarer than surface water disputes.³⁸ Nevertheless, increasing demand over fresh water on both sides of the border could aggravate future tensions, highlighting the need to facilitate an enabling environment for future cooperation for the management of transboundary aquifers.

²⁸ See further: "Articles on the Law of Transboundary Aquifers" (United Nations, 2013), http://legal.un.org/avl/pdf/ha/alta/alta_ph_e.pdf.

²⁹ Rivera, "Transboundary Aquifers along the Canada–USA Border."

³⁰ Patricia Wouters, "International Law: Facilitating Transboundary Water Cooperation" (Global Water Partnership, 2013), <https://www.gwp.org/globalassets/global/toolbox/publications/background-papers/17-international-law---facilitating-transboundary-water-cooperation-2013-english.pdf>.

³¹ Wouters.

³² Wouters.

³³ "Gabriel Eckstein: Implications of the UN Watercourses Convention for Groundwater Resources," *International Water Law Project Blog* (blog), August 5, 2014, <https://www.internationalwaterlaw.org/blog/2014/08/05/professor-gabriel-eckstein-implications-of-the-un-watercourses-convention-for-groundwater-resources/>; cited in Rivera, "Transboundary Aquifers along the Canada–USA Border."

³⁴ Wouters, "International Law."

³⁵ Rivera, "Transboundary Aquifers along the Canada–USA Border."

³⁶ Rivera.

³⁷ Rivera.

³⁸ Rivera.

In order to improve the understanding of major agricultural nitrogen flows at the ASA and estimate the amounts of surplus nitrogen over the geographic extent of the aquifer in South Western British Columbia (SWBC) and Northwestern Washington State (NWS), this study will conduct a nitrogen budget analysis to provide a comparative transboundary estimation of major agricultural nitrogen inputs and outputs over the aquifer.

A comparative nitrogen budget at the ASA is an efficient instrument for visualizing nitrogen flows and predicting potential impacts on the environment, specifically, elevated levels of nitrate in groundwater bodies. It provides policymakers, environmental managers, farmers, and other stakeholders with additional information to help identify intervention measures and develop effective solutions to reduce the amounts of nitrogen surplus in the aquifer and promote sustainable management.

Facts and Figures from the Abbotsford – Sumas Aquifer

Site description

The Abbotsford – Sumas aquifer (ASA) extends over an area of approximately 240 km² between southwestern British Columbia (SWBC), Canada and northwestern Washington State (NWWS), United States (US). The SWBC constitutes 39% and the NWWS constitutes 61% of the total area of the aquifer.³⁹ See Figure 2.⁴⁰ The aquifer is a shallow, regionally extensive unconfined aquifer that is vulnerable to nitrate contamination due to intensive agricultural practices that occur in the region.^{41,42} Long-term monitoring has detected nitrate concentrations that exceed both the United States Environmental Protection Agency (USEPA), maximum contamination level (MCL) and the Health Canada, maximum acceptable contamination (MAC) of 10 mg/L.⁴³ Despite several intervention efforts aimed at reducing the concentration of nitrate in the aquifer, such as a wide variety of nutrient management strategies, elevated nitrate concentrations persist. This continues to be a challenge for environmental managers, farmers, and stakeholders decades after the issue was first identified.⁴⁴

The aquifer provides water supply to 10,000 people in the US.⁴⁵ In Canada, it provides water primarily for agricultural uses, in addition to drinking water for a limited number of people in the city of Abbotsford. In the US., the aquifer supplies the towns of Sumas, Lynden, Ferndale, Everson and scattered agricultural establishments north of the Nooksack River in northern Whatcom County. In Canada, most of the supply goes to the city of Abbotsford, and some to the township of Langley.⁴⁶ Many of these towns depend highly on the aquifer as their main drinking water source and for irrigation.⁴⁷ However, the city of Abbotsford relies on other sources for its drinking water supply, with only 5% is sourced from wells in south Abbotsford.⁴⁸ Norrish Creek, located around 19 km north of the city of Abbotsford, is its main drinking water source, covering 85% of total drinking water supply.

The Abbotsford aquifer is among the highest rated vulnerable aquifers in the province, due to its high productivity, demand, and vulnerability.⁴⁹ The rating is based on the British

³⁹ The area of the ASA aquifer was measured using remote sensing with the application of GIS techniques.

⁴⁰ The ASA SWBC was delineated based on the B.C. Ministry of Environment's aquifers classification geospatial database. The ASA SWBC was delineated based on the aquifer borders as described in the literature; "Ministry of Environment - Water Stewardship Division - Abbotsford-Sumas Aquifer International Task Force," accessed August 1, 2018, http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/absumas.html; Nadine Schuurman, Aparna Deshpande, and Diana M. Allen, "Data Integration across Borders: A Case Study of the Abbotsford-Sumas Aquifer (British Columbia/Washington State)1," *JAWRA Journal of the American Water Resources Association* 44, no. 4 (August 1, 2008): 921–34, <https://doi.org/10.1111/j.1752-1688.2008.00192.x>.

⁴¹ G. Graham, D. M. Allen, and B. Finkbeiner, "Climate Controls on Nitrate Concentration Variability in the Abbotsford-Sumas Aquifer, British Columbia, Canada," *Environmental Earth Sciences* 73, no. 6 (March 1, 2015), <https://doi.org/10.1007/s12665-014-3072-5>.

⁴² Mitchell et al., "Nitrate Distributions and Source Identification in the Abbotsford-Sumas Aquifer, Northwestern Washington State."

⁴³ Mitchell et al.

⁴⁴ Tanya L. Gallagher and Sarah E. Gergel, "Landscape Indicators of Groundwater Nitrate Concentrations: An Approach for Trans-Border Aquifer Monitoring," *Ecosphere* 8, no. 12 (December 1, 2017), <https://doi.org/10.1002/ecs2.2047>.

⁴⁵ Robert Mitchell et al., "Abbotsford-Sumas Aquifer Monitoring Project: Final Report," *Western Washington University*, 2000.

⁴⁶ Gallagher and Gergel, "Landscape Indicators of Groundwater Nitrate Concentrations."

⁴⁷ B. Carey, "Focus on Groundwater Quality in Whatcom County: Report Summarizes 30 Years of Nitrate Studies in the Sumas-Blaine Aquifer," *Washington State Department of Ecology*, no. 12 (2012).

⁴⁸ "Abbotsford Mission Water & Sewer Services: Our Water Matters," accessed July 31, 2018, <https://www.ourwatermatters.ca/water-quality-faqs>.

⁴⁹ Li Kevin and Hans Schreier, "Evaluating Long-Term Groundwater Monitoring Data in the Lower Fraser Valley" (BC-WLAP, 2004).

Columbia aquifer classification system, which has been developed to facilitate systematic management of groundwater resources.⁵⁰

Projections of population growth and future changes in climate could add increasing pressures on the current drinking water sources in and around the ASA. For instance, the population of the city of Abbotsford is expected to grow from 141,500 in the year 2015 to 182,000 in the year 2041.⁵¹ Climate projections for the Fraser Valley region for the period 2020 to 2050 predict warmer temperatures in all seasons. An increase in the magnitude, frequency, and intensity of extreme events, for both temperature and rainfall are also forecast to increase.⁵²

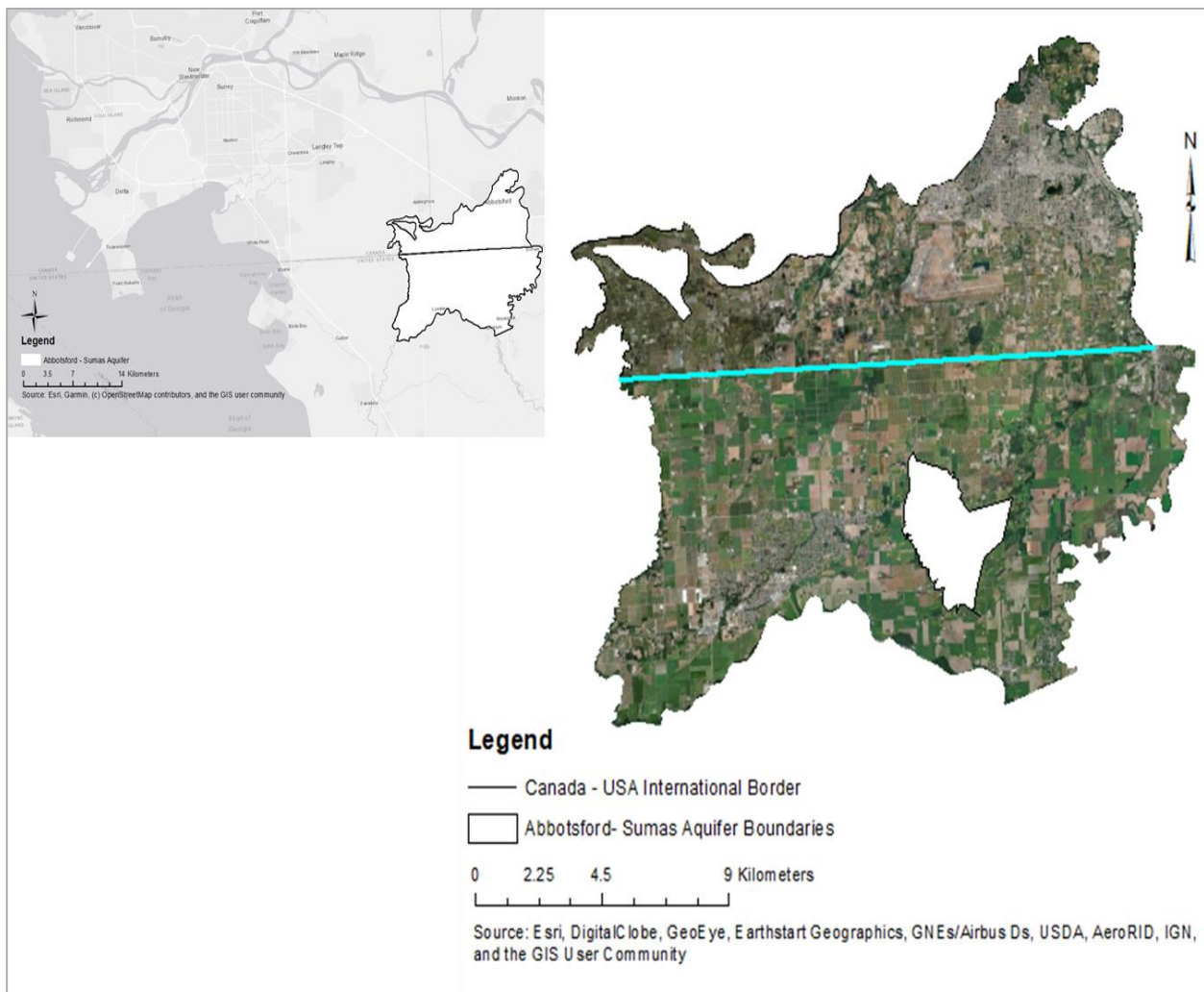


Figure 2: Boundaries of the Abbotsford – Sumas Aquifer

⁵⁰ According to the classification, the Abbotsford aquifer has a rating of IA (20). The classification rating includes the following components: a. Numerals (I, II, III) which considers the aquifers' level of development and demand. a lower number indicates a higher demand and productivity. b. A letter (A, B or C) which represents the level of vulnerability where A is more vulnerable than c. A regular number; which is the sum of values assigned based on seven criteria; productivity, vulnerability, aquifer area, water demand, water use type, quality concerns and quantity concerns. The ranking ranges from 5 to 21; a higher factor represents a larger degree of severity of the seven factors.

⁵¹ "City of Abbotsford - Statistics FAQ's," accessed July 31, 2018,

https://www.abbotsford.ca/business_and_development/statistics/statistics_faq_s.htm?PageMode=Print.

⁵² "Regional Adaptation Strategies Series -- Fraser Valley," *British Columbia Agriculture & Food Climate Action Initiative*, 2015.

