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AN ASSESSMENT OF POTENTIAL SOURCES OF GROUNDWATER CONTAMINATION IN BRITISH COLUMBIA, CANADA.

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INTRODUCTION

This study assesses the major potential sources of groundwater contamination in British Columbia (B.C.), and provides recommendations for preventative and remedial measures for groundwater quality protection.

OBJECTIVES

The objectives of this project are to: (1) identify and assess the most common potential sources of groundwater contamination in B.C.; (2) recommend preventative and remedial measures for groundwater quality protection; and (3) provide information to stakeholders, including government regulatory agencies; land use planning; water management; environmental health protection; and community development.

WHAT IS GROUNDWATER?

Groundwater is water that fills the pores and fractures of underground geological materials, such as sediments (sand and gravel), and rocks (e.g. high pore volume sandstones, and fractured granites). Because groundwater has to make its way through the pores and fractures in these materials, its movement is generally slow, at rates of 7-60 centimetres (3-25 inches) per day in an aquifer. This means that groundwater can remain in an aquifer for hundreds or thousands of years before being discharged (USGS, 2020b).

WHAT ARE AQUIFERS?

When the water stored in underground rocks or sediments occurs in sufficient volume and available for use (e.g. public supply, irrigation, and industry) and flows easily out of the ground, either naturally or through pumping, the geological material that contains that water is defined as an aquifer. If water is stored in a geological material that is not capable of transmitting significant quantities of water, that material is defined as an aquiclude. A confined aquifer is an aquifer located between two aquitards (non-permeable barriers). An unconfined aquifer, or water-table aquifer, is an aquifer that occurs near the ground surface (Freeze and Cherry, 1979). Unconfined aquifers are generally more susceptible to contamination due to being directly connected to the soil surface, whereas confined aquifers are protected by an impermeable layer that blocks infiltration (B.C. MoE, 2004).

WHAT ARE CONTAMINANTS? HOW DO THEY REACH AQUIFER SYSTEMS?

The term “contaminant” in water may be defined broadly as “anything other than water molecules” (U.S. EPA, 2016), or as specific as “substances (i.e. chemical elements and compounds) or groups of substances that are toxic, persistent and liable to bioaccumulate, and other substances or groups of substances which give rise to an equivalent level of concern” (Tornero & Ribera, 2014). In this study, “contaminant” will be referred to as the former, broader definition given by the U.S. Environmental Protection Agency Safe Drinking Water Act: “Any physical, chemical, biological or radiological substance or matter in water.” Therefore, it is expected that safe drinking water may contain small amounts of some contaminants (U.S. EPA, 2016).

Contaminants may be introduced to the environment by human activities, such as wastewater discharge into rivers, leaky septic systems, or application of fertilizers; or they may be naturally occurring, such as through the dissolution of rocks and minerals, or the intrusion of seawater into freshwater aquifers. Contaminants may reach aquifer systems the same way as rain: via infiltration through soil until it reaches the aquifer. This means that substances used in any activities, whether underground or on the soil surface, have the potential to contaminate groundwater. Therefore, all types of land use, including agricultural, industrial, commercial, municipal, and residential activities, may cause groundwater contamination (Cherry, 1987).

WHAT IS THE DIFFERENCE BETWEEN CONTAMINATION AND POLLUTION?

The B.C. Environmental Management Act defines "pollution" as "the presence in the environment of substances or contaminants that substantially alter or impair the usefulness of the environment". Pollution, therefore, happens when an environment has high enough concentrations of contaminants to negatively affect ecosystems or individual organisms. Thus, the difference between contamination and pollution is not always clear, and it involves variables such as the type of community affected and the bioavailability or toxicity of contaminants. As a result, there are different concentration guidelines for different purposes of water use, such as drinking water or the support of aquatic life (Chapman, 2007; Stengel et al., 2006).

THE GLOBAL WATER CRISIS: CANADA AND BRITISH COLUMBIA

Freshwater scarcity is a growing global crisis, continuously exacerbated by climate change, population growth, and pollution (Aldhous, 2003). Contrary to popular belief, Canada is not exempt from the threats of diminishing drinking water supply and quality and the deterioration of aquatic ecosystems (University of Saskatchewan, 2019; Gower & Barroso, 2019). In B.C., approximately 63% of the population (2.9 million people) live in water-stressed areas. Droughts, wildfire smoke, and water restrictions are becoming the "new normal" for British Columbians, as temperatures rise, and the population continues to grow (Gower & Barroso, 2019).

THE IMPORTANCE OF GROUNDWATER

Freshwater is often thought of as water that occurs in rivers, lakes, reservoirs, and wetlands. However, surface water makes up only slightly over 1.2% of the world's freshwater, while groundwater accounts for approximately 30%, with the remaining global freshwater supply stored in glaciers and ice caps (Shiklomanov, 1993). Groundwater accounts for 98-99% of the global stock of liquid freshwater (Margat & van der Gun, 2013).

Groundwater supplies one-third of all freshwater withdrawals globally, with an estimated contribution of 36% of domestic use, 42% of agricultural use, and 27% of industrial use. Groundwater sustains rivers, lakes, and wetlands baseflows in many environments during periods of low or no precipitation, including many areas of B.C. where groundwater baseflow is critical for the survival of fish populations during periods of low flow (Government of Canada, 2013; Taylor et al., 2012).

GROUNDWATER IN BRITISH COLUMBIA

In British Columbia, around 562 million m^3 of groundwater are used annually. Agriculture is the sector with the highest consumption (38%), followed by finfish aquaculture (21%), industry (16%), municipal water distribution systems (15%), and domestic private well users (11%) (Forstner & Gleeson, 2019; Government of Canada, 2013). In 2010, "An Audit of the Management of Groundwater Resources in British Columbia" (Office of the Auditor General of British Columbia, 2010) reported that "government is not effectively ensuring the sustainability of the province's groundwater resources". More specifically, information about groundwater was deemed insufficient to ensure its sustainability, and there was no groundwater protection from depletion and contamination to ensure the viability of the ecosystems it supports. Moreover, little control over access to groundwater made it insufficient to sustain the resource and key organizations were found to lack adequate authority to take appropriate local responsibility.

Until 2016, B.C. was the only province in Canada, and one of the few jurisdictions in North America, without any form of licensing requirements for groundwater use at any level (Nowlan, 2007). Introduced in 2016, the Water Sustainability Act (WSA) replaced the Water Act, that had been in place since 1909. The new Act regulates the licensing of groundwater for non-domestic use, establishes new fees and rentals for water use, provides stronger protection for aquatic ecosystems, and greater protection of groundwater-related to well construction and maintenance. A transition period of six years from 2016 was conceded to allow for approximately 20,000 existing non-domestic groundwater users to apply for a water license. This approach to groundwater regulation was criticized due to the fact that it does not acknowledge First Nations Aboriginal and Treaty rights to water use, and that the current use of groundwater in B.C. is, as identified by the 2010 "Audit of the Management of Groundwater Resources in British Columbia", not ecologically sustainable (Joe et al., 2017).

