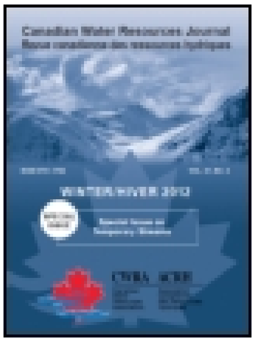

Canadian Water Resources Journal / Revue canadienne des ressources hydriques

ISSN: 0701-1784 (Print) 1918-1817 (Online) Journal homepage: https://www.tandfonline.com/loi/tcwr20

Unseen and overlooked: methods for quantifying groundwater abstraction from different sectors in a data-scarce region, British Columbia, Canada

Tara Forstner & Tom Gleeson

CANADIAN WATER RESOURCES JOURNAL / REVUE CANADIENNE DES RESSOURCES HYDRIQUES
https://doi.org/10.1080/07011784.2019.1652116

Unseen and overlooked: methods for quantifying groundwater abstraction from different sectors in a data-scarce region, British Columbia, Canada

Tara Forstner and Tom Gleeson

Department of Civil Engineering and School of Earth and Ocean Sciences, University of Victoria

ABSTRACT

Groundwater is considered a reliable resource, relatively insensitive to seasonal or even multi-year climatic variation; however, quantifying aquifer-scale estimates of stress in diverse hydrologic environments is particularly difficult due to data scarcity and the limited methods for deriving stress parameters, such as groundwater use and availability, which can be applied over a large spatial area. On a global scale, most methods focus on one major sector, such as irrigated agriculture which accounts for a substantial portion of groundwater use on a global-scale. However, this may misrepresent groundwater abstractions in regions significantly impacted by other sectors on a local-scale. The objective of this paper is to quantify annual average groundwater use through a multi-method sectoral approach for regions where groundwater abstraction data are scarce. Sectoral methods are developed for the annual volumetric quantification and spatial distribution of groundwater use for municipal water distribution systems, private domestic well users in municipal and rural regions, industrial use for manufacturing, mining, and oil and gas industries, irrigated agriculture, and finfish aquaculture. Results suggest that British Columbia (BC) uses a total of ∼562 million cubic metres of groundwater annually. The largest annual groundwater use by major sector is agriculture (38%), finfish aquaculture (21%), industrial (16%), municipal water distribution systems (15%), and domestic private well users (11%). This paper highlights the implications of using downscaled values of groundwater use from global datasets for aquifer-scale estimates, which can be misrepresentative in regions where groundwater use is unregulated or newly regulated, as is the case in BC. The sectoral methods developed in this paper provide a framework for estimating groundwater-specific use estimates in data scarce regions critical for groundwater management plans and aquifer-scale groundwater stress studies which depend on spatially-distributed groundwater use data.

RÉSUMÉ

Les eaux souterraines sont considérées comme une ressource fiable, relativement insensible aux variations climatiques saisonnières, voire pluriannuelles. Toutefois, il est particulièrement difficile de quantifier le stress hydrique à l'échelle d'un aquifère dans divers environnements hydrologiques en raison de la rareté des données et des méthodes limitées pour calculer certains paramètres de stress (utilisation et disponibilité) et ce, appliqués à une grande zone spatiale. À l'échelle globale, la plupart des méthodes sont axées sur un secteur majeur, comme l'agriculture irriguée, représentant une part importante de l'utilisation des eaux souterraines à l'échelle mondiale. Cependant, ces méthodes peuvent également faussement représenter les captages d'eaux souterraines dans des régions touchées de manière significative par d'autres secteurs. Ainsi, l'objectif de cet article est de quantifier l'utilisation annuelle et moyenne des eaux souterraines au moyen d'une approche multiméthodes et multisectorielle pour des régions où les données de captage des eaux souterraines sont rares. En effet, des méthodes sectorielles ont déjà été développées pour la quantification volumétrique annuelle et la distribution spatiale de l'utilisation des eaux souterraines pour les systèmes municipaux de distribution d'eau, pour les utilisateurs de puits domestiques privés dans les régions municipales et rurales, pour les utilisations industrielles des industries manufacturières, minières et pétrolières et pour l'agriculture irriguée et l'aquaculture de poisson. Les résultats suggèrent que la Colombie-Britannique utilise environ 562 millions de mètres cubes d'eau souterraine par an où les principaux secteurs d'utilisation annuelle sont l'agriculture (38 %), la pisciculture (21 %), l'industrie (16 %), les réseaux de distribution d'eau municipaux (15 %) et les utilisateurs domestiques de puits privés (11 %). Ce document met en évidence les répercussions de l'usage de données réduites d'utilisation des eaux souterraines à partir d'ensemble de valeurs globales pour des estimations à l'échelle des aquifères, pouvant être faussement représentatives dans des régions où l'utilisation des eaux souterraines n'est pas réglementée ou nouvellement réglementée, tel qu'en Colombie-Britannique. Les méthodes sectorielles développées dans cet article fournissent un

ARTICLE HISTORY
Received 8 February 2019
Accepted 1 August 2019

KEYWORDS
Groundwater abstraction; groundwater use; data analysis;

CONTACT Tom Gleeson tgleeson@uvic.ca

Supplemental data for this article can be accessed https://doi.org/10.1080/07011784.2019.1652116.

cadre pour estimer l'utilisation spécifique des eaux souterraines dans les régions où les données sont rares et qui sont critiques pour les plans de gestion et pour les études détaillant les pressions exercées sur les eaux souterraines, eux-mêmes basés sur des données d'utilisation spatiale.

1. Introduction

Groundwater is considered a reliable resource, relatively insensitive to seasonal or even multi-year climatic variation (Lapworth et al. 2013; Pavelic et al. 2012; Manga 1999; Kundzewicz and Döll 2009), often favorable over surface water especially in rural regions, dry regions with limited surface water or during periods of drought (Bredehoeft and Young 1983; Rutulis 1989; Tsur 1990; Siebert et al. 2010). However, in some regions the risk of overexploitation is large (Llamas 1998; Changming, Jingjie, and Kendy 2001; Konikow and Kendy 2005; Aeschbach-Hertig and Gleeson 2012; Scanlon et al. 2012; Famiglietti 2014). Groundwater depletion is widespread in both developed and developing countries (Wada et al. 2010; Aeschbach-Hertig and Gleeson 2012; Barlow and Leake 2012; Scanlon et al. 2012; Dalin et al. 2017) and tracking and estimating the magnitude of depletion is challenging in a large part due to a sparsity of data on subsurface conditions and uncertainty in interpreting available data (Konikow and Kendy 2005). Water stress studies provide frameworks to mitigate groundwater depletion and stress (Gleeson et al. 2012; Gleeson and Wada 2013; Richey et al. 2015); however, groundwater use is a critical flux in these equations and often pumping data are unavailable.