Nitrate contamination and groundwater flows

Climatic factors, as well as soil properties of the region, exacerbate the risk of contamination of the aquifer. The area is characterised by a high annual precipitation of about 1,538 mm/year.⁵³ This, and the mobile nature of nitrate facilitates leaching into the groundwater system through the predominantly well-drained soil.^{54,55}

The aquifer is mostly unconfined and ranges from 0 to 65 meters thick. It is predominantly made up of uncompacted sand and gravel, coarse-grained sediments of a glacial outwash plain, which provides high permeability and infiltration rates. In the transboundary area, the water table in the aquifer ranges between 3 to 25 meters below land surface.⁵⁶

The primary source of groundwater recharge to the Abbotsford - Sumas aquifer is direct precipitation.⁵⁷ Groundwater flow direction is generally south, moving across the international boundary from Canada to the United States.⁵⁸ Models indicate that a particle of water would take 6-7 years to travel 10 m below the water table by advection. They also suggest the age of groundwater in the aquifer is between 0.9 and 33 years old.⁵⁹ Aquifer discharge mainly occurs through pumping and seepage to streams, in particular Fishtrap Creek, Marshall Creek and the Nooksack River.⁶⁰

Agricultural land use and transboundary sources of nitrate

Sources of nitrate vary between the two sides of the Canada-US border. The city of Abbotsford is one of the largest agricultural producers in British Columbia, generating 21% of the province's agricultural revenue.⁶¹ The most dominant form of land use on the Canadian portion (SWBC) is agricultural, with increased urban development on the northern portion.^{62,63}

The dominant type of animal production on the Abbotsford, SWBC is poultry farming. The dominant agricultural crops are raspberries and blueberries at 31% and 22%, respectively, of the 40% total cropped land in 2012.⁶⁴

⁵³ Environment and Climate Change Canada, "Government of Canada. Meteorological Service of Canada. Canadian Climate Normals," October 31, 2011, http://climate.weather.gc.ca/climate_normals/index_e.html.

⁵⁴ Graham, Allen, and Finkbeiner, "Climate Controls on Nitrate Concentration Variability in the Abbotsford-Sumas Aquifer, British Columbia, Canada."

⁵⁵ Mitchell et al., "Nitrate Distributions and Source Identification in the Abbotsford-Sumas Aquifer, Northwestern Washington State."

⁵⁶ Stephen E Cox and Hugh Liebscher, "Ground-Water Quality Data from the Abbotsford- Sumas Aquifer of Southwestern British Columbia and Northwestern Washington State, February 1997," *U.S. Geological Survey and Environmet Canada*, 1999.

⁵⁷ Cox and Liebscher.

⁵⁸ Liebscher, Hugh, et. al., "Nitrates and pesticides in the Abbotsford Aquifer, southwestern British Columbia: North Vancouver, BC, Environment Canada, Inland Waters Directorate, 83. (1992); Cited in Cox, 1999

⁵⁹ Chesnaux, 2012

⁶⁰ Cox, 1999

⁶¹ Zbeetnoff and Serecon Consulting, "City of Abbotsford: Agriculture Strategy," City of Abbotsford (2011).

⁶² Basil Hii, Liebscher Hugh, and Mazalek Mike, "Groundwater Quality and Flow Rates in the Abbotsford Aquifer, British Columbia" (Environment Canada, 1999).; Cited in Bernie J. Zebarth et al., "Groundwater Monitoring to Support Development of BMPs for Groundwater Protection: The Abbotsford-Sumas Aquifer Case Study," *Groundwater Monitoring & Remediation* 35, no. 1 (February 1, 2015), <https://doi.org/10.1111/gwmr.12092>.

⁶³ Zebarth, et. al., "Groundwater Monitoring to Support Development of BMPs for Groundwater Protection: The Abbotsford-Sumas Aquifer Case Study," *Monitoring and Remediation* (2015).

⁶⁴ Bernie J. Zebarth et al., "Groundwater Monitoring to Support Development of BMPs for Groundwater Protection: The Abbotsford-Sumas Aquifer Case Study," *Groundwater Monitoring & Remediation* 35, no. 1 (February 1, 2015), <https://doi.org/10.1111/gwmr.12092>.

The US area overlying the Sumas aquifer in northwest Washington State (NWWWS) lists dairy farming as the main agricultural activity.⁶⁵ The region also is a producer of raspberries in the state of Washington.⁶⁶

Long-term groundwater nitrate monitoring

The objective of this section is to evaluate long-term trends in groundwater nitrate contamination in the ASA with the aim of observing and determining the ranges of nitrate levels on both sides of the border.

According to a joint survey of nitrate in the ASA in Northwestern B.C. in 2004,⁶⁷ 40% of the 150 sampled wells had nitrate concentrations above drinking water guidelines. In some, the concentration was as high as 78.4 mg N/L. Moreover, 60% of wells had nitrate concentrations above 3.0 mg N/L, indicating inputs from anthropogenic sources. The study also observed that elevated nitrate concentrations have occurred more frequently in areas where agriculture is the primary land use activity and the water table is closest to the surface.⁶⁸

To better conceptualize long-term nitrate trends over the ASA, nitrate concentrations in samples over the aquifer were collected from a range of sources and literature available. Over the ABA SWBC, this included Environment and Climate Change Canada (ECCC) and B.C. Ministry of Environment.^{69,70,71,72,73} Samples presented in these sources were taken from a variety of domestic observational wells and piezometer wells over the expanse of the northern portion of the aquifer. Long-term nitrate concentration levels in samples from 230 wells between 1955 and 2017 are presented in Figure 3.

In Figure 3, sample concentrations are presented in light blue. The black lines represent the average annual nitrate concentration. The green constant line represents the 10 mg/l maximum acceptable contamination (MAC) of nitrate in drinking water.

Long-term annual average nitrate concentration in groundwater samples has frequently exceeded drinking water guidelines. The Figure shows an increase in the average annual nitrate concentration from 4.8 mg -N/L in 1955 to just above drinking water guidelines in 1979.

⁶⁵ Carey, "Sumas-Blaine Aquifer: Long Term Groundwater Quality Monitoring, 2009-2016," *State of Washington Department of Ecology* (2017)

⁶⁶ Mitchell et al., "Nitrate Distributions and Source Identification in the Abbotsford-Sumas Aquifer, Northwestern Washington State."

⁶⁷ Basil Hii et al., "Abbotsford-Sumas Aquifer, British Columbia, Canada -- 2004 Groundwater Quality Survey - Nitrate and Bacteria" (Environment Canada, Vancouver, BC, 2006).

⁶⁸ Hii et al.

⁶⁹ Liebscher Hugh, Basil Hii, and Duane McNaughton, "Nitrate and Pesticides in the Abbotsford Aquifer Southwestern British Columbia" (Environment Canada, 1992).

⁷⁰ Basil Hii, Liebscher Hugh, and Mazalek Mike, "Groundwater Quality and Flow Rates in the Abbotsford Aquifer, British Columbia" (Environment Canada, 1999).

⁷¹ Kevin and Schreier, "Evaluating Long-Term Groundwater Monitoring Data in the Lower Fraser Valley."

⁷² Kevin and Schreier.

⁷³ Hii, Zubel, Scovill, et al., "Abbotsford-Sumas Aquifer, British Columbia, Canada -- 2004 Groundwater Quality Survey - Nitrate and Bacteria."

Throughout the period between 1989 and 2017, the average concentration continued to fluctuate slightly from one year to another. This could be due to land use, and climatic factors. Several quality control issues could have also influenced samples' precision, such as changes in sampling time and location over the years.⁷⁴

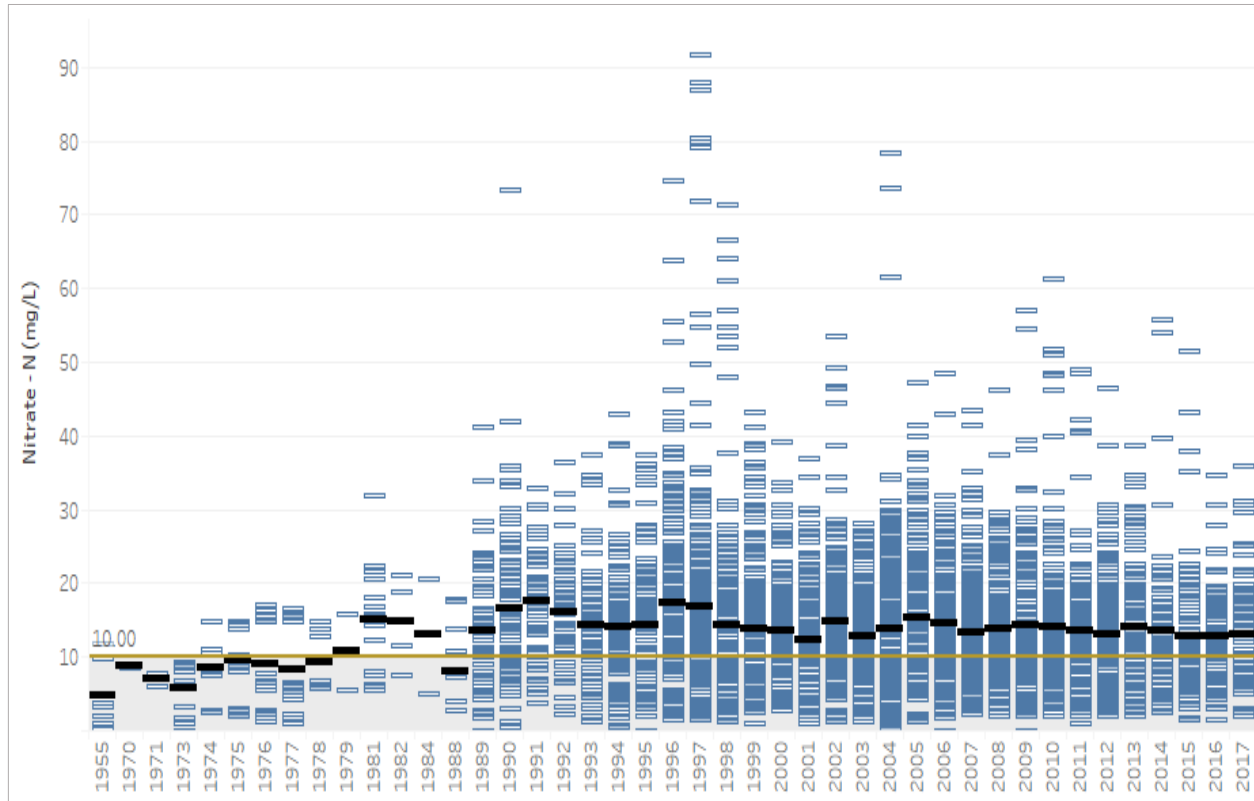


Figure 3: Long Term Nitrate – N Concentration from groundwater wells over the ASA SWBC (1955 – 2017)

A similar trend was observed when analyzing nitrate samples from 12 ECCC groundwater wells (8m to 46m depth), which have full sampling records over the period from 1997 to 2017 as illustrated in Figure 4.

The Figure shows a substantial number of samples exceeding the MAC for drinking water. The average annual nitrate concentration remained above the guidelines for the entire period. The average minimum for all samples in the study period was 3.34 mg -N/L, with minimum values ranging from 0.3 to 13.4 mg -N/L. The average maximum for all samples in the study period was 35 mg –N/L, with values ranging from 14.2 to as high as 91.9 mg-

⁷⁴ Several quality control issues should be kept in mind when dealing with long term monitoring such as changes in analytical methods, timing and frequency of sampling, gaps in sequence of sampling, seasonal variations and water level fluctuations; See: Li Kevin and Hans Schreier, "Evaluating Long-Term Groundwater Monitoring Data in the Lower Fraser Valley"

N/L. However, a linear trend model (degrees of freedom = 2) for mg -N/L for the period between 1997 to 2017 shows a statistically significant downward trend (p-value = 0.02).