WHY PROTECT GROUNDWATER QUALITY?

In a water-scarce world, the protection of our water resources from pollution is imperative. While the issue of pollution of surface waters is easily detected and relatively simple to solve, groundwater pollution is more difficult to detect, prevent, and to mitigate. Its complexity is due to the complex and heterogeneous systems through which groundwater flows, and through which pollutants may enter groundwater systems. Furthermore, because of the slow movement of water in the subsurface, long periods are usually required for pollutants to be flushed from aquifers. The length of time it takes for groundwater to replenish itself is called the residence time, which can last for hundreds or thousands of years. Thus, in some cases, once groundwater is contaminated, the damage to an aquifer or parts of an aquifer is considered permanent or irreparable from a human time frame (USGS, 2020b, Kralik, 2015, Freeze & Cherry, 1979).

HOW IS GROUNDWATER QUALITY PROTECTED?

Scientifically, the protection of groundwater resources involves identifying the areas and mechanisms by which potential pollutants can enter aquifers, and the development of predictions of the transport of contaminants within the flow systems (Freeze and Cherry, 1979).

In B.C., the Well Protection Toolkit was developed and published by the government as a guide on developing and implementing a well protection plan (B.C. MoE, 2004). It includes six steps: 1: form a community planning team; 2: define the capture zone (recharge area) of the community well; 3: map potential sources of pollution in the capture zone; 4: develop and implement protection measures to prevent pollution; 5: develop a contingency plan against any accidents; and 6: monitor, evaluate, and report on the plan annually. This guide is intended to be used in small scale projects, in which a survey can be conducted in a community area to identify the potential sources of pollution in the defined capture zone.

STUDY AREA

British Columbia is the westernmost and third largest province in Canada, in both area (944,735 km^2) and population (5,071,336 people). The province is characterized by mountainous topography (75% of the land), and substantial areas of lowland and plateau highlands. Some of B.C.'s major industries that affect groundwater include agriculture, fishing, construction, forestry, manufacturing, mining and oil and gas extraction, accommodation and food services, transportation and warehousing, and utilities (British Columbia, 2020; B.C. Ministry of Finance, 2019; WorkBC, 2019).

Groundwater in B.C. can occur in sand and gravel aquifers but more commonly in fractured aquifers (bedrock) (Berandinucci & Ronneseth, 2002). The government of B.C. has mapped and classified more than 1100 aquifers across the province since 1994, based on usage and vulnerability to contamination (Fostner, 2018; Office of the Auditor General of British Columbia, 2010). Approximately 25% of the mapped aquifers are considered highly vulnerable to contamination (Office of the Auditor General of British Columbia, 2010).

METHODOLOGY

This study is based on a literature review, and on the analysis of data from government databases to identify the major potential sources of groundwater contamination in British Columbia. The selected sources, as well as information on common contaminants, are based on the works of Capel et al. (2018), Stevenazzi et al. (2017), Żychowski & Bryndal (2015), Mansilha et al. (2014), Singhal & Gupta (2010), Arvanitoyannis (2008), Syms (2008), Buckler & Grenato (1999), U.S. EPA (1993), and Cherry (1987). Data used include the Waste Discharge Authorizations dataset, British Columbia's Mineral Inventory database (British Columbia, 2020e), BC Airports dataset, Golf Courses dataset, and BC Farm Counts by Size Type and Revenue from B.C.'s Data Catalogue (British Columbia, 2020c).

SCOPE AND LIMITATIONS

This document focuses on an assessment of the major potential sources of groundwater contaminants in the province of British Columbia and does not include details such as aquifers' capture zones (groundwater recharge areas), aquifers' vulnerability levels, the amount and specific types of possible contaminants, or localized hazards. The aim is to provide insight and draw attention to the most significant sources of pollutants in the province so that preventative measures to protect groundwater quality are planned and initiated.

POTENTIAL SOURCES OF GROUNDWATER CONTAMINATION

Potential sources of groundwater contamination are essentially the same as potential sources of surface water contamination. Groundwater contamination can be **anthropogenic** (caused by human activities) or the result of **natural** causes such as geologic processes (geogenic) and sea-water intrusion in aquifers (Stefanakis et al., 2015; Singhal & Gupta, 2010). Potential groundwater contamination sources can be **point sources** or **diffuse (non-point) sources**. Point sources are stationary and localized in relatively small areas – which means they are unconnected or discrete sources that cover only a small fraction of the land area of most aquifers. Examples of point sources include landfills, waste dumps, septic tanks, manure storage, underground gasoline storage tanks (gasoline stations), and industrial facilities. Diffuse sources are distributed along relatively large areas that are subject to widespread inputs of a range of contaminants. Examples of diffuse sources include fertilizer and pesticides used in agricultural lands, salt and metals runoff from roads and paved areas, and natural sources such as the dissolution of minerals and rocks and seawater intrusion in aquifers (Stefanakis et al., 2015; Singhal & Gupta, 2010; Cherry, 1987).

Table 1 contains a list of the identified potential sources of groundwater contamination in B.C. The source activities were categorized by land use for the purpose of aiding possible determination of toxicological effects of contaminants, potential exposure pathways, and remedial measures.

TABLE 1 COMMON POTENTIAL SOURCES OF GROUNDWATER CONTAMINATION BY LAND USE

Category	Source Type	Contaminant Source	
Agriculture	Diffuse	Manure spreading areas	Irrigation areas
		Fertilizer use	Compost windrows
		Pesticides (including herbicides, insecticides, nematicides, and fungicides) use	Sewage or sewage sludge (biosolids) use
		Fly ash use	Aquaculture (fish hatcheries)
	Point	Manure storage areas	Fly ash storage
		Animal feedlots	Compost piles
		Fertilizer storage	Animal burial areas
		Pesticide/herbicide storage	
Industry	Point	Agri-industrial: Food processing plants, including brewing and malting, and distilling of spirits	Oil and Gas: Pipelines
		Manufacturing: Asphalt (production and equipment cleaning sites)	Mining (metals and coal): tailing ponds, rock waste piles
		Manufacturing: Concrete, ceramics, cement and plaster works	Mining: coal carbonization plants
		Manufacturing: Electrical and electronics	Forestry: Pulp/paper mills
		Manufacturing/Storage: Chemicals (organic and inorganic)	Forestry: Wood preservation
		Manufacturing: Foundries/metal fabricators and finishing	Machine/metalworking shops
		Manufacturing: Pharmaceuticals	Septage lagoons and sludge sites
		Manufacturing: paints, varnishes, ink	Underground injection wells
		Manufacturing: textiles, tanneries	Toxic and hazardous spills/leaks
		Oil and Gas: Petroleum refineries	Wells (operating/abandoned)
			Open burning sites
Commercial Facilities	Point	Boatyards/Dockyards and wharves	Golf courses
		Airports	Metal plating: Automotive, jewellery
		Auto repair shops	Graveyards
		Dry cleaners and laundromats	Construction sites
		Railroad tracks and yards	Car washes
		Scrap and junkyards	Toxic and hazardous spills/leaks