Quantifying groundwater use can be especially challenging as direct measurements requires pumping data which are often unreported. Therefore, this study relies on indirect methods of quantification (Richey et al. 2015; Srinivasan et al. 2015; Ireson, Makropoulos, and Maksimovic 2006). On a global scale, most methods focus on one major sector (Castaño, Sanz, and Gómez-Alday 2010; Siebert et al. 2010; Y. Wada, Wisser, and Bierkens 2014), which could be misleading on a local or regional scale. For example, studies which only identified groundwater use for irrigated agriculture sector – which accounts for a substantial portion of groundwater use on a global-scale – may misrepresent groundwater abstractions in regions significantly impacted by other sectors on a local-scale (Howard and Gelo 2002). Furthermore, while global or regional studies are useful for identifying global-scale trends, global analysis using low-resolution models are limited in drawing conclusions about individual aquifers, watersheds, or communities (Alley et al. 2018).

The objective of this paper is quantifying annual groundwater use through a multi-method sectoral approach for regions where groundwater abstraction data are scarce. This study faces two key challenges. Firstly, the lack of established peer reviewed methods for sectoral groundwater use of aquifers $<1\,\mathrm{km}^2$. And secondly, most reported groundwater use data are at the national or provincial scale. As aquifer stress studies are very sensitive to the "use" component, groundwater use estimation at an aquifer-scale or local-scale is critical. Sectoral methods are developed for the annual volumetric quantification and spatial distribution of groundwater use for municipal water distribution systems, private domestic well users in municipal and rural regions, industrial use for manufacturing, mining, and oil and gas industries, irrigated agriculture, and finfish aquaculture. The methods presented here are useful for aquifer-scale estimates for the use in aquifer stress and management studies. The developed methods are applied to British Columbia (BC), a province of diverse hydrologic environments, representative of humid to semi-arid climates where groundwater use is derived locally based on demand from various sectors. For example, the Interior has a semi-arid climate supporting economically significant agriculture, whereas, in coastal regions, island aquifers sustain small urban populations. The major sectors were identified based on current reporting categories outlined in the *Water Sustainability Act* (Province of British Columbia 2016), provincial and federal surveys, and previous studies (Hess 1986; Rutherford 2004).

This paper first describes the region of interest and introduces the motivation, local challenges, and scope. Following sections describes the individual methods for the major sectors of use and subsequently, the results and concluding discussion. Since terminology can be confusing, it is important to clarify the technical terms used herein to discuss water availability. *Groundwater use* is a general term for the utilization of groundwater. *Groundwater abstraction* is the volume of water removed from an aquifer without considering return flows or leakage. *Groundwater consumption* is the difference between water abstraction and the quantity of water returned to the aquifer, for example, via leakage or over irrigation.

2. Groundwater use in British columbia

Several issues arise in deriving spatially distributed groundwater consumptive data for the province. The

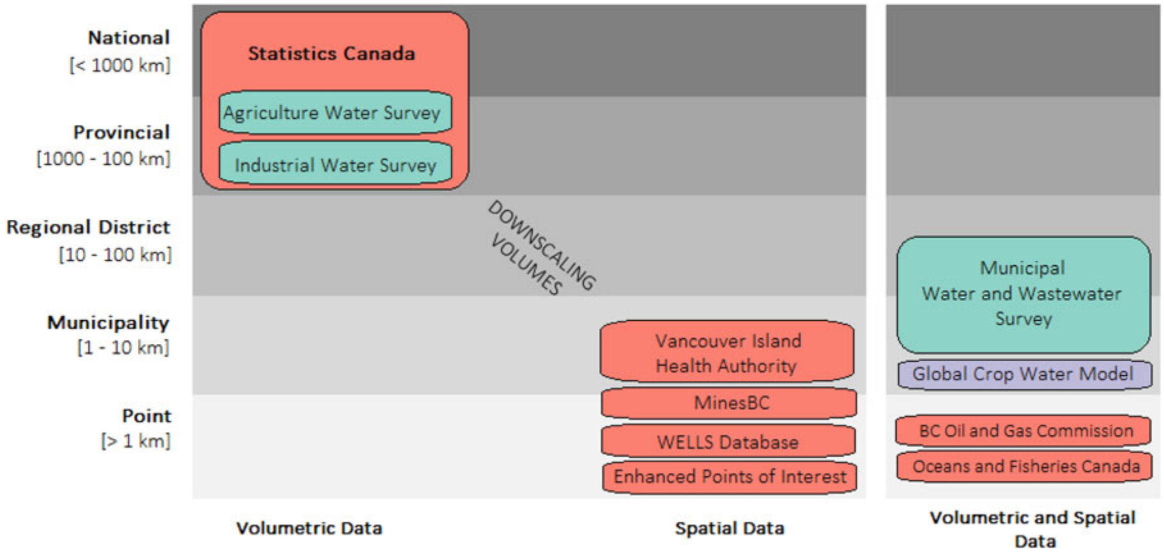

Figure 1. Scales of data. The majority of volumetric data are reported on the national and provincial scale. Spatial data on the scale of regional district, municipal, and point scale are used to downscale volumetric values. The colour of the box indicated the type of data: model data (purple), federal survey data (green), other (pink).

primary challenge in this study is the historical lack of reporting standards and provincial groundwater regulation under the *Water Act* (Province of British Columbia 1909) which has since been replaced by the *Water Sustainability Act* (WSA - Province of British Columbia 2016) which came into effect February 29, 2016. Most groundwater data in BC are disseminated across many sources, and the data are often reported on a range of spatial scales from municipal-scale data to single representative provincial values. If the reported scale is greater than the aquifer scale a proxy is required to spatially distribute and downscale the volumes of groundwater consumed. To be useful in quantifying groundwater use, data needs both the volume of groundwater used (volumetric data) as well as the location (spatial data). Most regional-scale data do not have refined spatial data. Very little of the data has both volumetric and spatial data at the scale of aquifers in BC (Figure 1).