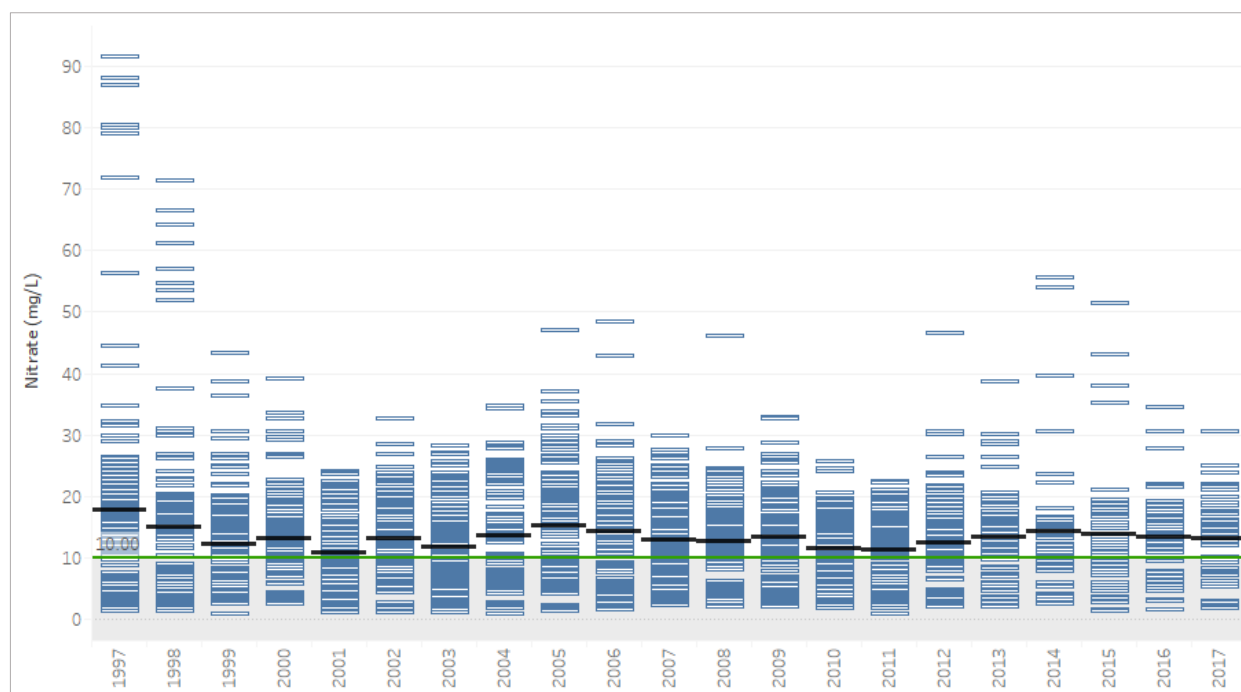


Figure 3: Nitrate – N concentration from 12 wells over the ASA SWBC (1997 – 2017)

A similar analysis was conducted at the ASA, Northwest Washington state (NWWWS). Nitrate data illustrated in Figure 5 was obtained from the State of Washington Department of Ecology. It encompasses long-term nitrate data obtained from 15 domestic groundwater wells located over the ASA Aquifer between the period between 1997 and 2016.⁷⁵

The figure indicates an overall decrease in the number of wells exceeding the nitrate in drinking water maximum contamination level (MCL) between the years 1997 and 2016. Overall, the annual average nitrate concentration has decreased from 11.3 to 8.4 mg - N/L between 1997 and 2016. However, in 2016 two samples remained above the guidelines, with one reaching a high of 28.4 mg -N/L.

⁷⁵ Barbara M. Carey, "Sumas-Blaine Aquifer Long-Term Groundwater Quality Monitoring, 2009-2016" (Washington State Department of Ecology, 2017), <https://fortress.wa.gov/ecy/publications/summarypages/1703013.html>.

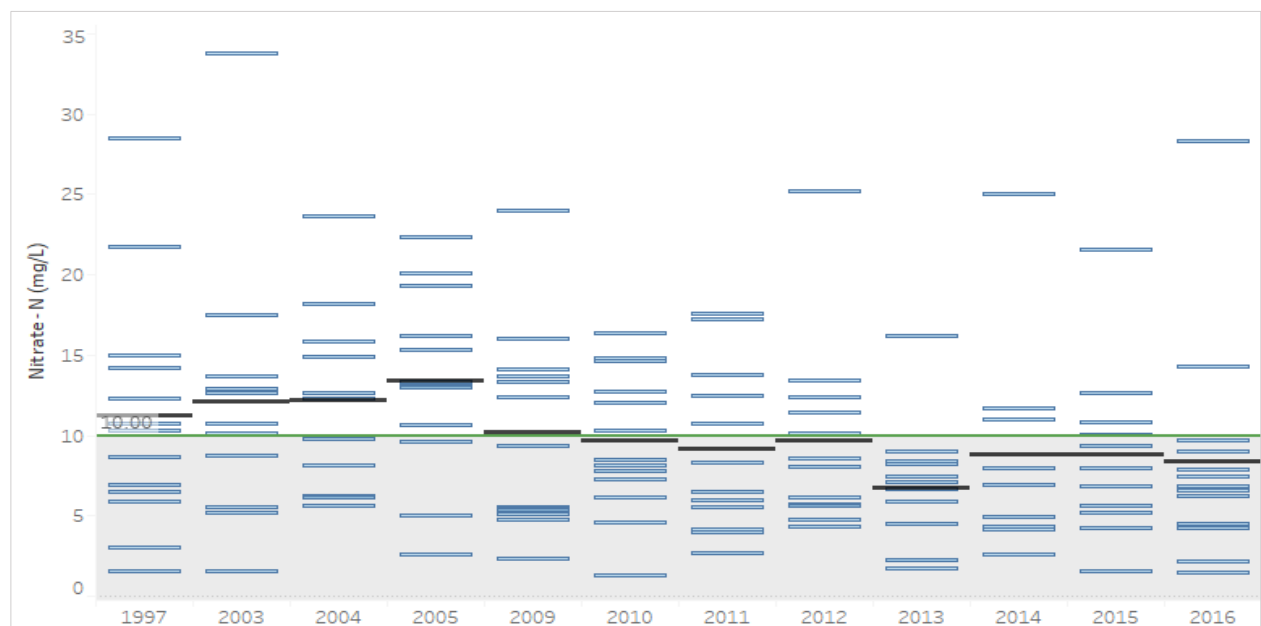


Figure 4: Long term Nitrate - N concentration from 15 wells over the ASA NWWs (1997 – 2016)

Methodology

Balance Equation

The main objective of the ASA nitrogen budget is a transboundary estimation of the nitrogen surplus on the aquifer. The surplus is calculated as the difference between nitrogen inputs and outputs first at the Canadian side of the aquifer (SWBC), and secondly at the ASA in NWWs.

The understanding of the nitrogen budget analysis is based on the balance equation:

$$(Output - N) + (Stock-change - N) - (input - N) = 0$$

A nitrogen balance is defined as the balance of a pool, a sub-pool, or a full nitrogen budget equal to zero, indicating a closed cycle.⁷⁶ Ideally, all nitrogen flows can be explained by the balance equation as either output, input or a stock change. A closed balance is theoretically possible, however, in practice, it is not a requirement of a nitrogen budget.⁷⁷ Many nitrogen flows can be unfeasible to measure. This, together with data unavailability and measurement errors could lead to an open balance equation that has a residual outcome not equal to zero.

Comparative Nitrogen Budget at the Abbotsford – Sumas Aquifer

The ASA nitrogen budget will provide a comprehensive estimation of N-surplus amounts on the aquifer. A large and persistent nitrogen surplus indicates a potential risk of N emissions to the air, and leaching and runoff to nearby water bodies, including groundwater sources.

The ASA nitrogen budget includes major nitrogen inputs and output in the ASA area. It will consist of a quantification of all major agricultural nitrogen flows as well as atmospheric deposition.

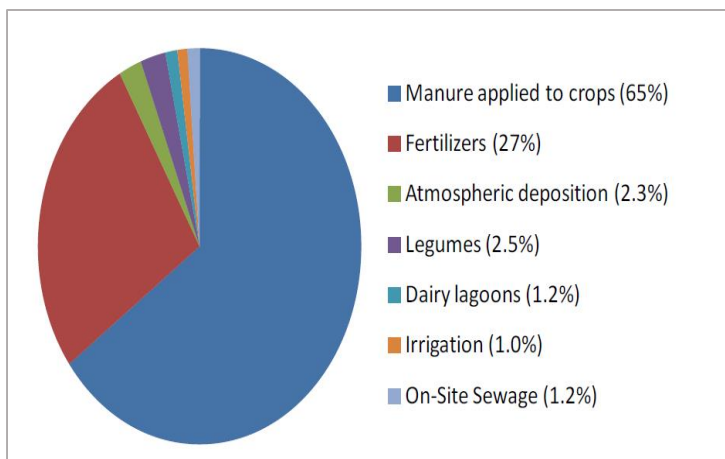


Figure 5: Distribution of estimated annual nitrogen inputs to the land and subsurface of the Sumas-Blaine Aquifer, NWWs
Source: Carey Barbara, "Sumas-Blaine Aquifer Nitrate Contamination Summary," WSDE (2013)

⁷⁶ "Draft Decision on Adoption of Guidance Document on National Nitrogen Budgets" (Executive Body for the Convention on Long-range Transboundary Air Pollution, Geneva: Economic Commission for Europe, 2012), https://www.unece.org/fileadmin/DAM/env/documents/2012/EB/ECE_EB.AIR_2012_L8_Draft_decision_on_adoption_of_guidance_document_on_national_nitrogen_budgets_GP.pdf.

⁷⁷ "Draft Decision on Adoption of Guidance Document on National Nitrogen Budgets."

Agricultural practices are a key driver in the local nitrogen cycle at the ASA. According to a study by the State of Washington Department of Ecology on the Sumas-Blain Aquifer; the south-western extension of the Abbotsford-Sumas aquifer, it has been found that manure application to crops is the largest nitrogen contributor to the aquifer at 65%, followed by fertilizer application, atmospheric deposition, and legumes at 27%, 2.3% and 2.5%, respectively. This is illustrated in Figure 6.⁷⁸

This ASA nitrogen budget includes major nitrogen inputs and outputs in the ASA area. Namely, manure application, fertilizer application, crop nitrogen uptake and atmospheric depositions. Other N processes such as plant N fixation, farm emissions, and on-site sewage systems will not be included as part of the analysis in this report. This is because nitrogen budget analysis is data intensive. An ideal implementation of a nitrogen budget at the ASA should include all nitrogen inputs and outputs including nitrogen fixation, crop residues input, on-site sewage. However, due to time restrictions and data unavailability, this study will only analyze major nitrogen flows over the aquifer as demonstrated in Table 1.

Total N-Inputs	Total N-Output	N-Surplus Estimation
Fertilizers- N application	Crop- N uptake	ASA N Surplus = Total Input – Total Output
Manure- N application	Manure- N atmospheric	
Atmospheric N deposition	loss	

Table 1: Components of the ASA nitrogen budget analysis

Data requirement and data sources

This section provides a description of the data requirement of each of the components of the nitrogen budget.

a) Manure production

To estimate manure production at the ASA aquifer, the annual animal population per animal category was estimated based on a combination of resources.

On the ASA-SWBC, data including poultry types and numbers for approximately 65% of poultry farms in SWBC was available from the Census of Agriculture, Statistics Canada (2016). To estimate the annual total number of poultry on the aquifer, a visual land use digitization was made using an Orthophoto, 2017 and ArcGIS.⁷⁹ The total poultry population was then calculated by multiplying the number of farms by the average number of poultry per farm as obtained from the agricultural census.

On the ASA-NWWS data was obtained from two different sources. First, information on licensed grade “A” cow milk dairy milking facilities on the aquifer in 2018 was obtained

⁷⁸ Barbara Carey, “Sumas-Blaine Aquifer Nitrate Contamination Summary” (Washington State Department of Ecology, 2013).