		Transportation/warehouse companies and terminals Storage tanks: gas stations, others Waste management: transfer stations, landfills, hazardous waste landfills, incinerators, and recycling/reduction facilities Paint shops	Wells (operating/abandoned) Natural gas distribution Diesel power plants Biomass power plants
Residential Facilities	Point	Fuel oil Household hazardous products Household lawns Septic systems/cesspools and sewer lines	Swimming pools (chemical storage) Wells (operating/abandoned) Compost piles Furniture stripping/refinishing
Municipal Facilities	Point	Waste management: transfer stations, landfills, hazardous waste landfills, incinerators, and recycling/reduction facilities Water and wastewater systems: sewer lines and stormwater drains/basins	Road de-icing salt storage Road maintenance depots
Others	Point	Roads and highways Spills related to highway or railway accidents	Open burning sites Deforestation
	Diffuse	Rain, snow and dry atmospheric fallout	
Natural Sources	Diffuse	Seawater intrusion Wildfires Dissolution of minerals and rocks	

MAJOR SOURCES OF POTENTIAL GROUNDWATER CONTAMINATION

The history of anthropogenic groundwater contamination in British Columbia is part of the greater history of environmental pollution due to the rapid intensification of urbanization and industrialization that began in the early twentieth century. For decades, effluents were freely discharged into water bodies and/or on land by residences and municipalities (urban wastes), and the industrial activities of mining and pulp/paper mills. Many of these activities contributed to the long-term degradation of water quality, as anti-pollution regulations were not established until the 1970s (Keeling, 2004). The expansion and intensification of agriculture have also led to the degradation of water quality through the excessive input of nutrients and other chemicals, aided by the great increases in fertilizer and pesticide use starting in the 1960s (USGS, 2020a; MoE, 2006).

Today, although with more regulations in place, the challenges faced regarding water quality and quantity are continuously increasing in both size and complexity. The accelerating climatic changes, population growth, urbanization, land use changes such as deforestation and soil degradation, changing diets, and expanding societal wealth are all impacting the quantity and quality of both surface and groundwater resources (Schuster-Wallace et al., 2019). According to Berandinucci & Ronneseth (2002), the known common sources of groundwater contamination in B.C. in 2002, were fertilizers, septic systems, gasoline stations, waste disposal, mining, industrial processing, product storage, transportation activities, and seawater intrusion. More recently, there have been growing concerns about contamination of water from oil and gas extraction resulting from developments in horizontal drilling techniques and multi-stage hydraulic fracturing in northeast B.C. (Wisen et al., 2020; Canadian Water Network, 2015; Krzyzanowski, 2012).

In this section, the following major sources of groundwater contamination that have been commonly identified in B.C. are presented by land use: agricultural; industrial (mining); commercial (gasoline stations); residential (septic systems); municipal/industrial (landfills); and natural (seawater intrusion). They have been selected based on their pervasiveness in the province, high concentrations and level of hazard of contaminants released.

AGRICULTURE

Agricultural activities are considered to be the most important source of contaminants to groundwater worldwide today (USGS, 2020a; WWAP, 2013; Kuroda & Fukushi, 2008; Freeze & Cherry, 1979). However, the impact of agricultural practices on surface and groundwater quality was not as readily recognized as are point-source pollution from industrial activities and urban wastes. Most of the sources of contaminants from agriculture are diffuse, and there is commonly a lag time between the input and the impacts on water quality due to complex site conditions, soil processes, and pathways (Hall & Schreier, 1996).

The application of fertilizers (chemical, animal manure, sludge) rich in nitrogen and phosphorus is the main agricultural practice that can impact groundwater quality (USGS, 2020a; WWAP, 2013; Kuroda & Fukushi, 2008; MoE, 2006; Freeze & Cherry, 1979)

When excess fertilizer is applied on land, nutrients that are not consumed by plants are carried by water (rain, irrigation, or snowmelt), either through runoff over land or through leaching into the soil. Nutrients that are carried by runoff will eventually reach both surface and groundwater bodies, where they cause eutrophication (U.S. EPA, 2020). Nutrients that leach into the soil eventually reach aquifer systems, contaminating groundwater.

Other activities of concern include the application of pesticides, and the storage and disposal of livestock or poultry wastes on land (U.S. EPA, 2020; WWAP, 2013; Kuroda & Fukushi, 2008; MoE, 2006; Freeze & Cherry, 1979). Pesticides include a wide variety of organic contaminants that may cause poisoning, cancer, and many other health issues. Animal manure is a source of nitrate and of a wide range of bacterial, viral, and parasitic pathogens that can be mobilized from manure on land (McAllister & Topp, 2012). Both types of sources can contaminate groundwater systems the same way as fertilizers do, through multiple pathways (McAllister & Topp, 2012; Woudneh et al., 2009).

In British Columbia, the Water Quality Check Program run by the Ministry of Environment from 1977 to 1993 identified nitrate concentrations above the MAC in rural wells near Langley, Abbotsford, Armstrong, Grand Forks, Kamloops, Osoyoos, Salmon Arm, Vernon and Williams Lake, particularly in intensive agricultural areas or locations where septic tanks are the main method of sewage disposal (B.C. MoE, 2007). In 2012, the Southwest of B.C. (Fraser Valley, Metro Vancouver, Sunshine Coast, and Squamish-Lillooet) was identified as the most intensively managed agricultural area in the country, with more livestock per unit area than any other part of Canada (Statistics Canada, 2012).

The adoption of nutrient management techniques is a commonly used method to reduce nutrient loss to water bodies. Nutrient management involves applying only the amount of nutrients that a crop needs, at the right time, form, and placement to prevent the discharge of excess nutrients to the environment (British Columbia, 2020f). In B.C., the Environmental Farm Plan program, created in 2004, helps farmers to implement a nutrient management plan. However, the plan is only mandatory for certain areas for small periods and has so far not been widely adopted (Dobb, 2013). For the 2019 and 2020 growing seasons, only operations greater than 5 ha within the Hullcar Vulnerable Aquifer Recharge Area are required to adopt the nutrient management plan (British Columbia, 2020d). The Hullcar Aquifer is located in the Hullcar Valley in North Okanagan and its population has been under drinking water advisories since 2014 due to nitrate contamination (British Columbia, 2020d).

INDUSTRY

MINING

Mining in British Columbia began in the mid-1800s with coal mines on Vancouver Island, and placer gold camps in the Cariboo region. Today, British Columbia is Canada's largest exporter of coal, leading producer of copper, and only producer of molybdenum. The province also produces large amounts of gold, silver, lead, and zinc, as well as industrial (non-metallic) minerals (Clarke et al., 2020; Statistics Canada, 2020).