Groundwater and surface water sources supply the population via water distribution systems, self-supplied via private wells or diverted from streams/reservoirs (Figure S1). Two major methods of water supply were considered in this study, municipal water distribution systems, and self-supplied by wells. Hauled water is used in isolated communities, and accounts for less than 2% of all water supplied in the province, and therefore is not considered in this analysis. Major and minor sectors were based on a previous groundwater use study by Hess (1986), which identified main sectors as domestic, commercial, industrial, agriculture, and finfish aquaculture. Domestic water is described as water used for the purpose of household use and residential irrigation. Commercial water use includes water use to support businesses, hotels, restaurants, etc. For the purpose of this study, commercial water use is assumed to be included in municipal water use. Industrial use for the purpose of this study is water used by oil and gas, mining, and manufacturing. Agricultural irrigation is water used for crop irrigation, not including livestock or greenhouses. Finfish aquaculture is water used for hatcheries (ie. salmon), as large quantities of groundwater is often extracted due to physical and chemical properties.

Due to the classification of historically reported data, some sectors were lumped. For example, municipal water distribution systems (MWDS) supply water to a diverse network of sectors where partitioning volumes was not possible. As a result, MWDS was considered its own sector of use supplying to all major sectors. Where possible, major sectors were partitioned into minor sectors such as with the domestic and industrial groundwater use sectors. Private water purveyors (ex. improvement districts) were not included in this analysis for lack of data. Improvement districts are common in rural areas of BC, where local authorities provide specific water services at the request of landowners. They vary in size from small subdivisions to larger communities.

3. Data and methods

The following section contains the methods for each of the major sectors. Regional or global models are used to supplement regions with little to no local coverage for the agricultural sector (Figure 2). Before discussing the methodology for each sector, the three

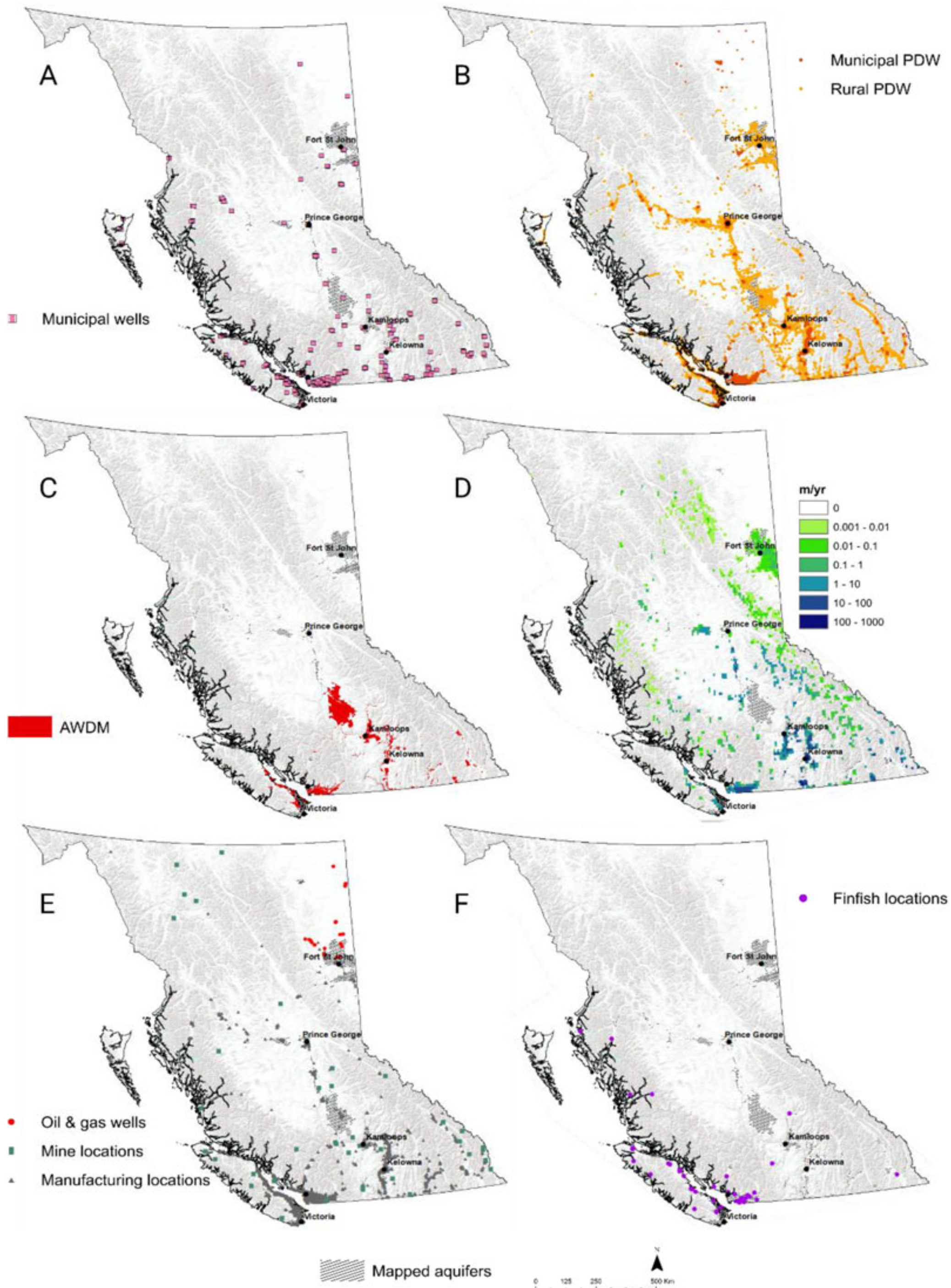

Figure 2. Distribution of spatial data available for each major sector. A) Derived municipal wells for the purpose of water distribution systems; B) private domestic wells (PDW) within municipalities (red) and in rural areas (orange); C) aquifers with reported groundwater abstraction volumes reported by the Agricultural Water Demand Model (AGWM) associated with irrigated agriculture (red); D) coverage of the Global Crop Water Model (GCWM) for total irrigated volume required in mm yr^{-1}; E) industrial diversion locations for oil and gas wells (red), manufacturing (grey) and mining locations (green); F) locations of finfish hatcheries (purple).

steps in attributing aquifer groundwater volumes is described since they are common to all sectors. Firstly, for each sector, groundwater volumes are categorically derived, for example by city or by type of manufacturing. Secondly, derived volumes are subsequently spatially distributed to wells or locations. The final step is attributing the well location to a source aquifer, which is either reported or estimated.