⁷⁹ Orthophoto, 2017, available from the city of Abbotsford, B.C.

from Washington State Department of Agriculture (WSDA) Geo-dataset. The dataset includes all active dairy milking facilities with some information expressed in ranges for non-disclosure requirements. Secondly, with the utilization of ArcGIS and remote sensing techniques using ArcGIS base maps and Google Maps 2017, the total number of cattle farms on the aquifer was estimated

The annual population number was then multiplied by manure and manure- N excretion coefficients available in the literature for each poultry and cattle category, as will be illustrated in later in the data analysis section.

b) Mineral Fertilizers

The amount of mineral fertilizers nitrogen applied on the area of the aquifer was estimated as following:

$$(Total\ Fertilizer- N) = (Total\ farm\ area\ per\ crop\ category) \times (Annual\ rate\ of\ fertilizer- N\ application\ per\ crop\ type)$$

The total crop farming area over the ASA SWBC was measured by visual digitization of agricultural land use using remote sensing, and GIS techniques using the Orthophoto, 2017. Crop farm area for the ASA NWWS in 2017 was obtained from an agricultural land use geodatabase, available from the Washington State Department of Agriculture (WSDA).

c) Atmospheric deposition

Annual atmospheric nitrogen deposition to the ASA is estimated based on data from a research study at the University of British Columbia.⁸⁰ Nitrogen deposition estimates are based on daily simulations over the geographical area covering a large extent of southwestern British Columbia and Washington State. According to the study, total annual nitrogen deposition ranged from <1 to >30 kg N/ha/yr. See Figure 7. High values over the ASA are associated

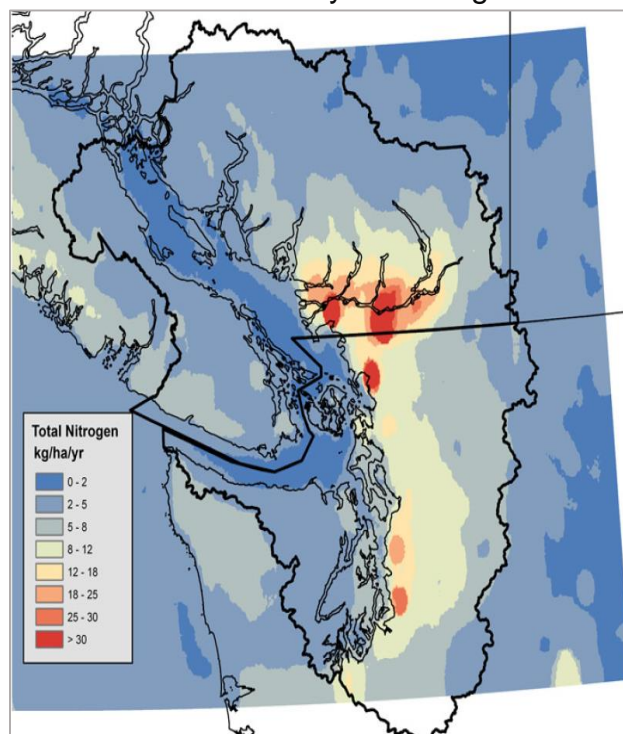


Figure 6: Modelled annual total nitrogen deposition over the Georgia Basin/Puget Sound (SWBC & NWWS). Map generated with CMAQ data from UBC (2007)

Source: Georgia Basin Report (2014)

⁸⁰R. Vingarzan, R. So, and R. Kotchenruther, eds., "Georgia Basin - Puget Sound Airshed Characterization Report, 2014" (Environment Canada, Pacific and Yukon Region, Vancouver (BC). U.S. Environmental Protection Agency, Region 10, Seattle (WA), July 1, 2002), <http://publications.gc.ca/site/eng/9.698425/publication.html>.

with areas of intensive poultry and livestock production.⁸¹

d) Plant Nitrogen Uptake:

Nitrogen removal by crop production is estimated using crop N-uptake rates for the different crops within the ASA as following:

Crop N- uptake. This rate is then multiplied by the total crop area to estimate the total N-uptake per crop on the aquifer.

e) Manure – N emissions

Manure-N losses are of considerable concern with respect to nitrogen use efficiency and environmental pollution. Manure-N loss factors in the literature range between 10 – 40% for storage systems and 10 to 30% for land application methods.⁸² Generally, manure-N loss estimations are made for the three phases: housing, storage and application. In Canada, losses during housing, and storage are often estimated together. This is due to the difficulty in separating them as a result of the short time between excretion and delivery to a storage system.⁸³

Manure-N loss starts shortly after manure is excreted. Nitrogen in poultry and cattle excretion transforms into ammonia and diffuses into the surrounding air due to its high volatility.⁸⁴ Several factors control the ammonia loss rate including air movement across the exposed surface area and the level of exposure, which is largely affected by animal housing design and manure removal and application practices.⁸⁵

During application as fertilizer, manure nitrogen loss varies widely, and is highly dependant on the method of incorporation. The most common methods include irrigation, broadcast spreading, band spreading, and injection into the soil. Ammonia volatilization occurs during the application process with typical values from 5 to 10%.⁸⁶ Volatilization continues from the field surface, causing an additional loss of as high as 35% of nitrogen applied.⁸⁷

Other crop production related N losses such as losses associated with fertilizer–N application will not be considered in this study. Direct NH₃ emissions from N-fertilizers are

⁸¹ R. Vingarzan.

⁸² Based on C. A. Rotz, "Management to Reduce Nitrogen Losses in Animal Production," *Journal of Animal Science* 82, no. suppl_13 (January 1, 2004): E119–37, https://doi.org/10.2527/2004.8213_supplE119x. And; J. Y. Yang et al., "Estimating the Impact of Manure Nitrogen Losses on Total Nitrogen Application on Agricultural Land in Canada," *Canadian Journal of Soil Science* 91, no. 1 (January 1, 2011), <https://doi.org/10.4141/cjss10052>.

⁸³ D. L. Burton and E. G. Beauchamp, "Nitrogen Losses from Swine Housings," *Agricultural Wastes* 15, no. 1 (January 1, 1986), [https://doi.org/10.1016/0141-4607\(86\)90126-5](https://doi.org/10.1016/0141-4607(86)90126-5); Cited in Yang et al., "Estimating the Impact of Manure Nitrogen Losses on Total Nitrogen Application on Agricultural Land in Canada."

⁸⁴ G. J. Monteny and J. W. Erisman, "Ammonia Emission from Dairy Cow Buildings: A Review of Measurement Techniques, Influencing Factors and Possibilities for Reduction," *NJAS Wageningen Journal of Life Sciences*, December 1, 1998.; Cited in Rotz, "Management to Reduce Nitrogen Losses in Animal Production."

⁸⁵ Rotz, "Management to Reduce Nitrogen Losses in Animal Production."

⁸⁶ S. G. Sommer and N. Hutchings, "Techniques and Strategies for the Reduction of Ammonia Emission from Agriculture," *Water, Air, and Soil Pollution* 85, no. 1 (December 1, 1995): 237–48, <https://doi.org/10.1007/BF00483704>; Cited in Rotz, "Management to Reduce Nitrogen Losses in Animal Production."

⁸⁷ L. M. Safley, J. C. Barker, and P. W. Westerman, "Loss of Nitrogen during Sprinkler Irrigation of Swine Lagoon Liquid," *Bioresource Technology* 40, no. 1 (January 1, 1992): 7–15, [https://doi.org/10.1016/0960-8524\(92\)90112-B](https://doi.org/10.1016/0960-8524(92)90112-B); Cited in Rotz, "Management to Reduce Nitrogen Losses in Animal Production."

dependant on a wide range of factors, such as soil pH, type of soil, and type of fertilizer. Emission factors for total NH_3 emissions from soils due to fertilizer-N volatilization is approximately 0.02⁸⁸ and its impact will be only marginal on the land extent of the aquifer. Therefore, it is excluded from the ASA nitrogen budget analysis.

⁸⁸ Kentaro Hayashi, "Nitrogen Fertilizer Applications as a Source of Atmospheric Ammonia" (National Institute for Agro-Environmental Sciences, Japan, n.d.), <http://www.ftc.agnet.org/library.php?func=view&id=20130422103754#pict2%20pdf>.

Data Analysis

This section summarizes the different poultry and dairy animal production numbers at the aquifer area, which is used for the estimation of Manure-N production and application within the area of the ASA. It also estimates fertilizer-N application, atmospheric-N deposition and crop-N uptake, all of which feed into calculations of the surplus-N on the ASA aquifer.

With the aim of developing a comparative transboundary analysis, calculations were developed separately on the two sides of the ASA. First, components of the nitrogen budget were estimated for the ASA, SWBC followed by the area of the ASA in SWWS.

Data Analysis on the Abbotsford Sumas Aquifer Southwest BC, Canada

Total number of poultry at the ASA

The poultry industry in the larger Abbotsford area has experienced large growth between 1996 and 2016 as seen in Figure 8. The poultry population went up from 5.7 million in 1996 to 9.8 million in 2016. However, a decrease in poultry numbers after 2006 is believed to be a result of the veterinary outbreak of avian flu occurring in the same year.

Poultry production over the ASA experienced similar growth pattern to that of the City of Abbotsford. In this section the number of poultry are estimated based on data from 2016 Census of Agriculture and the application of ArcGIS and remote sensing.

Census data from Statistics Canada included information on the number of farms and the total number of each poultry category in the area shaded in Figure 9. Poultry production was classified into pullets under 19 weeks, laying hens, layer and broiler breeders and broilers, roasters, and Cornish. Based on this, the average per farm poultry numbers were estimated.

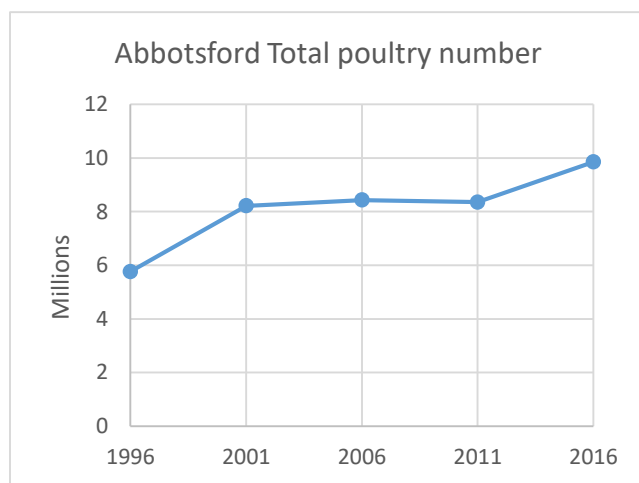


Figure 7: Total poultry population in the city of Abbotsford (1996 – 2016)

To cover the entire span of the aquifer. Poultry farms located outside of the census zone and inside the ASA boundary were identified using remote sensing and GIS techniques. The total poultry number was estimated assuming a similar average number of poultry per farm to that in the census zone.

The average number of poultry per farm in the aquifer area in 2016 was estimated at about 48,419. This number is higher than the average number of poultry in the larger Abbotsford area and the Lower Fraser Valley. Based on the 2016 Census of Agriculture, the average per farm poultry number over the aquifer was 70% higher than the average number of the City of Abbotsford and 174% higher than the average number of the Lower Fraser Valley as illustrated in Table 2. This indicates a relatively high animal population density at the ASA.

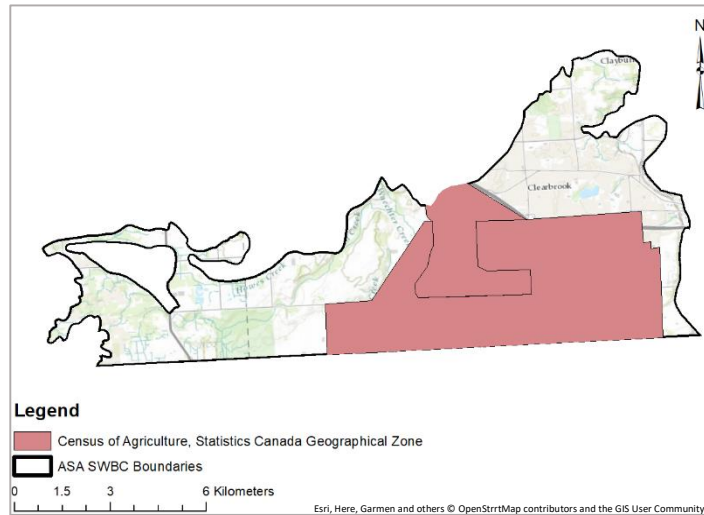


Figure 8: Census of agriculture information coverage

Area description	Poultry number	Farm number	Average poultry number per farm
Lower Fraser Valley	13,773,480	780	17,658
Abbotsford	9,853,992	348	28,316
Aquifer zone 1 & 2	2,856,708	59	48,419

Table 2: Average per farm poultry number variation based on geographic zone (2016)
Source: Estimates based on Census of Agriculture, Statistics Canada, 2016

The total number of poultry over the ASA estimated at the time of the census data was 4,406,114. This indicates an increase in poultry number over the aquifer by around 63% since 1996.⁸⁹ Several batches of pullet and broiler poultry are produced every year, which adds to the annual total number of poultry production at the aquifer. The estimated annual

⁸⁹ Estimations are based on census of Agriculture, Statistics Canada

number of poultry production including all categories is 21,873,184 poultry. See Table 3 for more information.