Legislation requiring companies to reclaim lands that have been disturbed by mining was not introduced until 1969 (British Columbia, 2020a), and many abandoned mine sites that have been causing long-term pollution through acid rock drainage and metal leaching still exist in the province (Government of Canada, 2020; Plourde & Zeidler, 2017; BCTRCR, 2011). Acid rock drainage (ARD) is the largest and most challenging environmental liability faced by the mining industry and one of the most pervasive environmental problems worldwide. ARD occurs when sulphide minerals (such as pyrite) are excavated and exposed to an oxygenated environment, which causes them to undergo oxidation, producing sulphuric acid. The resulting acidic runoff ($pH < 3$) laden with sulphate, heavy metals, and metalloids (metal leaching) can persist from decades to hundreds of years and is extremely difficult to predict on account of its many complex influencing parameters. When this untreated acidic water travels from the mine site by surface drainage and reaches streams and groundwater, it can severely degrade water quality, destroying aquatic life habitat and making it unsafe to use (Price & Errington, 1998; Evangelou & Zhang, 1995).

In North America, metal leaching and acid rock drainage caused by mining have led to a significant ecological loss, and multimillion-dollar cleanup costs for industry and government (Price & Errington, 1998; Evangelou & Zhang, 1995). Geological environments like metallic ore deposits, phosphate ores, oil shales, heavy mineral sands, and coal seams commonly contain large volumes of sulphide minerals which are often exposed in tailings dams, waste rock dumps, coal spoil heaps, heap leach piles, run-of-mine and low-grade ore stockpiles, waste repository embankments, open-pit floors and faces, underground workings, haul roads, road cuts, quarries, and other rock excavations (Lottermoser, 2010).

In B.C., the Britannia Copper mine, located 30 km north of Vancouver, is one of the largest metal pollution sources in North America. The mine opened in 1905 and was active for 70 years. At its peak, it was considered the largest copper producer in the British Commonwealth. After its closure in 1974, the mine was redeveloped as a museum and heritage site. However, until 2005 the contaminated water leaving the mine still flowed directly into the Howe Sound. To this day the site is still being remediated by the provincial government, having spent in excess of $46 million in the process, as of 2012 (British Columbia, 2020b; Rhatigan, 2016; Carman, 2012).

Another important case of acid mine drainage is related to the Tulsequah Chief mine by the Taku River in northwest B.C. Although the mine was closed in 1957, the acid mine drainage generated by the site still flows into one of the most important salmon rivers in the U.S., in Alaska (Plourde & Zeidler, 2017).

In the 2019 Spring Reports of the Commissioner of the Environment and Sustainable Development on "Protecting Fish from Mining Effluent" (Office of the Auditor General of Canada, 2019), it was found that inspections on each mine site were done every 1.5 years on average; 35% of 138 metal mines are out of compliance by not reporting data on pollutant release; 117 non-metal mine sites are not subject to mandatory monitoring of effects on fish; there is a lack of enforcement measures when mines show effects on fish and fish habitat, and there is a lack of transparency on pollution, spills, and effects to fish on a mine-per-mine basis, to inform the public and affected communities, as pointed out by MiningWatch Canada (MiningWatch Canada, 2019). Additionally, in the 2017 National Assessment of Environmental Effects Monitoring Data from Metal Mines (Government of Canada, 2017b) it was found that “Almost all mines (57/62 or 92%) with confirmed effects [on fish] observed at least one effect of a magnitude that may be indicative of a higher risk to the environment”.

As of August 2020, there are a total of 2,099 mines registered in the B.C.’s Mineral Inventory database (British Columbia, 2020e), of which 96 are active, and 2,003 are closed or abandoned. Of the active mines, 12 are coal mines, 13 metallic mines, and 71 non-metallic mines. The closed or abandoned sites include 81 coal mines, 1,627 metallic mines, and 295 non-metallic mines.

COMMERCIAL FACILITIES

GASOLINE STATIONS

Leakages and spills of petroleum products are a common threat to groundwater quality. Underground pipelines, tanker trucks carrying oil and gasoline, and gasoline stations are ubiquitous in industrialized areas (Meegoda & Hu, 2011; Cherry, 1987; Freeze and Cherry, 1979). Gasoline stations are considered to be the main source of petroleum product contamination in British Columbia (B.C. MoE, 2009; Berandinucci & Ronneseth, 2002).

Petroleum products, unlike other common groundwater contaminants, do not mix into water, but rather float on top. As a result, when oil leaks into the soil it moves mainly in the unsaturated zone, undetected. However, crude oil and its derivatives contain hydrocarbon components that are soluble in water. In general, lighter petroleum derivatives are more soluble, which is the case of commercial gasoline. Because its solubility is much greater than the concentration levels at which water is considered to be polluted, the dissolution of hydrocarbons is commonly a greater concern than the practically immobile zone of immiscible oil on or above the water table (Freeze & Cherry, 1979).

Gasoline stations started being constructed by the thousands in North America after World War II. Until the 1980s, underground storage tanks (UST's) were made of steel. To date, corrosion, along with poor installation and operation, has resulted in an increasing number of cases of groundwater contamination. Replacement of old UST's have been happening gradually, and leakage problems related to old UST's are common, particularly in locations with high water tables and frequent infiltration from precipitation (Meegoda & Hu, 2011; Freeze & Cherry, 1979).

In 1985, there were approximately 200,000 underground petroleum storage tanks in Canada, of which around 70,000 were located in gasoline stations. The remaining were used for transportation, industrial, commercial, and agricultural activities, and by households as furnace heating oil. In surveys from 1985, about 20-25% of USTs in gas stations in Canada were found or suspected to be leaking (Pupp, 1985). The number of gas stations in Canada decreased from more than 20,000 in 1989 to around 12,000 in 2016 (Schlesinger, 2016). In 2019 there were 11,937 operating gasoline stations, or 3.2 outlets for every 10,000 persons (Kent Group, 2020). This means that there are around 10,000 former gas stations in the country, many of which have left contaminated soil behind. The number of retail gasoline stations in B.C. is currently not available on government websites.

RESIDENTIAL FACILITIES

SEPTIC SYSTEMS

Residential septic systems were of great necessity in the absence of sewers during the rapid urban expansion in British Columbia before the First World War. In Vancouver, new communities emerged in Kerrisdale, Kitsilano, West Vancouver, South Vancouver, Point Grey, and Burnaby, as well as new territories such as D.L. 301 and Hastings Townsite. By 1948, around 25% of the city of Vancouver used septic tanks, and overflows and inadequate drainage were frequent. In 1952, an outbreak of polio in Point Grey was allegedly connected to septic tanks that served around 100 residences. The City quickly replaced the septic tanks with sewage systems in this area and the incident caused other areas to demand connection to sewage services (Keeling, 2004). In 2006, 19% of households in B.C. reported using private septic systems (Statistics Canada, 2006).

Septic tanks, also called onsite sewage systems, are watertight containers, located where sewage originates, for receiving, treating and settling domestic sewage (Public Health Act, Sewerage System Regulation, 2004). Septic tanks are designed so that solids settle on the bottom of the tank, while oils and grease float on the top. The liquid wastewater (effluent) is then discharged into on the ground, where it is theoretically filtered, degraded and absorbed by the surrounding soil, which may not always happen. Even in the best-designed systems, a portion of some contaminants will inevitably reach the water table. If a septic tank is malfunctioning, it may also release the solids and oil and grease portions into the environment. As a result, contaminants including bacteria, viruses, detergents, and household cleaners are often discharged into groundwater aquifers. Individually, septic tanks are point sources that are not very significant. However, the combined effect of widespread septic tanks releasing highly dangerous contaminants, such as pathogens is a major source of pollution (U.S. EPA, 2018; Cherry, 1987). Even though septic systems are a known major cause of groundwater contamination, they are often poorly monitored and not well studied (Government of Canada, 2017a).