3.1. Volume attribution to aquifers

Within the mapped region, aquifers generally fall into six aquifer types which describe unconsolidated sand

and gravel aquifers, and bedrock aquifers (Wei et al. 2014; Wei et al. 2007). Average aquifer size ranges by type from 4 – 27 km^2, and are generally constrained by the mountainous terrain and limited to valleys and floodplains. Unconsolidated aquifers are generally of glacial or fluvial depositional origin, mainly composed of sand and gravel material with small discontinuous silt or clay layers, in particular along streams of lower energy (Wei et al. 2014). The bedrock geology of the Cordillera is complex and regionally varying due to the regions geologic, tectonic, and volcanic history (Wei et al. 2014). Despite the complexity of the bedrock material, bedrock permeability exists primarily due to the development of fractures and faults from mechanical weathering processes and/or unloading causing relatively high fracture density (Welch and Allen 2014) and the permeability is often anisotropic as the fractures and faults have specific orientations (Wei et al. 2007). Bedrock aquifers can be composed of fractured sedimentary rock, fractured igneous intrusive, metamorphic, or volcanic rock.

Aquifer mapping has been limited to developed regions in BC, which are mainly in the southern and central region of the province (Berardinucci and Ronneseth 2002). The well database is based on voluntary submission of well log reports from drillers. Over 100,000 wells have been reported and the majority are categorized by well use: "Private domestic", "Commercial & Industrial", "Water supply system", "Irrigation", "Observation", "Test", "Other", or "Unknown".

The following sections describe methods used to derive annual groundwater volumes which are then attributed to either reported wells from the provincial database, attributed to locations, or directly attributed to the aquifer. When a volume is associated with a well, the method of aquifer attribution is based on the following priorities:

1. If an aquifer is associated with the reported well, abstracted groundwater volumes are attributed to this aquifer.
2. If the well only overlies one mapped aquifer, abstracted groundwater volume is attributed to this aquifer by default.
3. If the well overlies overlapping aquifers and no aquifer ID is reported with well, reported lithology is used to correlate the well to the abstracted aquifer. For example, if a well was overlying two unconsolidated aquifers and one bedrock aquifer but the well reported an aquifer material of "Sand and Gravel", derived groundwater volumes were attributed equally to both unconsolidated aquifers.

When a volume is associated with a location, such as with a business location or rasterized data from a model output, the volume is equally attributed to each overlapping aquifer underlying the location. Equally attributed means the volume is divided by the number of overlapping aquifers where there is no aquifer ID, or lithology data associated with the well or location. Realistically, most abstraction is focused in shallow aquifers; however, the current state of the provincial database precludes improving this methodology. If volumes are assumed to be abstracted from mapped aquifers, the methodology used here recognizes that volume attribution to overlapping aquifers is more uncertain than non-overlapping aquifers (Figure 3).

3.2. Municipal water distribution systems

The municipal water distribution system (MWDS) sector includes all users connected to a water distribution system operated by a municipality that supplies water to all major sectors within the proximity of the distribution network. MWDSs distribute freshwater from either surface water sources (such as reservoirs or streams), or from groundwater sources (abstracted from municipal wells). MWDSs are a key component in calculating groundwater abstraction as they often supply large volumes of groundwater to meet the municipal population demand. These demands are often met from a limited number of high yield wells concentrating large volumes of withdrawal to few aquifers, as opposed to distributing the sector's volumetric burden to many aquifers.

The following steps were used to determine annual volumes of groundwater abstracted for the MWDS sector:

1. determine population served water from a MWDS;
2. derive total groundwater volume supplying MWDSs; and
3. determine the location of the groundwater withdrawal through attribution of municipal groundwater volumes to municipal wells.

The Municipal Water and Wastewater Survey (MWWS) (Environment Canada 2011) provides the most recent municipal scale sample data for 134 municipalities and 28 regional districts in BC (Table 1). The survey reports on annual water use statistics based on data collected in 2009 and includes reported volumes total annual groundwater used per municipality and regional district. However, often this information was not reported, and therefore, other municipal, regional, or provincial scale data was used to infer total