	Total poultry number at the ASA	Pullets under 19 weeks, intended for laying - Number	Laying hens, 19 weeks and over - Number	Layer and broiler breeders (pullets and hens) - Number	Broilers, roasters and Cornish - Number
Poultry numbers (based on average animal/ farm from Statistics Canada)	4,406,113	611,785	1,277,332	196,496	2,320,500
Total number of poultry (poultry production/ year)	21,873,183	1,835,355	1,277,332	196,496	18,564,000
Average life in weeks*		19	52	62	6
Cycles per year		2.5	1	1	8

Table 3: Summary of Poultry numbers per category over the ASA SWBC

* Source: BCMOA, "Commodity Description: Poultry," . https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/agriculture-and-seafood/agricultural-land-and-environment/strengthening-farming/farm-practices/870218-23_poultry.pdf.

Poultry manure -N production and application at the ASA

After estimating poultry numbers on the ASA the amount of poultry manure and the amounts of nitrogen in manure produced on the Aquifer in SWBC could be estimated. The analysis in this section is based on the use of manure and manure-nutrient nitrogen values from the literature.^{90,91}

Annual total poultry manure produced on the aquifer is estimated at 141,253,813 kg/yr. (141,254 tonnes/yr). This accounts for 2,057,211 kg -N/yr (2,057 tonnes N/yr). A summary of manure and manure-N production per poultry type and Manure-Nitrogen excretion coefficients for all poultry categories are shown in Table 4.

⁹⁰ Yang et al., "Estimating the Impact of Manure Nitrogen Losses on Total Nitrogen Application on Agricultural Land in Canada."

⁹¹ T. Huffman et al., "Estimation of Canadian Manure and Fertilizer Nitrogen Application Rates at the Crop and Soil-Landscape Polygon Level," *Canadian Journal of Soil Science* 88, no. 5 (November 2008), <https://doi.org/10.4141/CJSS07020>.

Type	Manure -Nitrogen excretion (kg- N/ head/year)*	Manure excretion (Kg/ animal/ year)*	Manure production (kg/ year)	Manure- N Production (Kg- N/ year)
Pullets	0.40	28.0	17,129,980	244,714
Laying hens	0.60	42.0	53,647,924	766,399
Layer and broiler breeders	0.60	42.0	5,501,909	117,898
Broilers, roasters and Cornish Manure	0.40	28.0	64,974,000	928,200
Total			141,253,813	2,057,211

Table 4: Manure and manure-N excretion rates and coefficients per poultry category

Source of coefficients: Yang, Huffman et.al "Estimating the impact of manure nitrogen losses on total nitrogen application on agricultural land in Canada," Agriculture and Agri-Food Canada (2010).

While most of the produced poultry manure is believed to be applied on the area of the aquifer, part of it is removed from the aquifer by different groups for various reasons. However, little information is available on its movement within and out of the mapped boundaries of the aquifer. The majority of the percentage removed from the aquifer is a result of recent efforts by sustainable initiatives to reduce manure-N inputs to the aquifer. Other quantities of manure are believed to be reallocated to nearby areas outside of the aquifer boundary in SWBC and applied to berry field renovations. Another possibility for manure removal from the aquifer is for use by nearby dairy farms in forage production.

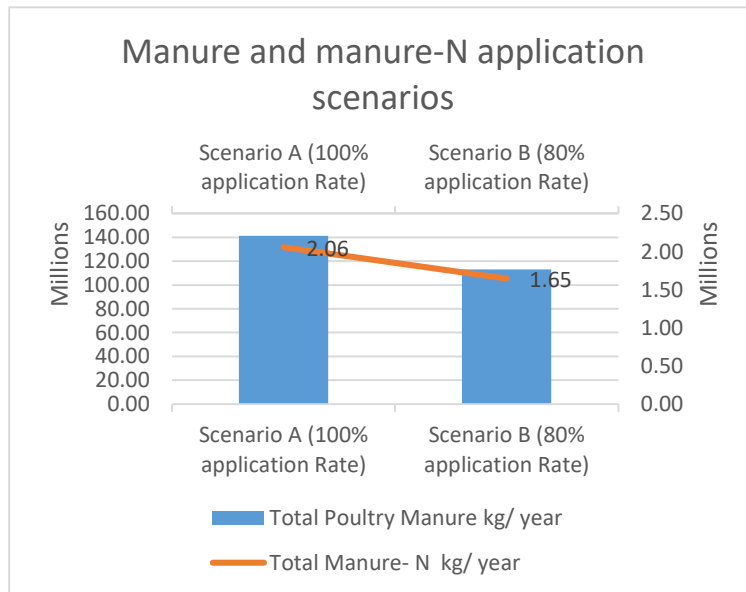


Figure 9: Annual poultry manure and manure -N application on the ASA SWBC based on the two application scenarios

To address these uncertainties, different scenarios were made by varying the quantity of manure applied within the aquifer in SWBC. Two scenarios were suggested for the

estimation of the amounts of manure-N applied on the area of the ASA SWBC. The first scenario assumes a 100% application rate of poultry manure over the area of the aquifer. The second assumes a removal of 20% of total manure produced, resulting in 80% manure application over the aquifer. Figure 10 shows estimates for annual poultry manure and manure-N application on the ASA SWBC based on the two scenarios.

Finally, it is important to note that only four dairy farms were located over the ASA SWBC using remote sensing. Therefore, manure-N contribution from dairy farming on this side of the aquifer was not included in this analysis.

Atmospheric N losses from manure

Typical emission values from the literature were used to estimate atmospheric nitrogen losses from manure. 30% and 12% will be used to calculate the ammonia losses in % total-N for poultry manure-N losses in storage/housing, and application respectively.⁹²

Nitrogen (kg/year)	Scenario A (100% application Rate)	Scenario B (80% application Rate)	Typical loss, % total N
Total Nitrogen	2,057,211	1,645,769	
N loss in storage and housing facility	617,163	493,731	30%
N loss in manure application	74,060	59,248	12%
Total manure- Nitrogen loss	691,223	552,978	

Table 5: Atmospheric Nitrogen loss from manure and ammonia losses as % total-N

Analysis of crop production

Based on estimates of crops at the ASA SWBC using remote sensing and ArcGIS, it was found that over 90% of the total crops covering the ASA SWBC are either berry (raspberries and blueberries) or forage crops (silage corn and hay). The area in hectares covered by berry and forage crops is shown in Figure 11.

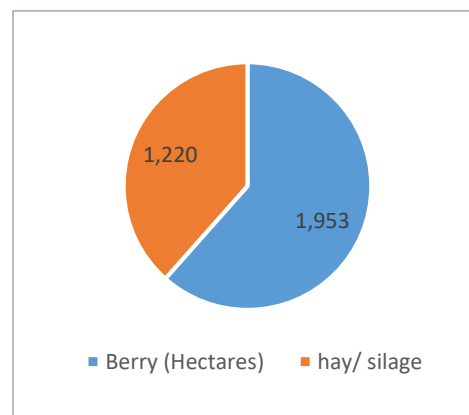


Figure 11: Berry and forage crops at the ASA SWBC, Area in hectares

⁹² Values adopted from; Rotz, "Management to Reduce Nitrogen Losses in Animal Production."

A specific classification of the variation of blueberry and raspberry production could not be detected by the use of the available imageries. Long-term census analysis over the city of Abbotsford suggests a growing number of blueberry production and a reduction in raspberry production. Figure 11 shows historic growth and decline of raspberries versus blueberries on the on the total area of Abbotsford between the years 1996 and 2016.

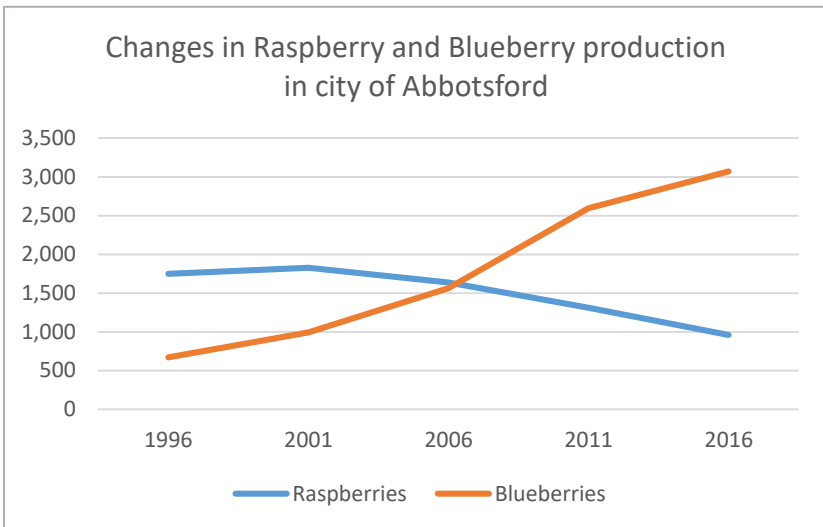


Figure 12: Growth and decline of raspberries versus blueberries on the ASA SWBC

Source: Estimates based on Census of Agriculture, Statistics Canada, 2016

In 2011 – 2013 the BC Ministry of Agriculture, estimated the number of raspberries over the aquifer at 1,136.7 hectares. This number is expected to have decreased since then as a result to shifts toward blueberry production.

Fertilizer application on the ASA SWBC

The rate of application of N-containing fertilizers on berry crops depends on a range of factors that include plant age, plant spacing, leaf tissue N level, and plant productivity. Values for blueberries and raspberries were averaged to 115 kg -N/ha for blueberries and 76 kg N/ha for raspberries.^{93,94} For simplification, the middle value of 95 kg-N/ha was used to estimate fertilizer nitrogen inputs on the area of the aquifer.

Similarly, two forage crops exist at the aquifer; silage corn with a fertilizer-N application rate of 140 Kg-N/ha and grass hay with a rate of 240 kg- N/ha. For simplification, the recommended rate for silage corn is applied for all forage crops at the aquifer.⁹⁵

Considering the two majority crops; berry and forage crops, total fertilizer nitrogen application on the ASA SWBC is 356,335 kg- N/yr., with an estimate of 185,535 kg- N/ yr. on berry fields, and 170,800 kg- N/yr. on silage/hay fields.

⁹³ B.C. MOA, "Results from the 2012 Fraser Valley Soil Nutrient Study – Blueberry: Nutrient Management Factsheet" (BC Ministry of Agriculture, 2015), https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/agriculture-and-seafood/agricultural-land-and-environment/soil-nutrients/600-series/631500-10_fvsns_blueberry.pdf.

⁹⁴ B.C. MOA, "Results from the 2012 Fraser Valley Soil Nutrient Study – Raspberry: Nutrient Management Factsheet," 2015, https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/agriculture-and-seafood/agricultural-land-and-environment/soil-nutrients/600-series/631500-11_fvsns_raspberry.pdf.

⁹⁵ P.E. Brisbin and G.G. Runka, "Application of Inorganic Fertilizers in the Lower Fraser Valley: Data Summary Report" (Environment Canada, 1995), http://publications.gc.ca/collections/collection_2015/ec/En83-6-1995-31-eng.pdf.

Nitrogen Uptake by crops

Based on the BC Berries Production Guide, the annual nitrogen requirements for blueberries range from 15 kg- N/ha for a 1-year-old field to 115 kg- N/ha for a field of 8 years or older. The guide also provides an estimation of raspberry nitrogen requirements for raspberries in the range between 40 kg- N/ha for lower productivity crops to 100 kg- N/ha for crops with a high yield potential.⁹⁶ For simplification, a 70 kg-N/ha will be used for nitrogen uptake calculations by all berry crops over the ASA aquifer.