In a recent case of pollution by septic systems, a septic leak on a school field in a suburb in Metro Vancouver was detected in 2018. The source was determined to be a condensed 51 home development in Anmore which had had a septic system leakage reportedly since 2015 (Zeidler, 2018). *E. coli* contamination was detected in the groundwater at the base of the failing septic system (Bartel, 2019). By February 2020, the issue had not yet been resolved (McElroy, 2020).

MUNICIPAL/INDUSTRIAL FACILITIES

LANDFILLS

In 2013 Canada was identified as the world's highest per capita municipal producer of solid waste (Conference Board of Canada, 2013). Landfills are the most common method of solid waste disposal worldwide, including Canada, and are considered a major threat to groundwater quality (Statistics Canada, 2012; Scott et al., 2005; Fatta et al., 1999; US EPA, 1984).

Prior to the 1970s, landfills were largely unregulated, and sites had been typically chosen solely on the basis of economics, without consideration of the complexity of hydrogeological settings (Christenson & Cozzarelli, 2003; Atwater, 1980). This led to numerous cases of surface and groundwater contamination worldwide. Landfills can contaminate both surface and groundwater when rain and snowmelt infiltrate through the layers of waste, producing leachate that seeps from the bottom of the landfill. The composition of leachate is highly complex and includes dissolved organic matter, inorganic salts, organic trace impurities, and heavy metals (Aziz et al., 2010; Cherry, 1987). Groundwater that is contaminated by landfill leachate may migrate to springs and discharge to surface water bodies. Today, even when considering the hydrogeological conditions of a site, incidents of groundwater contamination by leachate occur due to failure of engineered leachate collection systems, and faulty operation of the landfill site to ensure the lowest possible levels of leachate (Przydatek & Kanownik, 2019; Tsanis, 2006).

In B.C., there were approximately 92 operating landfills as of 2008 (Giroux, 2014). As of May 2020, there were 203 landfills with an active discharge authorization in the Waste Discharge Authorizations dataset published by the Ministry of Environment and Climate Change Strategy of British Columbia (British Columbia, 2020c).

NATURAL SOURCES

SEAWATER INTRUSION

Saltwater intrusion is defined by Bear (1999) as "the mass transport of saline waters into zones previously occupied by fresher waters." Seawater intrusion occurs in freshwater aquifers in contact with the ocean. Fresh groundwater naturally flows towards the ocean, driven by topography and hydraulic conductivity. However, when coastal aquifers are disturbed by sea-level rise, storm surges, and/or excessive pumping, especially wells close to the coast, saltwater migrates landward, intruding the freshwater. The land above where the seawater intrusion occurs is then also lost as an area of natural recharge to the aquifer (Klassen & Allen, 2017; Lyles, 2000; Bear, 1999).

As the global sea level rises due to melting ice sheets and thermal expansion of the ocean, coastal communities around the world face the hazards of eroding shorelines, inundated low-lying coasts, as well as the disturbance of freshwater aquifers by seawater intrusion (Liang & Kosatsky, 2020). In addition to climate change, seawater intrusion is also aggravated by overpumping due to the pressure on limited freshwater supplies to support population growth (Henderson, 1997). Areas at highest risk of seawater intrusion include regions with low to moderate slopes; peninsulas or small areas where groundwater recharge is limited; where there is a high density of wells; where there are high rates of pumping from a single or multiple wells; and where the static (non-pumping) groundwater level is at or below sea level (British Columbia, 2016).

In the Gulf Islands in B.C., groundwater is the main source of drinking water supply. Aquifers in this region are threatened by the cumulative impacts of seawater intrusion, dissolution of minerals (high arsenic, manganese, and iron concentrations), improper agricultural waste disposal, failed septic systems, and pesticides (Denny et al., 2007). The summer months are especially critical, as low precipitation rates combined with increased water consumption cause groundwater levels to drop, and saltwater to be drawn into the freshwater aquifers (Allen & Suchy, 2001). In a study on the risk of saltwater intrusion in the coastal bedrock aquifers of the Gulf Islands by Klassen and Allen (2017), it was found that many islands had a significant risk of seawater intrusion due to the high density of wells, especially in Gabriola and Mayne Islands. Coastal hazards of storm surge and sea-level rise were found to be limited to a few areas on Salt Spring Island, such as narrow bays and inlets, where up to approximately 400 m of inundation could occur. Other islands or portions of islands that are low-lying could be more impacted by coastal hazards (Klassen & Allen, 2017).

CONCLUSION AND RECOMMENDATIONS

With 63% of its population residing in water-scarce areas, groundwater resources are increasingly relevant in B.C. As the global freshwater crisis is aggravated by accelerating climate change, population growth, urbanization, and other land use changes, there are increasing efforts to prevent and remediate groundwater pollution, as well as to manage groundwater resources more sustainably. Major sources of potential groundwater contamination in B.C. arise from both the legacy from a lack of anti-pollution legislation until the 1970s and these current challenges.

All types of land use include at least one major source of potential groundwater contamination, and several minor sources (Table 1). The major sources identified in B.C. were selected based on their pervasiveness in the province, high concentration and level of hazard of contaminants released. Major sources include agriculture, mining (industry), landfills (municipal/industry), septic systems (residential), gasoline stations (commercial), and seawater intrusion (natural), which is similar to many industrialized regions.

Even though progress has been made since the 1970s with anti-pollution regulations, and, more recently, by the implementation of the Water Sustainability Act (WSA), preventable cases of groundwater pollution often occur, due to insufficient prevention, lengthy remediation, and toothless regulations.

Based on the findings in this study, on the works of the Office of the Auditor General of Canada. (2019), Government of Canada. (2017), Joe et al. (2017), Office of the Auditor General of British Columbia (2010), and Nowlan (2007), and on the fact that safe, clean, and sufficient water resources are imperative to life, the following is recommended:

Agriculture:

- Mandatory adoption of the nutrient management plan for all farms.
- Limit livestock density.

Mining and Gasoline Stations:

- Increased rigour and frequency in site inspections.
- Better enforcement for compliance with data reporting and measures for pollution mitigation.

Septic Systems:

- Replacement of residential septic systems with sewage systems, prioritizing areas of high vulnerability aquifers.

Landfills

- Diversion of waste to composting and recycling.
- Population outreach and education on waste reduction.

Seawater Intrusion

- Education and outreach of groundwater well users. Inform limit for the amount of groundwater pumped based on hydrogeological studies, especially in wells located in water-scarce regions.

Generally:

- Invest in hydrogeological studies in the province.
- Improve communication to public and affected communities on issues related to groundwater quality and quantity.
- Facilitate meaningful First Nations participation in water governance.