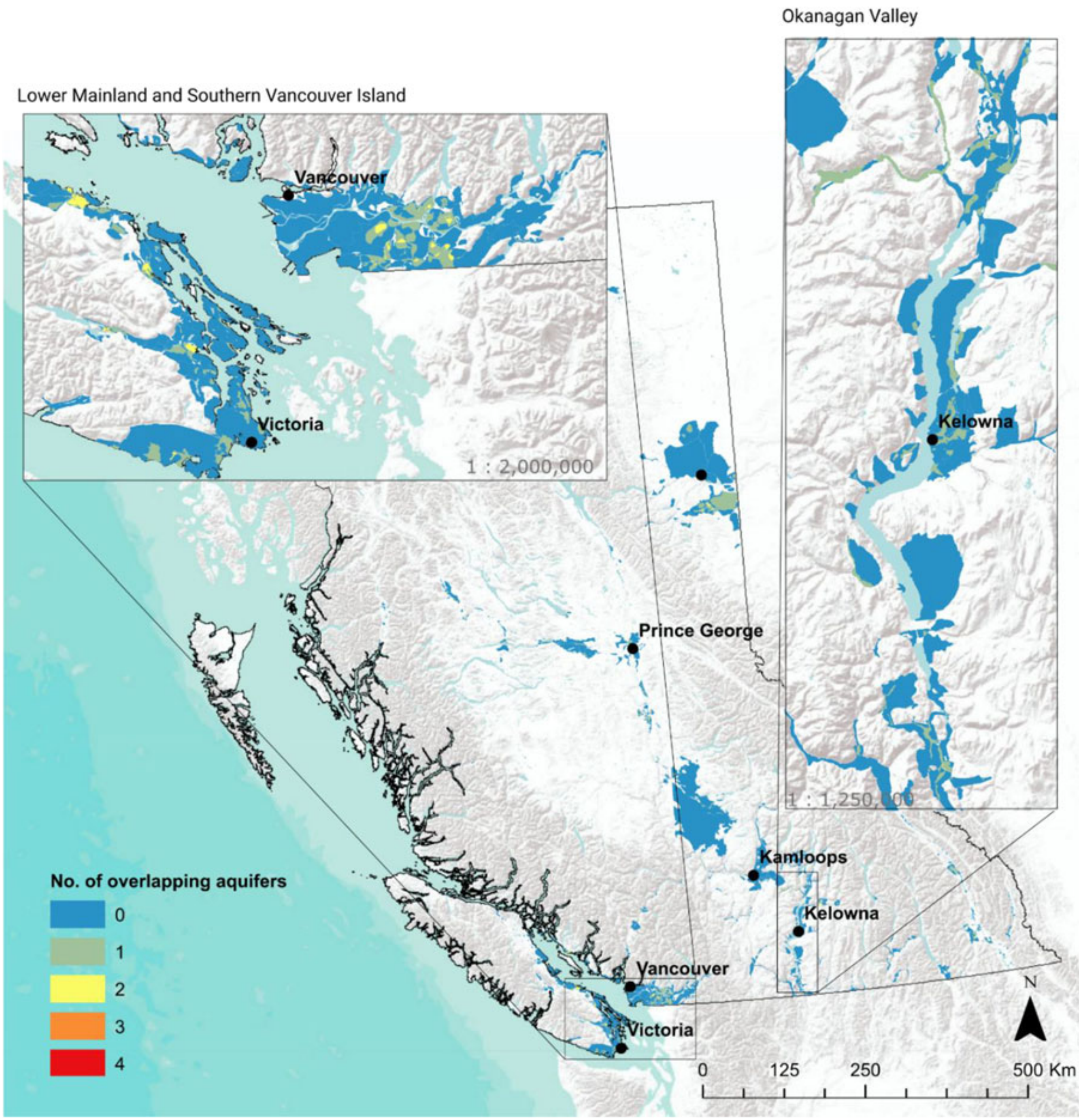

Figure 3. Status of provincially mapped aquifers (as of January 2018). Aquifer mapping has been prioritized in populated regions as many areas in the province are scarcely populated and consist of mountainous terrain. Non-overlapping mapped aquifers are illustrated in blue, with the two most populated regions enlarged. Although difficult to discern at the provincial-scale, in some local areas up to 4 overlapping aquifers have been mapped. Source: Authors.

Table 1. Sample data from the MWWS (Environment Canada 2011) for the 10 most populated municipalities in BC.

		Method of water supply				Annual volume	
Municipality	Population	MWDS	PDW	Hauled water	Sourced ground-water	Surface water & groundwater	Groundwater
		(% of total population)				(m^3)	
Vancouver	610,389	100	0	0	–	118,070,806	–
Surrey	453,252	98	2	0	–	72,000,000	–
Burnaby	223,063	NA	NA	NA	NA	NA	NA
Richmond	192,582	100	0	0	–	38,129,000	–
Abbotsford	134,988	82	18	0	7	20,904,000	1,463,280
Coquitlam	125,049	99	1	0	–	18,696,449	–
Kelowna	119,588	99	1	0	–	16,515,129	–
Saanich	112,332	NA	NA	NA	–	NA	NA
District of Langley	103,813	NA	NA	NA	NA	NA	NA
Delta	100,867	100	0	0	5	27,000,000	1,350,000

NA = data not reported.

annual groundwater abstracted per municipality. As BC has a total of 162 municipalities, if a municipality was not included in the MWWS, data was used from the representative regional district.

Where annual groundwater volume was unreported, groundwater was either derived from; a) total annual volume and percent population using groundwater sourced MWDS; or b) total annual volume and surface water licences.

If total volume of groundwater sourced, V_{GW}, was not reported for a municipality, it was derived by:

$$V_{GW} = P_{GW} \cdot V_T \tag{1}$$

where:

V_{GW} is total volume of groundwater serviced through a MWDS ($m^3\ yr^{-1}$)

P_{GW} is percent of population serviced MWDS from groundwater (%)

V_T is total volume used by a MWDS ($m^3\ yr^{-1}$)

If V_T was unreported, it was derived using municipal population statistics and per capita provincial-scale statistics of annual water use of 180 $m^3\ yr^{-1}$ (Honey-Roses, Gill, and Pareja 2016):

$$V_T = (P_{MWDS} \cdot p_{MUN}) \cdot V_{BC} \tag{2}$$

where:

V_T is total volume used by a MWDS ($m^3\ yr^{-1}$)

P_{MWDS} is percent population serviced MWDS (%)

p_{MUN} is municipal population (-)

V_{BC} is the per capita total volume of all water use ($m^3\ yr^{-1}\ pp^{-1}$)

If the percent of the population services MWDS was unreported, the P_{MWDS} is equal to 100%.

If P_{GW} was unreported, surface water licenses are used to constrain V_{GW}. The surface water license data are open-access and data was collected on existing municipal water licenses (as of July 18, 2017). The "Purpose of Use" variable was selected as "Waterworks: Local Provider" and the municipality was searched under the variable "Client Name". The "Quantity" variable indicates the maximum allowable annual stream diversion volume in $m^3\ yr^{-1}$. Surface water licenses managed by the municipality were totalled for the annual volume of surface water (V_{SW}). Surface water licences were reported as allowable annual allocations. No data exists on the actual annual volume of water diverted from a stream, therefore, groundwater volumes derived with this method have higher uncertainty, and are possibly underestimated. V_{GW} abstracted for a municipality was taken as:

$$V_{GW} = V_T - V_{SW} \tag{3}$$

where:

V_{GW} is the annual volume of groundwater used by a MWDS ($m^3\ yr^{-1}$)

V_T is total volume used by a MWDS ($m^3\ yr^{-1}$)

V_{SW} is the volume of surface water license allocations ($m^3\ yr^{-1}$)

V_{GW} was then spatially distributed to wells based on a well query to identify municipal wells. The WELLS Database is a publicly accessible catalogue of all recorded water wells in the province managed by the Ministry of Environment and Climate Change of BC. The WELLS Database was queried based on the municipality name and the prefix (such as "City", "Village", "Municipality", or "District") within the "Surname" variable. Based on the "General Remarks" and "Well Use", wells were removed if "Dry", "Test", "Abandoned", or "backfilled". If the well query returned no results, a manual investigation was done to distribute the spatial location of groundwater use.

3.3. Private domestic use

Domestic users include all users self-supplying water for domestic household use (such as household water needs, lawn and garden watering). Private domestic wells are expected to abstract similar magnitude per capita of groundwater to MWWS; however, the spatial distribution on a regional or municipal scale buffers the abstracted volume over several aquifers. Single household wells are not managed by the province and do not require licensing.