Similarly, silage corn seasonal N uptake changes depending on its growth stage. Crop nitrogen uptake values from the literature are averaged to 125 kg-N/ha.⁹⁷

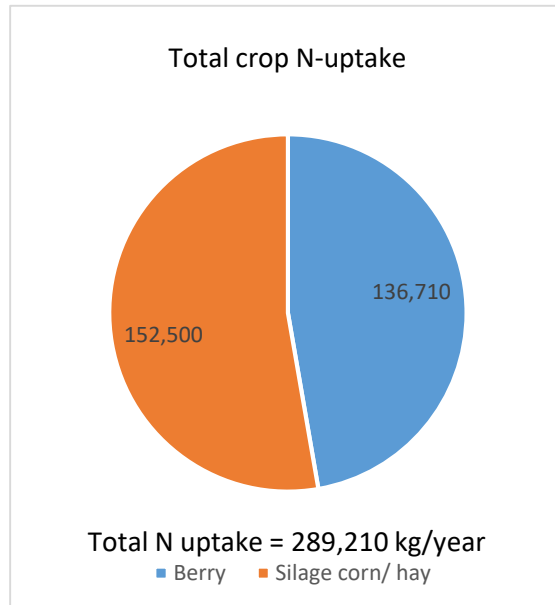


Figure 10: Nitrogen Uptake by crops on ASA SWBC (kg/year)

The total annual nitrogen uptake by berries and silage crops over the ASA SWBC is estimated to be 136,710 and 152,500 kg- N/ha respectively, totalling 289,210 kg- N/ha. See Figure 13.

Atmospheric N deposition at the ASA SWBC

Based on a joint report by the US. Environmental Protection Agency and Environment Canada. The atmospheric N deposition rate over the area of the ASA is 25 kg/ha/yr.⁹⁸ Therefore, N- deposition at the 95 km² ASA in SWBC is estimated to be approximately 237,500 kg-N/year.⁹⁹

Data Analysis on Abbotsford – Sumas aquifer Northwestern Washington State, US

Like the northern part of the aquifer, agriculture remains the most dominant land use. While poultry farming is the main agricultural activity over the aquifer in SWBC, dairy farming has been the predominant agricultural activity on the ASA NWS for the past 50 years, with berry production becoming more widespread in the past 20 years.¹⁰⁰ Regional figures suggest a growing trend in the average number of animals per farm. The average

⁹⁶ "Berries Production Guides," accessed July 31, 2018, <http://productionguide.agrifoodbc.ca/guides/14>.

⁹⁷ "Silage Corn N Uptake and Partitioning," accessed July 31, 2018, https://apps1.cdffa.ca.gov/FertilizerResearch/docs/N_Corn_Silage.html.

⁹⁸ Vingarzan, So, and Kotchenruther, "Georgia Basin - Puget Sound Airshed Characterization Report, 2014."

⁹⁹ The aquifer area was measured using remote sensing with the application of GIS techniques.

¹⁰⁰ Carey, "Sumas-Blaine Aquifer Nitrate Contamination Summary."

number of dairy cows per farm has increased from 201 to 384 between the years 1996 and 2016.

A study on the Sumas-Blain aquifer (SBA), which is the extension of the ASA to the south of the Nooksack river, estimates that 97% of annual nitrogen added to the SBA aquifer is from agricultural sources. The study suggests that two thirds of this amount is from manure applied to crops and a one third is from organic fertilizers. Other sources such as atmospheric deposition and on-site sewage systems make up to 2% and 1% respectively. Due to its low percentage and data unavailability, on-site sewage nitrogen loads are excluded from this study.¹⁰¹

An estimate of nitrogen inflows and outflows over the ASA SWWS are described in this section.

Analysis of dairy animal numbers

Estimates for dairy farm and cattle numbers in this section are based on data available for licenced grade “A” cow milk dairy milking facilities as reported by the State of Washington Department of Ecology (WSDE, 2018). Based on this, total number of dairy cows of different categories are estimated at 28,989, as shown in Figure 14.

It is important to mention that over 50 additional cattle farms exist over the area covering the US portion of the aquifer. Nevertheless, due to data unavailability on cattle type and numbers per farm, this study only focuses on dairy farms and animals reported by the WSDE.

Finally, based on remote sensing there is an estimated three chicken farms over the aquifer in SWWS. Therefore, poultry numbers will not be considered as part of the analysis of the NWWS ASA.

Dairy manure- N production and application at the ASA

Dairy manure estimates and the amounts of nitrogen in manure produced on the ASA NWWS are delineated in this section. Animal number estimates are used together with

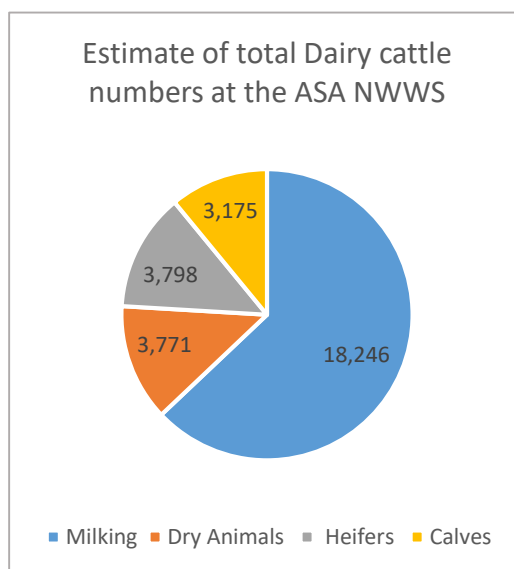


Figure 11: Total Dairy cattle numbers over the ASA based on WSDE geodatabase

¹⁰¹ Carey.

manure and manure-N per animal excretion values from the literature to conduct the following calculations.^{102 103}

Annual dairy manure produced on the aquifer is estimated at 514,115,725 kg/yr. (514,116 tonnes/yr.) for dairy farms reported by WSDA. This accounts for 2,821,068 kg -N/yr. (2,821 tonnes- N/ year). A summary of manure, manure- N production and Manure-Nitrogen excretion coefficients for all poultry categories are shown in table 6.

	Excretion Coefficients		Based on WSDA dairy farm Geodatabase (number of farms = 47)		
Dairy type	Annual total manure Kg/ animal/ yr.	Annual total nitrogen Kg-N /head/yr.	Total animal number	Annual total manure Kg/ yr.	Annual total nitrogen Kg-N /yr.
Milking	22,706	122	18,246	414,282,323	2,225,951
Dry Animals	13,870	83.95	3,771	52,296,835	316,533
Heifers	8,904	52.2	3,798	33,817,392	198,256
Calves	4,321	25.3	3,175	13,719,175	80,328
Total			28,989	514,115,725	2,821,068

Table 6: manure and manure- N production at the ASA NWWS

Source of coefficients: Yang, Huffman et.al "Estimating the impact of manure nitrogen losses on total," Agriculture and Agri-Food Canada (2010)

For manure nitrogen application estimations, this study assumes that 100% of manure produced by dairy farms at the aquifer will be spread on dairy farms' forage and grain crop fields.

Atmospheric N losses from manure

To estimate atmospheric nitrogen losses from manure, typical manure-N emission values were used from the available literature. 29% and 25% were used to calculate ammonia losses in %total-N terms for dairy manure-N losses in combined storage/housing, and application, respectively.¹⁰⁴ Table 7 summarizes manure nitrogen losses at each phase.

¹⁰² Source: Yang, Huffman et.al "Estimating the impact of manure nitrogen losses on total," Agriculture and Agri-Food Canada (2010)

¹⁰³ Huffman, Yang et. al "Estimation of Canadian manure and fertilizer nitrogen application rates at the crop and soil-landscape polygon level," <http://www.nrcresearchpress.com/doi/pdf/10.4141/CJSS07020>

¹⁰⁴ Values adopted from Rotz, "Management to reduce nitrogen losses in animal production,"

Nitrogen (kg/year)	Scenario A (based on WSDA dairy farm Geodatabase)	Scenario B (based on remote sensing)	Typical losses, %total N
Total Nitrogen	2,821,068	4,789,640	
N loss in storage and housing facility	804,004	1,365,047	29%
N loss in manure application	201,001	341,262	25%
Total manure- Nitrogen loss	1,005,005	1,706,309	

Table 7: Manure nitrogen losses on the ASA NWWS

Analysis of crop production

Based on the agricultural land use database developed by the Washington State Department of Ecology (WSDE),¹⁰⁵ the three main agricultural crops at the area of the aquifer are berries, cereal grains, and forage crops (hay/silage). These three crops represent over 90% of the total crop cover over the aquifer. The area covered by each crop type is shown in Figure 15.

Fertilizer application on the ASA NWWS

Fertilizer application rate is assumed to be the same at both sides of the aquifer. Like the ASA SWBC, a 95 kg /ha N-fertilizer is applied on berry products.^{106, 107} The fertilizer application rate on silage/hay and cereal grains is estimated at 140 kg- N/yr and 180 kg- N/yr respectively.¹⁰⁸

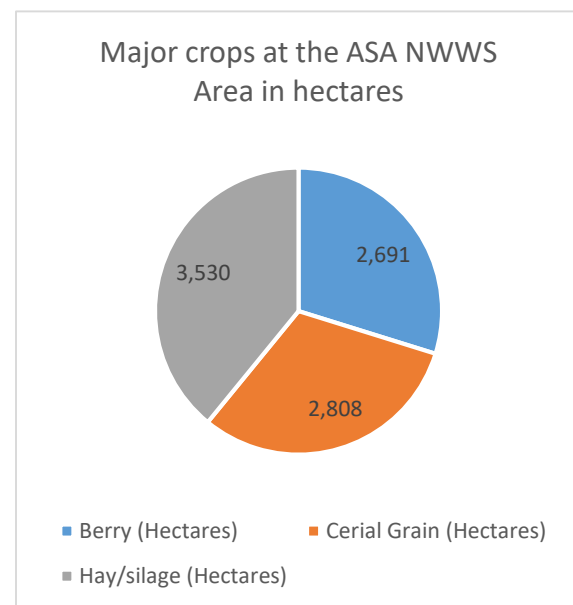


Figure 12: Area of crop field coverage of major crops at the ASA NWWS

Considering only the three major crops for estimations of the nitrogen budget, the total fertilizer N application on the ASA NWWS is 1,255,355 kg- N/yr with an estimate of 255,666 fertilizer-N kg/yr on berry fields, 505,489 kg- N/yr on cereal grain fields, and 494,200 kg- N/yr on silage corn fields within the area of the ASA NWWS.

¹⁰⁵ Available from <https://agr.wa.gov/pestfert/natresources/aglanduse.aspx>

¹⁰⁶ BC MOA, "Results from the 2012 Fraser Valley Soil Nutrient Study – Blueberry," BC Ministry of Agriculture (2015)

¹⁰⁷ MOABC, "Results from the 2012 Fraser Valley Soil Nutrient Study – Raspberry: Nutrient Management Factsheet," BC Ministry of Agriculture (2015)

¹⁰⁸ Brisbin and Runka, "Application of Inorganic Fertilizers in the Lower Fraser Valley: Data Summary Report."

Nitrogen Uptake by crops on ASA NWWs

Similar nitrogen uptake values to those in SWBC for berry and forage products were used for calculations on the ASA NWWs at 70 kg –N/ha and 125 kg- N/ha, respectively. N-uptake by cereal grain products is estimated at 105 kg-N/ha.^{109,110}

The total annual nitrogen uptake by berries, silage/hay crops, and cereal grain over the ASA SWBC is estimated to be 188,386, 441,250 and 294,000 kg- N/yr, respectively. Total nitrogen uptake estimates by the three major crops are 923,636 kg- N/yr.

Atmospheric N deposition at the ASA NWWs

Based on a joint report by the EPA and Environment Canada atmospheric N deposition over the area of the ASA is 25 kg/ha/yr. N-deposition rates for the 14,821 hectares of the ASA in NWWs is estimated to be approximately 370,525 kg-N/yr.¹¹¹ The area of the aquifer is measured based on aquifer boundaries from the literature.