REFERENCES

Aldhous, P. (2003). The world's forgotten crisis. *Nature*, *422*(6929), 251. https://doi.org/10.1038/422251a

Allen, D. M., & Suchy, M. (2001). Geochemical evolution of groundwater on Saturna Island, British Columbia. *Canadian Journal of Earth Sciences*, *38*(7), 1059–1080. https://doi.org/10.1139/e01-007

Arvanitoyannis, I. S. (2008). 15 - Waste Management in Food Packaging Industries. In I. S. B. T.-W. M. for the F. I. Arvanitoyannis (Ed.), *Food Science and Technology* (pp. 941–1045). Academic Press. https://doi.org/https://doi.org/10.1016/B978-012373654-3.50018-3

Atwater, J.W. (1980). "Impact of Landfills" in Fraser River Estuary Study, Water Quality series; prepared for the Fraser River Estuary Study Steering Committee; Environmental Protection Service, Environment Canada. Retrieved from https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/waterquality/monitoring-water-quality/south-coast-wq-docs/wq_fraser_estuary_landfills.pdf

Aziz, S. Q., Aziz, H. A., Yuso, M. S., Bashir, M. J., & Umar, M. (2010). Leachate characterization in semi-aerobic and anaerobic sanitary landfills: a comparative study. *Journal of Environmental Management, 91*(12), 2608–2614.

B.C. Ministry of Environment (MoE) (2004). Well protection toolkit. British Columbia.

B.C. Ministry of Environment (MoE). (2006). Ground Water Issues in British Columbia. Retrieved from http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/library/issues_bc.html

B.C. Ministry of Environment (MoE). (2007). Nitrate in Groundwater.

B.C. Ministry of Environment (MoE). (2009). An Introduction to Contaminated Sites in British Columbia. Retrieved from https://www2.gov.British Columbia.ca/gov/content/environment/air-land-water/site-remediation/contaminated-sites

B.C. Ministry of Finance. (2019). 2019 British Columbia Financial and Economic Review. Retrieved from https://www2.gov.bc.ca/gov/content/governments/finances/reports/financial-economic-review

Bartel, M. (2019). Septic solution for Anmore Green inches closer, but sewer hookup unlikely by Sept. Retrieved from https://www.tricitynews.com/news/septic-solution-for-anmore-green-inches-closer-but-sewer-hookup-unlikely-by-sept-1.23790436

Bear, J. (1999). Seawater intrusion in coastal aquifers: concepts, methods and practices. Boston. Mass: Kluwer Academic.

Berandinucci, J., & Ronneseth, K. (2002). *Guide to using the* British Columbia *aquifer classification maps for the protection and management of groundwater*. http://www.env.gov.British Columbia.ca/wsd/plan_protect_sustain/groundwater/aquifers/reports/aquifer_maps.pdf)

British Columbia Technical and Research Committee on Reclamation (BCTRCR). (2011). Mining in BC. Retrieved from http://www.trcr.bc.ca/mining-in-bc/

British Columbia. (2016). Best Practices for Prevention of Saltwater Intrusion. Retrieved from https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/water-wells/saltwaterintrusion_factsheet_flnro_web.pdf

British Columbia. (2020). Geography of B.C. Retrieved from https://www.welcomebc.ca/Choose-B-C/Explore-British-Columbia/Geography-of-B-C

British Columbia. (2020a). BC Mine Information: Reclamation. Retrieved from https://mines.nrs.gov.bc.ca/reclamation

British Columbia. (2020b). Britannia Mine. Retrieved from https://www2.gov.bc.ca/gov/content/environment/air-land-water/site-remediation/remediation-project-profiles/britannia-mine

British Columbia. (2020c). Data Catalogue. Retrieved from

British Columbia. (2020d). Hullcar Aquifer Information. Retrieved from https://www2.gov.bc.ca/gov/content/environment/air-land-water/site-permitting-compliance/hullcar-aquifer

British Columbia. (2020e). Mineral Inventory. Retrieved from https://www2.gov.bc.ca/gov/content/industry/mineral-exploration-mining/british-columbia-geological-survey/mineralinventory

British Columbia. (2020f). Nutrient Management Plans. Retrieved from https://www2.gov.bc.ca/gov/content/industry/agriculture-seafood/agricultural-land-and-environment/soil-nutrients/nutrient-management/nutrient-management-plans

Buckler DR, Grenato GE. 1999; Assessing Biological Effects from Highway Runoff Constituents. US Department of Transportation. Open file report 99-240.

Canadian Water Network. (2015). 2015 Water and Hydraulic Fracturing Report. Retrieved from https://cwn-rce.ca/report/2015-water-and-hydraulic-fracturing-report/

Capel, P. D., McCarthy, K. A., Coupe, R. H., Grey, K. M., Amenumey, S. E., Baker, N. T., & Johnson, R. L. (2018). Agriculture — A river runs through it — The connections between agriculture and water quality. *Circular*, 1–201. https://doi.org/10.3133/cir1433

Carman, T. (2012). Cost of cleaning up contaminated sites balloons in B.C.

Chapman, P. M. (2007). Determining when contamination is pollution — Weight of evidence determinations for sediments and effluents. *Environment International*, *33*(4), 492–501. https://doi.org/https://doi.org/10.1016/j.envint.2006.09.001

Cherry, J. A. (1987). Groundwater Occurrence and Contamination in Canada In M.C. Healey and R.R. Wallace (Eds.), *Canadian Aquatic Resources* (pp. 215-395). Ottawa, ON: Canadian Government Pub Centre.

Christenson, S.C. & Cozzarelli, I.M. (2003). The Norman landfill environmental research site: What happens to the waste in landfills? US Geological Survey, Washington, DC. Retrieved from https://pubs.usgs.gov/fs/fs-040-03/

Clarke, G., Northcote, B., Katay, F., and Tombe, S.P. (2020). Exploration and Mining in British Columbia, 2019: A summary. In: Provincial Overview of Exploration and Mining in British Columbia, 2019, British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Information Circular 2020-01, pp. 1-40.

Conference Board of Canada (2013) Environment: Municipal waste generation. Retrieved from https://www.conferenceboard.ca/hcp/details/environment/municipal-waste-generation.aspx

Denny, S.C., Allen, D.M. and Journeay, J.M. (2007) DRASTIC-Fm: a modified vulnerability mapping method for structurally controlled aquifers in the southern Gulf Islands, British Columbia, Canada. Hydrogeology Journal 15 (3), 483-493.

Dobb, A. (2013). BC farm practices & climate change adaptation: nutrient management. http://www.bcagclimateaction.ca. (July 28, 2020).

Evangelou, V.P. & Zhang, Y.L. (1995). A review: Pyrite oxidation mechanisms and acid mine drainage prevention, Critical Reviews in Environmental Science and Technology, 25:2, 141-199, DOI: 10.1080/10643389509388477

Fatta D, Papadopoulos A, Loizidou M. A study on the landfill leachate and its impact on the groundwater quality of the greater area. Environ Geochem Health. 1999;21(2):175–190. doi: 10.1023/A:1006613530137.