The methodology for deriving the distribution of annual groundwater volume withdrawn was based on the following steps:

1. determine populations serviced by groundwater from private wells;
2. derive total groundwater volume; and
3. calculate volume per well based on well density in each municipality and regional district, respectively.

As the MWWS reports on water use statistics for municipalities and regional districts, which encompasses the rural populations living outside municipality boundaries. Populations using private wells, p_{PDW}, are divided into rural and urban regions based on their location. If the well was located within a municipal boundary, the derived groundwater volume was based on municipal statistics. Otherwise, the derived groundwater volume was based on the representative regional district data, which encompasses the remaining provincial area. Municipal and regional district boundary shapefiles are obtained from DataBC.

p_{PDW} for each municipality or regional district was derived using the percent population on wells (P_{PDW}) and the total population for a municipality or regional district (p_T):

$$p_{PDW} = p_T \cdot \ P_{PDW} \tag{4}$$

where:

p_{PDW} is the population supplied residential water from a private domestic well (-)

p_T is total population of a municipality or regional district region (not including municipal populations) (-)

P_{PDW} is the percent of population supplied water via a private domestic well (%)

If P_{PDW} was unreported, municipal populations were assumed to be fully supported by the MWDS ($P_{PDW} =$ 0%). Conversely, rural populations were assumed to be supported by private domestic wells ($P_{PDW} =$ 100%).

Since the MWWS does not report on annual groundwater volumes for populations using wells, per capita annual residential water use, V_{BC}, was inferred from the provincial average, 130 m^3 person^{-1} yr^{-1} (Honey-Roses, Gill, and Pareja 2016). Based on V_{BC} and the p_{PDW}, the total annual groundwater volume for the private domestic sector (V_{PDW}) can be derived:

$$V_{PDW} = V_{BC} \ \cdot \ p_{PDW} \tag{5}$$

where:

V_{PDW} is total annual groundwater volume for the private domestic sector (m^3 yr^{-1})

V_{BC} is the per capita total volume of all water use (130 m^3 yr^{-1} pp^{-1})

p_{PDW} is the population supplied residential water from a private domestic well (-)

V_{PDW} is equally spatially distributed to all "Private Domestic" wells within the representative municipality or regional district (Figure 2b).

3.4. Industrial use

The industrial sector represents self-supplied annual groundwater volumes for manufacturing, mining, and oil and gas production. Industrial use of water can be intensive and concentrated regionally. Industrial industries are diverse, and so efforts were concentrated on estimating major industrial use within BC, namely, manufacturing, mining, and oil and gas.

Annual groundwater water volumes and well extraction locations for oil and gas operations were reported by the BCOGC for 2013-2015 (BC Oil & Gas Commission 2013; BC Oil & Gas Commission 2014; BC Oil & Gas Commission 2015) and averaged to represent groundwater use for the oil and gas sector (Table S1). Deep wells (>250 m depth) were not included as they were less likely to be drawing from any mapped freshwater aquifers.

All the volumetric data for manufacturing and mining were reported from surveys at the provincial or national scale. The following general steps were taken to distribute total annual groundwater volume:

1. groundwater volumes were derived based on water intensity, relative regional water use ratios, and provincial statistics;
2. determine manufacturing and mining locations; and
3. aquifer attribution inferred based on point location of each industry.

Statistics Canada reports total annual water volumes on a national scale for each manufacturing type based on a unique North American Industrial Classification System (NAICS) code.

The total annual groundwater volumes for BC were derived for manufacturing and mining industries from averages based on 2005-2011 Industrial Water Survey (Statistics Canada 2013). Mining water use does not include water extracted for mine dewatering, but rather focuses on the water used in ore production. Annual groundwater abstraction was reported per manufacturing type on a provincial-scale for all of Canada, and provincial annual groundwater volumes for total manufacturing industries in BC.

Some sub-sector manufacturing types are highlighted as being larger consumers of water, such as wood and paper manufacturing (Renzetti 1992). Several economic studies have been conducted on estimation techniques for industrial water demand (Mercer and Morgan 1974; Reynaud 2003; Worthington 2010); however, many require spatially distributed data unavailable for the province, such methods based on detailed economic demand and labour statistics. Therefore, a simpler analysis was conducted herein as a first order estimate.

For the sub-sectors of wood and paper manufacturing and mining (coal, metal, and non-metal sub-sectors), production volumes were used as a proxy to distribute national values to location points in BC based on a method by Vassolo and Döll (2005). The following equation was used to calculate total volume, V_T (m^3/yr), for each sub-sector based on total annual production, PV_i (tonne yr^{-1}), and water intensity, WI_i (m^3 tonne^{-1}) per sub-sector:

$$V_{BC} = PV_i \cdot WI_i \tag{6}$$

where:

Table 2. Groundwater coefficient applied to sub-sector volumes for manufacturing and mining industries.

Industrial Sub-Sector	Yearly range of bi-annual averages	Average self-supplied groundwater coefficient $f_{GW} = V_{GW} / V_T$
Manufacturing	2005–2013*	0.096
Mining	2005–2013**	0.354

*exclusive of 2009.
**exclusive of 2005, 2007, 2011.

V_{BC} is total annual volume required per sub-sector in BC (m^3 yr^{-1})

PV_i is the total annual production (tonne yr^{-1})

WI_i is the water intensity per sub-sector (m^3 $tonne^{-1}$)

WI_i values were calculated based on average production. Wood product manufacturing and paper manufacturing values are averaged over 2008 – 2012 (Table S2). The mining sub-sectors were averaged based on biannual reports over 2005 – 2013 (Table S3). This method assumes that national water intensity values can be applied to BC.