¹⁰⁹ "Berries Production Guide," BC Ministry of Agriculture available at <http://productionguide.agrifoodbc.ca/guides/14>

¹¹⁰ "Corn Grain N Uptake and Partitioning," accessed July 31, 2018, https://apps1.cdfa.ca.gov/FertilizerResearch/docs/N_Corn_Grain.html.

¹¹¹ Aquifer area is measured using remote sensing with the application of GIS techniques

Summary of major agricultural nitrogen flows and N- Surplus calculations

Total surplus nitrogen over the ASA SWBC is estimated as per the below equations. A summary of all major nitrogen flows calculated in the previous sections of this chapter are illustrated in Figure 16.

Total nitrogen input on the ASA = (manure-N application) + (fertilizer-N application) + (atmospheric-N deposition)

Total nitrogen outputs in the ASA = (Crop- N uptake) + (manure- N loss)

Total surplus- N = Total nitrogen input - Total nitrogen output

Total nitrogen surplus on the total area of the Abbotsford-Sumas aquifer

Total nitrogen surplus on the ASA SWBC

- For scenario 1, assuming a 100% rate of application of manure produced at the area of the aquifer. The total surplus equals 1,670,613 kg- N/yr.
- For scenario 2, assuming an 80% rate of application of manure produced at the area of the aquifer. The total surplus equals 1,397,416 kg- N/yr.

Total nitrogen surplus on the ASA NWWS

- Assuming a 100% application rate of dairy manure based on dairy farms reported by WSDA, (2018). The total surplus equals 1,817,003 kg- N/yr.

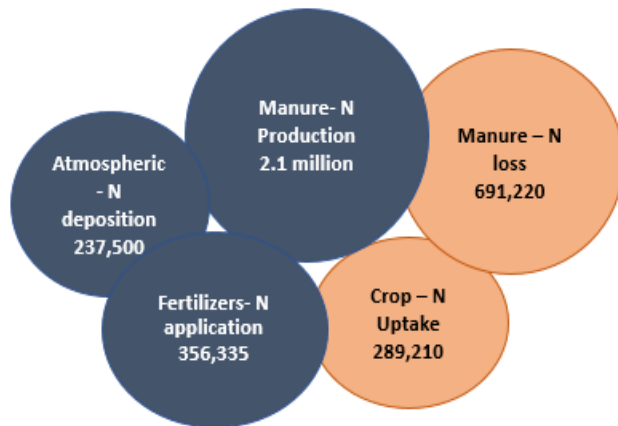
After estimating the N- surplus over the aquifer a $\pm 15\%$ level of uncertainty is applied to the results in table 8.

$\pm 15\%$ level of uncertainty (kg- N/yr)			
Abbotsford – Sumas Aquifer, Southwestern British Columbia			
Scenario description	Study estimation	+ 15% variation	- 15% variation
100% manure application rate	1,670,613	1,921,205	1,420,021
80% manure application rate	1,397,416	1,607,028	1,187,804
Abbotsford – Sumas Aquifer, Northwestern Washington State			
Scenario description	Study estimation	+ 15% variation	- 15% variation
Dairy farms	1,817,003	2,089,553	1,544,453

Table 8: changes in total nitrogen surplus at the ASA based on a level of uncertainty of 15%

Summary of Nitrogen Flows over the ASA

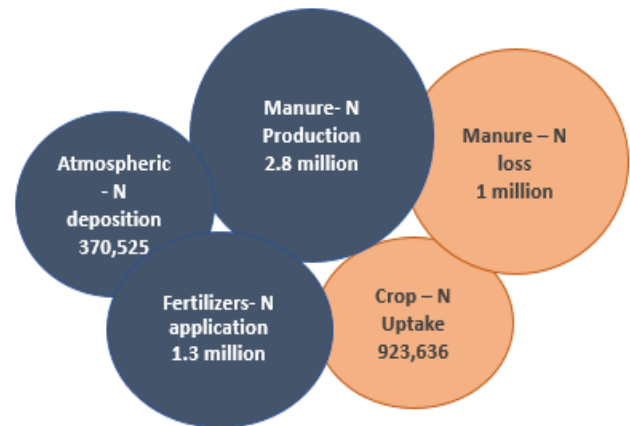
Nitrogen flows over the Canadian portion of the aquifer Kg- N/yr.



Total N- Surplus (Area of ASA U.S. portion = 9500 hectares)

100 % poultry manure application rate	80% poultry manure application rate
1.7 million kg- N /yr.	1.4 million kg- N/yr.

Nitrogen Flows over the U.S. portion of the Aquifer kg- N/yr.



Total N- Surplus (Area of ASA Canada portion = 14,821 hectares)

100% dairy manure application rate
1.8 million kg- N/yr.

Figure 13: Summary of major agricultural nitrogen flows kg- N/year over the ASA SWBC and NWW. Blue and orange represents input and output values in the ASA nitrogen budget respectively.

Total nitrogen surplus per hectare

The total nitrogen surplus per hectare on the ASA SWBS was first estimated by assuming an 80% and 100% poultry manure application rates on berry farms within the aquifer. The total nitrogen surplus on berry farms ranged between 610 – 750 kg- N/ha based on the two scenarios of application. If a 100% poultry manure application rate was applied on both berry and forage crops within the Canadian portion of the aquifer the surplus nitrogen amount would be 477 kg- N/ha.

The total nitrogen surplus per hectare on the ASA NWW was estimated assuming a 100% dairy manure application rate on dairy farms' forage and grain crop fields. The total nitrogen surplus per hectare was estimated around 353 kg- N/ha.

Data limitations

Results of the ASA nitrogen budget and the calculated surplus- N over the ASA were based on a range of data assumptions. The main limitations are summarized below in this section.

First, anecdotal information indicated that several factors influence the movement of manure in and out of the area of the aquifer which makes the estimation of application rates over the aquifer challenging. For example, some poultry manure is relocated for field renovations outside of the aquifer and other quantities are moved as part of sustainable farming initiatives to reduce nitrate applications to the aquifer. Furthermore, manure application on farms is not always done on yearly bases, for instance, berry farmers do not apply manure on their fields unless they are renovating it in order to meet food safety standards.

Fertilizer-N application rates, crop-N uptake and manure-N losses in this study were estimated using sources from the literature. Those rates may not precisely reflect the specific conditions at the ASA.

Poultry population and average number of poultry per farm numbers were based on limited Statistics Canada, Census of Agriculture data, which did not cover the entire area of the aquifer. Therefore, data from the census were combined with data obtained through visual digitization of agricultural land use using remote sensing and ArcGIS techniques to estimate numbers for the remainder of the ASA SWBC area.

Finally, this study takes a practical approach for the estimation of the surplus- N at the ASA. This approach has excluded other nutrient flows such as on-site sewage systems, biological nitrogen – fixation, and stock changes of nitrogen in the soil.

Conclusion

Long-term nitrate level analysis over the Abbotsford-Sumas aquifer has shown elevated concentrations that exceed the 10 mg- N/L drinking water guidelines in Canada and USA. High concentrations have persisted since the early 1980s and have been linked to intensive agricultural practices in the area.

Primary sources of nitrate over the ASA aquifer in Southwestern British Columbia and Northwestern Washington state are extensive berry production and the use of poultry manure, and other inorganic, commercial fertilizers to a lesser extent.¹¹²

Over the past two decades, there has been a clear growth in the agricultural sector over the aquifer. For instance, berry farms became more widespread, and poultry production on the Abbotsford portion of the aquifer has expanded by about 60% between 1996 and 2016.¹¹³ Although ASA NWWS, similarly, has a large regional berry production, a high percentage of nitrate seeping into the aquifer is believed to be associated with regional large-scale dairy farming, which has also experienced fast growth over the past decade. Consequently, nitrate sources include a mix of inorganic, commercial fertilizers, and animal manure.¹¹⁴

A comparative nitrogen budget at the ASA is an effective tool to conceptualize nitrogen flows over the aquifer in SWBC and NWWS and estimate the amounts of nitrogen surplus that could be leaked to the environment and contribute to the high nitrate levels in the ASA. Climatic factors and soil properties specific to the ASA aggravate the risk of nitrate seepage into the aquifer and increase its vulnerability to nitrate surpluses.

This report summarized the main nitrogen flows over the area of the ASA. Namely, manure- N, fertilizer- N, atmospheric- N deposition, crop- N uptake, and manure-N loss; all of which are either inputs or outputs in the nitrogen budget analysis. The highest contributor to the nitrogen budget was animal manure, specifically poultry and dairy animals on the Canadian and US portion of the aquifer, respectively.

The difference between nitrogen inputs and outputs is equal to the amount of surplus nitrogen. High surplus nitrogen was estimated on the ASA. This figure is estimated at 1.4 to 1.7 million kg- N/yr on the aquifer SWBC and 1.8 million kg- N/yr over the aquifer NWWS.

Estimates of N-surplus per hectare over the Canadian portion of the aquifer in SWBC were higher than the estimate over the southern portion of the aquifer in NWWS. This is consistent with the relatively lower nitrate levels in groundwater samples from the ASA in NWWS. First, assuming 80% and 100% application rates of poultry manure on berry

¹¹² Zearth et al., "Groundwater Monitoring to Support Development of BMPs for Groundwater Protection."

¹¹³ Value for 1996 is based on census of agriculture and 2016 based on estimations by this study

¹¹⁴ Mitchell et al., "Nitrate Distributions and Source Identification in the Abbotsford-Sumas Aquifer, Northwestern Washington State."

crops on the Canadian portion of the aquifer, the surplus- N was estimated to range between 610 and 750 kg- N/ha. Secondly, on the US portion of the aquifer, assuming a 100% application of dairy manure on dairy farms forage and grain crop fields. The total nitrogen surplus was estimated at 353 kg- N/ha.

Amidst a persistent high level of nitrate that exceeds drinking water thresholds in samples from both sides of the ASA, and agricultural production characterized mainly by a growing animal population and an increased number of animals per farm, there is need for effective and long-term solutions that aim to balance economic benefits with the protection of the aquifer.

To reduce the amounts of nitrogen fertilizer on the aquifer, several measures could be further investigated and analysed. Some approaches policy makers could pursue and discuss with stakeholders are increasing the percentage of manure removed from the aquifer, relocating livestock farms outside of the area of the aquifer, implementing restrictions based on land carrying capacity, and processing manure in regional facilities to convert it to biogas and fertilizers.

Bibliography

"Abbotsford Mission Water & Sewer Services: Our Water Matters." Accessed July 31, 2018. <https://www.ourwatermatters.ca/water-quality-faqs>.

Albert, Tuinhof, Stephen Foster, Karin Kemper, Hector Garduno, and Marcella Nanni. "Groundwater Monitoring Requirements for Managing Aquifer Response and Quality Threats." The World Bank, January 1, 2004. <http://documents.worldbank.org/curated/en/334871468143053052/Groundwater-monitoring-requirements-for-managing-aquifer-response-and-quality-threats>.

"Articles on the Law of Transboundary Aquifers." United Nations, 2013. http://legal.un.org/avl/pdf/ha/alta/alta_ph_e.pdf.

"Atlas of Transboundary Aquifers: Global Maps, Regional Cooperation and Local Inventories; 2009." UNESCO, 2009, 322.

B.C. MOA. "Results from the 2012 Fraser Valley Soil Nutrient Study – Blueberry: Nutrient Management Factsheet." BC Ministry of Agriculture, 2015. https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/agriculture-and-seafood/agricultural-land-and-environment/soil-nutrients/600-series/631500-10_fvsns_blueberry.pdf.

BCMOA, "Commodity Description: Poultry,". https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/agriculture-and-seafood/agricultural-land-and-environment/strengthening-farming/farm-practices/870218-23_poultry.pdf.

"Results from the 2012 Fraser Valley Soil Nutrient Study – Raspberry: Nutrient Management Factsheet," 2015. https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/agriculture-and-seafood/agricultural-land-and-environment/soil-nutrients/600-series/631500-11_fvsns_raspberry.pdf.