Forstner, T., & Gleeson, T. (2019). Unseen and overlooked: methods for quantifying groundwater abstraction from different sectors in a data-scarce region, British Columbia, Canada. *Canadian Water Resources Journal / Revue Canadienne Des Ressources Hydriques*, 44(4), 382–400. doi: 10.1080/07011784.2019.1652116

Freeze, A. R. & Cherry, J. A. (1979). *Groundwater* (1st ed.). Englewood Cliffs, New Jersey: Prentice Hall.

Giroux, L. (2014). State of waste management in Canada. Canadian Council of Ministers of the Environment, Giroux Consulting.

Government of Canada. (2013). Water sources: groundwater. Retrieved May 25, 2020, from https://www.canada.ca/en/environment-climate-change/services/water-overview/sources/groundwater.html

Government of Canada. (2017a). Groundwater contamination. Retrieved June 27, 2020, from https://www.canada.ca/en/environment-climate-change/services/water-overview/pollution-causes-effects/groundwater-contamination.html

Government of Canada. (2017b). Third national assessment of environmental effects monitoring data from metal mines. Retrieved from https://www.canada.ca/en/environment-climate-change/services/managing-pollution/publications/third-national-assessment-monitoring-data.html

Government of Canada. (2020). Mining and Quarrying: Region of Western Canada and the Territories: 2017-2019. Retrieved from https://www.jobbank.gc.ca/content_pieces-eng.do?cid=13155

Gower, T. & Barroso, A. (2019). Tapped Out: A Special Report on Water Scarcity and Water Solutions in British Columbia. *Prepared for Watershed Watch Salmon Society*, Coquitlam, B.C. 24 pp.

Hall, K, Schreier, H. (1996) Urbanization and agricultural intensification in the Lower Fraser Valley: impacts on water use and water quality. GeoJournal 40:135–146

Henderson, J. D. (1997). An ecosystem approach to groundwater management in the Gulf Islands (Unpublished master's thesis). University of Calgary, Calgary, AB. doi:10.11575/PRISM/20803

JASON SCOTT, DONIA BEYDOUN, ROSE AMAL, GARY LOW & JULIE CATTLE (2005) Landfill Management, Leachate Generation, and Leach Testing of Solid Wastes in Australia and Overseas, Critical Reviews in Environmental Science and Technology, 35:3, 239-332, DOI: 10.1080/10643380590917969

Joe, N., Bakker, K., & Harris, L. (2017). Perspectives on the BC Water Sustainability Act : First Nations Respond to Water Governance Reform in British Columbia [Article]. doi:http://dx.doi.org/10.14288/1.0347525

Józef Żychowski, Tomasz Bryndal; Impact of cemeteries on groundwater contamination by bacteria and viruses – a review. ***J Water Health*** 1 June 2015; 13 (2): 285–301. doi: https://doi.org/10.2166/wh.2014.119
Mansilha, Catarina & Carvalho, A. & Guimarães, P. & Espinha Marques, Jorge. (2014). Effects of forest fires on groundwater contamination. 10.13140/2.1.5119.2324.

Keeling, A. M. (2004). The Effluent Society: Water Pollution and Environmental Politics in British Columbia, 1889-1980. *ProQuest Dissertations and Theses*, *65*(July), 1889–1980. http://search.proquest.com/docview/305057652?accountid=13828

Kent Group. (2020). National Retail Site Census. Retrieved from https://www.kentgroupltd.com/analytics/retail-site-census/

Klassen, J., & Allen, D. M. (2017). Assessing the risk of saltwater intrusion in coastal aquifers. *Journal of Hydrology*, *551*, 730–745. https://doi.org/https://doi.org/10.1016/j.jhydrol.2017.02.044

Klassen, J., Allen, D. M., & Kirste, D. (2014). *Chemical Indicators of Saltwater Intrusion for the Gulf Islands, British Columbia*. *June*, 43. http://www.sfu.ca/personal/dallen/Chemical Indicators of SWI_Final.pdf

Kralik, M. (2015). How to Estimate Mean Residence Times of Groundwater. *Procedia Earth and Planetary Science*, *13*, 301–306. https://doi.org/https://doi.org/10.1016/j.proeps.2015.07.070

Krzyzanowski, J. (2012). Environmental pathways of potential impacts to human health from oil and gas development in northeast British Columbia, Canada. *Environmental Reviews*, *20*(2), 122+.

Kuroda K., Fukushi T. (2008) Groundwater Contamination in Urban Areas. In: Takizawa S. (eds) Groundwater Management in Asian Cities. cSUR-UT Series: Library for Sustainable Urban Regeneration, vol 2. Springer, Tokyo.

Liang, K. & Kosatsky, T. (2020). Health impacts of sea level rise on bc's coastal communities. BC Medical Journal, vol. 62, no. 2, march, 2020, page(s) 71,73. Retrieved from https://bcmj.org/bccdc/health-impacts-sea-level-rise-bcs-coastal-communities

Lottermoser B.G. (2010). Sulfidic Mine Wastes. In: Mine Wastes. Springer, Berlin, Heidelberg.

Lyles, J.R. (2000). Is seawater intrusion affecting ground water on Lopez Island, Washington? USGS Numbered Series, U.S. Geological Survey. Fact Sheet FS-057-00.

Margat, Jean & van der Gun, Jac. (2013). Groundwater in the global water cycle. In: Groundwater around the World: A Geographic Synopsis.

McAllister, T.A. & Topp. E. (2012). Role of livestock in microbiological contamination of water: Commonly the blame, but not always the source, ***Animal Frontiers***, Volume 2, Issue 2, April 2012, Pages 17–27, https://doi.org/10.2527/af.2012-0039

McElroy, J. (2020). Regulatory mess of 'Fecal Mountain' one step closer to being resolved. Retrieved from https://www.cbc.ca/news/canada/british-columbia/anmore-middle-school-septic-problem-council-vote-1.5452199

Meegoda, J. N., & Hu, L. (2011). A review of centrifugal testing of gasoline contamination and remediation. *International journal of environmental research and public health*, *8*(8), 3496–3513. https://doi.org/10.3390/ijerph8083496

MiningWatch Canada. (2019). New Environment Commissioner Audit: Canada Fails to Protect Waters & Fish from Mine Pollution. Retrieved from https://miningwatch.ca/news/2019/4/2/new-environment-commissioner-audit-canada-fails-protect-waters-fish-mine-pollution

Nair, R. (2009). Retrieved from Pollutants leaking from Cache Creek landfill https://bc.ctvnews.ca/pollutants-leaking-from-cache-creek-landfill-1.381505

Nowlan, L. (2007). Out of sight, out of mind? Taking Canada’s groundwater for granted. In Eau Canada: The Future of Canada’s Water. UBC Press. Vancouver, British Columbia. pp. 55–83

Office of the Auditor General of British Columbia. (2010**).** An audit of the management of groundwater resources in British Columbia**.** Retrieved from https://www.British Columbiaauditor.com/pubs/2010/report8/audit-management-groundwater-resources-british-columbia