Where production volumes were not readily available, the water intensity was calculated per business location as opposed to per tonne of production. This water intensity per business was calculated based on the statistically significant correlation between the number of businesses in Canada compared to BC; therefore, inferred volumes of water used follow this trend (Figure S2). The number of industrial businesses in Canada (n_{CAN}) and BC (n_{BC}) were derived from Enhanced Points of Interest (EPOI) (DMTI Spatial Inc. 2015), and the total annual water volumes (V_{CAN}) were reported by Statistics Canada to derive the total volume of annual water use per sub-sector for industries in BC, V_{BC}:

$$V_{BC} = \frac{V_{CAN}}{n_{CAN}} \cdot \ n_{BC} \tag{7}$$

where:

V_{BC} is the total annual water use per sub-sector in BC (m^3 yr^{-1})

V_{CAN} is the total annual water use per sub-sector in Canada (m^3 yr^{-1})

n_{CAN} is the number of businesses per sub-sector (-)

The proportion of V_{BC} sourced from groundwater was determined based on national surveys from Statistics Canada. The ratio per sub-sector of average annual self-supplied groundwater, f_{GW}, is determined per sub-sector and assumes all industrial businesses are represented by this ratio (Table 2.2). Total self supplied groundwater per sub-sector, V_{GW}, was derived by:

$$V_{GW} = f_{GW} \cdot V_{BC} \tag{8}$$

where:

V_{GW} is the total annual groundwater use per sub-sector in BC (m^3 yr^{-1})

f_{GW} is the self-supplied groundwater coefficient per sub-sector (-)

V_{BC} is the total annual water use per sub-sector in BC (m^3 yr^{-1})

Derived annual groundwater volumes for manufacturing and mining (Tables S4 and S5), respectively, are equally allocated to locations based on the NAICS code (Figure 2e) and the spatial distribution of locations from EPOI and operating mines as of 2015 compiled based on the British Columbia Geological Survey open file (Arnold 2016). The verification of location accuracy was out of scope for this project, therefore, location uncertainty is inherently associated with the dataset. Mining industry locations were obtained from "Selected exploration projects and operating mines in BC" by the British Columbia Geological Survey (accessed November 2016).

3.5. Irrigated agricultural use

Agricultural water use includes all self-supplied groundwater for crop irrigation. Groundwater for irrigation obtained from all off-farm sources (tap water, treated wastewater, provincial sources, private sources, and other) was not included due to lack of readily available data. Volumes of groundwater sourced from municipal water, and treated wastewater for agricultural irrigation were reported in the MWDS sector.

For this sector, two agriculture water use models were used to derive annual groundwater volumes associated with irrigated agriculture. The first was a local-scale Agricultural Water Demand Model (AWDM) which was originally developed by the BC Ministry of Agriculture to predict water requirements for lands reserved for agriculture in the Okanagan Valley, BC. The model provides current and future estimates of water demand by calculating and field verifying water use on a property by property basis. Groundwater was assigned when no surface water licences exist on the property and when there were no obvious surface water sources. Crop irrigation system type, soil type and climate data were used to calculate water demand. Groundwater volumes are derived from crop irrigation for the following crop groups: alfalfa, apple, berry, cherry, domestic outdoor, forage, fruit, and golf. The model has been extended to include several regions in BC; however, many areas remain uncovered by the AWDM. The Global Crop Water Model (GCWM) was used to supplement the AWDM and was developed to simulate consumptive crop water use and crop yields in rain-fed and irrigated agriculture (Siebert and Döll 2008). This dataset was based on the global land use data set MIRCA2000 (Portmann, Siebert, and Döll 2010) which provides monthly growing patterns for 26 crop classes under rain-fed and irrigated conditions for the period of 1998–2002. The model has a spatial resolution of roughly 10 x 10 km^2 (5 arc minute).

Firstly, data output from the GCWM was used to determine the annual flux of supplemental irrigation water required per crop in addition to precipitation ($V_{irr,c}$). The data was in the form of a raster (cell i) which was summed to obtain the total volume of irrigation (V_{irr}) per cell:

$$V_{irr} = \sum V_{irr,c} \tag{9}$$

where:

V_{irr} is the total annual flux of water required for all 26 crops (m yr^{-1})

$V_{irr,c}$ is the total annual flux of water required for a specific crop (m yr^{-1})

In order to determine the total annual groundwater volume from the V_{irr}, a groundwater coefficient, f_{GW}, was applied based on the method from Esnault et al. (2014). Percent irrigation water from self-supplied on-farm groundwater was reported in the Agricultural Water Survey (Statistics Canada 2014) and was used as the groundwater coefficient. The annual groundwater volume was derived based on the average area weighted value of V_{irr} and the aquifer area. To calculate the groundwater volume per aquifer:

$$V_{GW} = \left(\overline{V_{irr}} \cdot A_A\right) \cdot f_{GW} \tag{10}$$

where:

V_{GW} is the volume of irrigated groundwater required per aquifer (m^3 yr^{-1})

$\overline{V_{irr}}$ is the weighted average annual flux of water required for all 26 crops (m yr^{-1})

A_A is the aquifer area (m^2)

f_{GW} is the percent irrigation water from self-supplied on-farm groundwater (%)

Attribution to aquifers was applied based on priority of data availability. On an aquifer by aquifer basis, the AWDM was prioritized over the GCWM dataset as it is a local scale dataset; however, it does not have complete coverage in BC. Therefore, where the AWDM has no reported groundwater volume, the GCWM derived V_{GW} was used (Figure 2c and d).

3.6. Finfish aquacultural use

Finfish aquaculture use represents self-supplied groundwater volumes for the purpose of conservation (ie. maintaining natural populations of salmon) and industrial finfish freshwater hatcheries. The methodology for deriving the annual groundwater withdrawal volume is based on the following steps (Table 3):

1. locate hatcheries;
2. derive annual groundwater volume from Fisheries and Oceans Canada (DFO) (MacKinlay and Howard 2004); and
3. groundwater volume attributions to wells.

As the data are derived from several different sources (Figure 2f), duplicate values were removed based on availability of data and reliability of source. Freshwater Finfish Hatcheries (FFH) was the primary data source since it contains the largest number of locations and was available from DataBC, a reliable provincial database. Salmon Hatcheries (SH) dataset supplies information on type of hatchery; therefore, net cage locations were removed from the analysis as they are often used in the latter stages of salmon development and are kept in the ocean.

The EPOI reports on locations categorized as Aquaculture (NAICS code:112511 Finfish Farming and Fish Hatcheries). Since the culture type was unidentified, every location was assumed to be a freshwater facility. The Salmonid Enhancement Facilities (MacKinlay and Howard 2004) is a draft document prepared by the DFO Canada and highlights the location of all provincial hatcheries, information on water sources, and seasonal flow rates. If the SF, NFA, or the SAF hatchery locations were within 100 m of the FFH, they were assumed to be a duplicate.

Groundwater volumes are often used seasonally due to the reliable supply of water and constant

Table 3. Summary of data sources for finfish aquaculture in BC.

	Freshwater finfish hatcheries (FFH)	Salmon hatcheries (SH)	NAICS finfish aquaculture (NFA)	Salmonid Enhancement facilities (SAF)
Data Source	DataBC	DataBC	EPOI 2016	DFO
Number of locations	63	35	62	16
Water source reported	no	no	no	yes
Groundwater flow rate reported	no	no	no	yes

Table 4. Annual groundwater volume results compared to Hess (1986).