"Berries Production Guides." Accessed July 31, 2018. <http://productionguide.agrifoodbc.ca/guides/14>.

Biswas, Asit K. "Indus Water Treaty: The Negotiating Process." *Water International* 17, no. 4 (1992): 201–9. <https://doi.org/10.1080/02508069208686140>.

Brisbin, P.E., and G.G. Runka. "Application of Inorganic Fertilizers in the Lower Fraser Valley: Data Summary Report." Environment Canada, 1995. http://publications.gc.ca/collections/collection_2015/ec/En83-6-1995-31-eng.pdf.

Burton, D. L., and E. G. Beauchamp. "Nitrogen Losses from Swine Housings." *Agricultural Wastes* 15, no. 1 (January 1, 1986): 59–74. [https://doi.org/10.1016/0141-4607\(86\)90126-5](https://doi.org/10.1016/0141-4607(86)90126-5).

Canada, Environment and Climate Change. "Government of Canada. Meteorological Service of Canada. Canadian Climate Normals," October 31, 2011. http://climate.weather.gc.ca/climate_normals/index_e.html.

Canter, Larry W. *Nitrates in Groundwater*. CRC Press, 1996.

Carey, Barbara. "Focus on Groundwater Quality in Whatcom County: Report Summarizes 30 Years of Nitrate Studies in the Sumas-Blaine Aquifer." Washington State Department of Ecology, 2012.

Carey, Barbara. "Sumas-Blaine Aquifer Nitrate Contamination Summary." Washington State Department of Ecology, 2013.

Carey, Barbara M. "Sumas-Blaine Aquifer Long-Term Groundwater Quality Monitoring, 2009-2016." Washington State Department of Ecology, 2017. <https://fortress.wa.gov/ecy/publications/summarypages/1703013.html>.

Choudhury¹, Enamul, and Shafiqul Islam². "Nature of Transboundary Water Conflicts: Issues of Complexity and the Enabling Conditions for Negotiated Cooperation." *Journal of Contemporary Water Research & Education, Universities Council on Water Resources*, no. 155 (2015): 43–52.

"City of Abbotsford - Statistics FAQ's." Accessed July 31, 2018.
https://www.abbotsford.ca/business_and_development/statistics/statistics_faq_s.htm?PageMode=Print.

"Convention on the Law of the Non-Navigational Uses of International Watercourses, 1997." United Nations, 2014.

Cox, Stephen E, and Hugh Liebscher. "Ground-Water Quality Data from the Abbotsford- Sumas Aquifer of Southwestern British Columbia and Northwestern Washington State, February 1997." *U.S. Geological Survey and Environmet Canada*, 1999, 32.

"Draft Articles on the Law of Transboundary Aquifers (2008)." *United Nations* adopted by the International Law Commission at its sixtieth session (2008).
http://legal.un.org/ilc/texts/instruments/english/draft_articles/8_5_2008.pdf.

"Draft Decision on Adoption of Guidance Document on National Nitrogen Budgets." Geneva: Economic Commission for Europe, 2012.
https://www.unece.org/fileadmin/DAM/env/documents/2012/EB/ECE_EB.AIR_2012_L8_Draft_decision_on_adoption_of_guidance_document_on_national_nitrogen_budgets_GP.pdf.

Gallagher, Tanya L., and Sarah E. Gergel. "Landscape Indicators of Groundwater Nitrate Concentrations: An Approach for Trans-Border Aquifer Monitoring." *Ecosphere* 8, no. 12 (December 1, 2017): e02047.
<https://doi.org/10.1002/ecs2.2047>.

Graham, G., D. M. Allen, and B. Finkbeiner. "Climate Controls on Nitrate Concentration Variability in the Abbotsford-Sumas Aquifer, British Columbia, Canada." *Environmental Earth Sciences* 73, no. 6 (March 1, 2015): 2895–2907. <https://doi.org/10.1007/s12665-014-3072-5>.

Hayashi, Kentaro. "Nitrogen Fertilizer Applications as a Source of Atmospheric Ammonia." National Institute for Agro-Environmental Sciences, Japan, n.d.
<http://www.ffc.agnet.org/library.php?func=view&id=20130422103754#pict2%20pdf>.

Hii, Basil, Liebscher Hugh, and Mazalek Mike. "Groundwater Quality and Flow Rates in the Abbotsford Aquifer, British Columbia." Environment Canada, 1999.

Hii, Basil, Marc Zubel, Dean Scovill, and Gwyn Graham. "Abbotsford-Sumas Aquifer, British Columbia , Canada -- 2004 Groundwater Quality Survey - Nitrate and Bacteria." Environnent Canada, Vancouver, BC, 2006.

Huffman, T., J Y Yang, C F Drury, R. De Jong, X M Yang, and Y C Liu. "Estimation of Canadian Manure and Fertilizer Nitrogen Application Rates at the Crop and Soil-Landscape Polygon Level." *Canadian Journal of Soil Science* 88, no. 5 (November 2008): 619–27. <https://doi.org/10.4141/CJSS07020>.

Hugh, Liebscher, Basil Hii, and Duane McNaughton. "Nitrate and Pesticides in the Abbotsford Aquifer Southwestern British Columbia." Environment Canada, 1992.

Kevin, Li, and Hans Schreier. "Evaluating Long-Term Groundwater Monitoring Data in the Lower Fraser Valley." BC-WLAP, 2004.

Kremer, Anne Miek. "Methodology and Handbook Eurostat/ OECD: Nutrient Budget." *European Comission Eurostat*, no. Version 1.02. Eurostat and OECD, Luxembourg (2013): 112.

"Manure Chemistry – Nitrogen, Phosphorus, & Carbon." Natural Resources Conservation Services, USDA, 2007. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_043440.pdf.

“Ministry of Environment - Water Stewardship Division - Abbotsford-Sumas Aquifer International Task Force.” Accessed August 1, 2018.
http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/absumas.html.

Mirumachi, Naho. “Transboundary Water Security: Reviewing the Importance of National Regulatory and Accountability Capacities in International Transboundary River Basins.” *Department of Geography, King’s College London*, 2013, 24.

Mitchell, Robert, Scott Babcock, Robin A Matthews, and Robin Vandersypen. “Abbotsford-Sumas Aquifer Monitoring Project: Final Report.” *Western Washington University*, 2000.

Mitchell, Robert J., R. Scott Babcock, Sharon Gelinas, Leora Nanus, and David E. Stasney. “Nitrate Distributions and Source Identification in the Abbotsford-Sumas Aquifer, Northwestern Washington State.” *Journal of Environmental Quality* 32, no. 3 (June 2003): 789–800.

Monteny, G. J., and J. W. Erisman. “Ammonia Emission from Dairy Cow Buildings: A Review of Measurement Techniques, Influencing Factors and Possibilities for Reduction.” *NJAS Wageningen Journal of Life Sciences*, December 1, 1998, 225–47.

National Research Council (US) Subcommittee on Nitrate and Nitrite in Drinking Water. *Nitrate and Nitrite in Drinking Water*. Washington (DC): National Academies Press (US), 1995.
<http://www.ncbi.nlm.nih.gov/books/NBK231046/>.

“Nitrate in Groundwater.” British Columbia Ilbc, 2002.
http://www.ilbc.leg.bc.ca/public/pubdocs/bcdocs/358316/nitrate_2002.pdf.

“Professor Gabriel Eckstein: Implications of the UN Watercourses Convention for Groundwater Resources.” *International Water Law Project Blog* (blog), August 5, 2014.
<https://www.internationalwaterlaw.org/blog/2014/08/05/professor-gabriel-eckstein-implications-of-the-un-watercourses-convention-for-groundwater-resources/>.

Razowska-Jaworek, Lidia, and Andrzej Sadurski, eds. “Nitrates in Groundwater: IAH Selected Papers on Hydrogeology 5.” In *CRC Press*. Routledge, 2014. <https://www.crcpress.com/Nitrates-in-Groundwater-IAH-Selected-Papers-on-Hydrogeology-5/Razowska-Jaworek-Sadurski/p/book/9789058096647>.

“Regional Adaptation Strategies Series -- Fraser Valley.” *British Columbia Agriculture & Food Climate Action Initiative*, 2015, 51.

Rivera, Alfonso. “Transboundary Aquifers along the Canada–USA Border: Science, Policy and Social Issues.” *Journal of Hydrology: Regional Studies* 4 (September 2015),
<https://doi.org/10.1016/j.ejrh.2015.09.006>.

Rotz, C. A. “Management to Reduce Nitrogen Losses in Animal Production.” *Journal of Animal Science* 82, no. suppl_13 (January 1, 2004): E119–37. https://doi.org/10.2527/2004.8213_supplE119x.

Safley, L. M., J. C. Barker, and P. W. Westerman. “Loss of Nitrogen during Sprinkler Irrigation of Swine Lagoon Liquid.” *Bioresource Technology* 40, no. 1 (January 1, 1992): 7–15. [https://doi.org/10.1016/0960-8524\(92\)90112-B](https://doi.org/10.1016/0960-8524(92)90112-B).

Schuurman, Nadine, Aparna Deshpande, and Diana M. Allen. “Data Integration across Borders: A Case Study of the Abbotsford-Sumas Aquifer (British Columbia/Washington State)1.” *JAWRA Journal of the American Water Resources Association* 44, no. 4 (August 1, 2008). <https://doi.org/10.1111/j.1752-1688.2008.00192.x>.

“Silage Corn N Uptake and Partitioning.” Accessed July 31, 2018.
https://apps1.cdffa.ca.gov/FertilizerResearch/docs/N_Corn_Silage.html.

Sommer, S. G., and N. Hutchings. "Techniques and Strategies for the Reduction of Ammonia Emission from Agriculture." *Water, Air, and Soil Pollution* 85, no. 1 (December 1, 1995). <https://doi.org/10.1007/BF00483704>.

Vingarzan, R., R. So, and R. Kotchenruther, eds. "Georgia Basin - Puget Sound Airshed Characterization Report, 2014." Environment Canada, Pacific and Yukon Region, Vancouver (BC). U.S. Environmental Protection Agency, Region 10, Seattle (WA), July 1, 2002. <http://publications.gc.ca/site/eng/9.698425/publication.html>.

Vries, Jacobus J. de, and Ian Simmers. "Groundwater Recharge: An Overview of Processes and Challenges." *Hydrogeology Journal* 10, no. 1 (February 1, 2002). <https://doi.org/10.1007/s10040-001-0171-7>.

"Water Resources Management Overview." Accessed July 31, 2018. <http://www.worldbank.org/en/topic/waterresourcesmanagement>.

Winter, Thomas C., Judson W. Harvey, O. Lehn Franke, and William M. Alley. "Ground Water and Surface Water; a Single Resource." USGS Numbered Series. Circular. U.S. Geological Survey, 1998. <http://pubs.er.usgs.gov/publication/cir1139>.

Wouters, Patricia. "International Law: Facilitating Transboundary Water Cooperation." Global Water Partnership, 2013. <https://www.gwp.org/globalassets/global/toolbox/publications/background-papers/17-international-law---facilitating-transboundary-water-cooperation-2013-english.pdf>.

Yang, J. Y., E. C. Huffman, C. F. Drury, X. M. Yang, and R. De Jong. "Estimating the Impact of Manure Nitrogen Losses on Total Nitrogen Application on Agricultural Land in Canada." *Canadian Journal of Soil Science* 91, no. 1 (January 1, 2011). <https://doi.org/10.4141/cjss10052>.

Yoffe, Shira, Greg Fiske, Mark Giordano, Meredith Giordano, Kelli Larson, Kerstin Stahl, and Aaron T. Wolf. "Geography of International Water Conflict and Cooperation: Data Sets and Applications." *Water Resources Research* 40, no. 5 (May 1, 2004). <https://doi.org/10.1029/2003WR002530>.

Zebarth, Bernie J., M. Cathryn Ryan, Gwyn Graham, Thomas A. Forge, and Denise Neilsen. "Groundwater Monitoring to Support Development of BMPs for Groundwater Protection: The Abbotsford-Sumas Aquifer Case Study." *Groundwater Monitoring & Remediation* 35, no. 1 (February 1, 2015): 82–96. <https://doi.org/10.1111/gwmr.12092>.