Office of the Auditor General of Canada. (2019). Report 2—Protecting Fish from Mining Effluent - 2019 Spring Reports of the Commissioner of the Environment and Sustainable Development to the Parliament of Canada. (2019). Retrieved from https://www.oag-bvg.gc.ca/internet/English/parl_cesd_201904_02_e_43308.html

Plourde, F. and Zeidler M. (2017). 60 years later, Alaska still calling B.C. to task on a mine leak flowing through its river. Retrieved from

Price, W.A. & Errington, J.C. (1998). Guidelines for Metal Leaching and Acid Rock Drainage at Mine Sites in British Columbia. Ministry of Energy and Mines, British Columbia

Przydatek, G., Kanownik, W. Impact of small municipal solid waste landfill on groundwater quality. *Environ Monit Assess* **191,** 169 (2019). https://doi.org/10.1007/s10661-019-7279-5

Public Health Act, Sewerage System Regulation (2004, B.C. Reg. 326/2004 O.C. 701/2004). Retrieved from https://www.bclaws.ca/civix/document/id/complete/statreg/22_326_2004#section5

Pupp, C. 1985. An assessment of ground water contamination in Canada, Part 1. (Available from Environmental Interpretation Division, Environment Canada, Hull, P.Q.)

Rhatigan, J. (2016). *Afterlife of a mine : the tangled legacies of the Britannia mine* (T). University of British Columbia. Retrieved from https://open.library.ubc.ca/collections/ubctheses/24/items/1.0319337

Schlesinger, J. (2016). Life after Corner Gas: The challenges of developing old service stations. Retrieved from https://www.theglobeandmail.com/report-on-business/industry-news/property-report/life-after-corner-gas-the-challenges-of-developing-old-service-stations/article32219739/

Schuster-Wallace C.J., Sandford, R., and Merrill, S. 2019. Water Futures for the World We Want University of Saskatchewan, Saskatoon, Canada

Shiklomanov, L.A. (1993). World Freshwater Resources In Gleick, P.H. (Ed.), *Water in Crisis: A Guide to World's Freshwater Resources* (pp. 13-24). New York, NY: Oxford University Press.

Singhal, B. B. S., & Gupta, R. P. (2010). Groundwater Contamination. *Applied Hydrogeology of Fractured Rocks*, 221–236. https://doi.org/10.1007/978-90-481-8799-7_12

Statistics Canada. (2006). Households' use of water and wastewater services. Retrieved from https://www150.statcan.gc.ca/n1/pub/16-002-x/2008004/article/10752-eng.htm

Statistics Canada. (2012). Solid Waste. Retrieved from https://www150.statcan.gc.ca/n1/pub/16-201-x/2012000/part-partie3-eng.htm

Statistics Canada. (2020). Annual Statistics of Mineral Production, 2019. Retrieved from https://sead.nrcan-rncan.gc.ca/prod-prod/ann-ann-eng.aspx

Stefanakis, A.I., Zouzias, D., and Marsellos, A. (2015). **Groundwater Pollution: Human and Natural Sources and Risks** *In: Environmental Science and Engineering Vol. 4: Water Pollution, Edition: 1st* Edited by:J.N. Govil. Studium Press LLC.

Stengel, D., O'Reilly, S., & O'Halloran, J. (2006). *Contaminants and pollutants*. 361–389. https://doi.org/10.1007/1-4020-4504-2_15

Stevenazzi, Stefania & Masetti, Marco & Tiepolo, Massimo & Ferrari, Elena. (2017). How much does air pollution affect groundwater quality?. 10.13125/flowpath2017/2846.,

Syms, P. (2008). Industrial Activities: Contaminants, Processes and Case Studies. In Previously Developed Land, P. Syms (Ed.). doi:10.1002/9780470759141.oth1,

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., … Treidel, H. (2012). Ground water and climate change. *Nature Climate Change*, *3*(4), 322–329. https://doi.org/10.1038/nclimate1744

Tornero, V., & Ribera d'Alcalà, M. (2014). Contamination by hazardous substances in the Gulf of Naples and nearby coastal areas: A review of sources, environmental levels and potential impacts in the MSFD perspective. *Science of The Total Environment*, *466–467*, 820–840. https://doi.org/https://doi.org/10.1016/j.scitotenv.2013.06.106

Tsanis, I. K. (2006). Modeling leachate contamination and remediation of groundwater at a landfill site. *Water Resources Management*, *20*(1), 109–132. https://doi.org/10.1007/s11269-006-4634-4

U.S. Environmental Protection Agency (EPA). (1993). *Wellhead Protection: A Guide for Small Communities*. Retrieved from https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=30004L42.TXT

U.S. Environmental Protection Agency (EPA). (2016). Types of Drinking Water Contaminants. Retrieved from https://www.epa.gov/ccl/types-drinking-water-contaminants

U.S. Environmental Protection Agency (EPA). (2018). How Your Septic System Works. Retrieved from https://www.epa.gov/septic/how-your-septic-system-works

U.S. Environmental Protection Agency (EPA). (2020). Nutrient Pollution - The Sources and Solutions: Agriculture. Retrieved from https://www.epa.gov/nutrientpollution/sources-and-solutions-agriculture

United Nations World Water Assessment Programme (WWAP). (2013). The United Nations World Water Development Report 2013). Paris, United Nations Educational, Scientific and Cultural Organization.

United States Environmental Protection Agency (US EPA). (1984). Office of Drinking Water, A Ground Water Protection Strategy for the Environmental Protection Agency. 1984. p. 11.

United States Geological Survey (USGS). (2020a). Agricultural Contaminants in Water Resources, accessed July 14, 2020 at URL https://www.usgs.gov/mission-areas/water-resources/science/agricultural-contaminants

United States Geological Survey (USGS). (2020b). What is groundwater? Retrieved from https://www.usgs.gov/faqs/what-groundwater

University of Saskatchewan. (2019). How Canada can solve its emerging water crisis. Retrieved from https://news.usask.ca/articles/research/2019/how-canada-can-solve-its-emerging-water-crisis.php

Wisen, J., Chesnaux, R., Werring, J., Wendling, G., Baudron, P., & Barbecot, F. (2020). A portrait of wellbore leakage in northeastern British Columbia, Canada. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(2), 913–922. https://doi.org/10.1073/pnas.1817929116

WorkBC. (2019). Industry Profiles. Retrieved from https://www.workbc.ca/Labour-Market-Industry/Industry-and-Sector-Information/Industry-Profiles.aspx

Woudneh, M. B., Ou, Z., Sekela, M., Tuominen, T., & Gledhill, M. (2009). Pesticide multiresidues in waters of the Lower Fraser Valley, British Columbia, Canada. Part II. Groundwater. *Journal of environmental quality*, *38*(3), 948–954. https://doi.org/10.2134/jeq2007.0523

Zeidler, M. (2018). 'How can this still be going on?' Parents fed up with development's septic leak on school field. Retrieved from https://www.cbc.ca/news/canada/british-columbia/how-can-this-still-be-going-on-parents-fed-up-with-development-s-septic-leak-on-school-field-1.4630888