Sector (sub-sector)	Annual Groundwater Volume (Mm^3) This Study: Sector	This Study: Sub-Sector	Hess, 1986: Sector	Hess, 1986: Sub-Sector
Municipal Water Distribution Systems	83.7		60.5*	
Self-supplied:				
Domestic	61.8		21.4*	
Municipalities		16.6		
Regional Districts		45.2		
Industrial	89.3		44.1	
Manufacturing		80.5		27.3
Mining		8.3		16.9
Oil and gas		0.56		
Irrigated agriculture	211		59.1	
Finfish aquaculture	116		126	
Total	562		311	

*Hess (1986) *reported groundwater volumes for municipalities and rural users, MWDS was equated to Hess's municipalities; and self-supplied domestic and commercial users were equated to Hess's rural users.*

temperature (MacIsaac 2010). Annual groundwater volumes are unreported for all data sources; therefore, inferences are made based on available daily flow data provided by the DFO in the "Fish Health Plan for All Major Salmonid Enhancement Facilities" for many of the salmonid enhancement hatcheries (MacKinlay and Howard 2004). Reported groundwater daily flow rates were extrapolated over four months of seasonally active groundwater abstraction. Groundwater use was assumed if the hatchery was within 100m of a well categorized as "Industrial and Commercial" based on attribution from the WELLS Database. Where a facility was assumed to be using seasonal groundwater, an average value of abstraction was derived from the reported daily flows from the DFO, which was 8.93 x 10^6 m^3 yr^{-1} (10 ft^3 s^{-1} extrapolated over four months). Groundwater volumes were equally attributed to wells within 100 m proximity of the facility and tagged as "Industrial & Commercial" wells (Figure 2f).

The error in the final calculated value for the methods described in Sections 3.1–3.6 is relative to the limitations, assumptions, and uncertainty within each of the datasets, as well as, the relative importance of each of the datasets in total groundwater abstraction. For example, if a sector only account for 5% of the total groundwater abstraction based on extremely uncertain/bias dataset; this will result in less error than if the other sectors accounting for 95% of the groundwater abstraction have more reliable data.

4. Results

The combined annual groundwater abstraction from all major sectors was 562 Mm^3, of which 80% can be attributed to mapped aquifers and 20% of all abstractions were from unmapped aquifers. Of the mapped aquifers in BC, 1031 aquifers (n = 1130) are being sourced for some quantity of groundwater. Self-supplied irrigated agriculture accounts for the highest proportion of annual groundwater withdrawal accounting for 37% of the total volume. Finfish aquaculture, industrial, municipal water distribution systems and private domestic wells account for 21%, 16%, 15%, and 11% respectively. Table 4 illustrates the volumetric comparison between the results from this study and the last reported estimation of groundwater abstraction completed by Hess (1986). Total groundwater use has increased by 81% from 1981 to 2009, which is in trend with Statistics Canada population census of a 60% provincial population increase during this period.

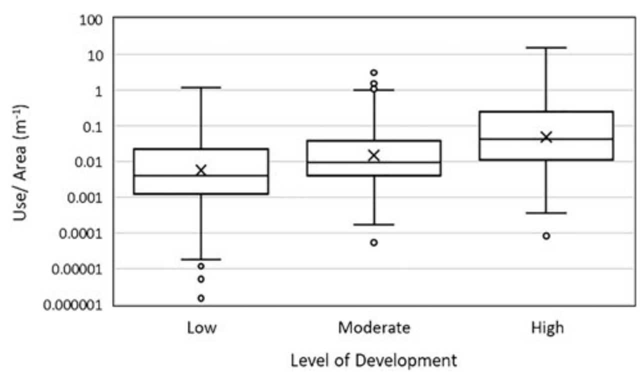

Figure 4. Groundwater flux per aquifer compared to provincial classification of different levels of aquifer development.

Figure 5 illustrates the magnitude and spatial distribution of groundwater use per sector. Private domestic wells impact the largest number of mapped aquifers, abstracting from 79% of aquifers; however, most annual areal abstraction fluxes are <0.1 m per year. Conversely, municipal water distribution systems and finfish aquaculture impact a limited number of

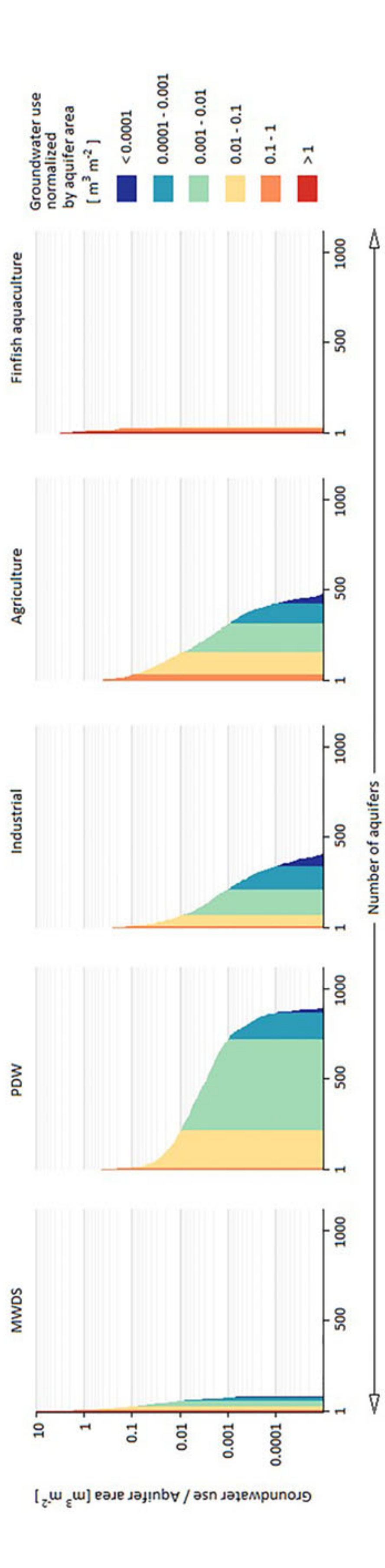

Figure 5. Groundwater use by sector normalized by aquifer area plotted per major sector illustrating the magnitude of use from individual aquifers and the distribution of use across the number of aquifers.

individual aquifers; however, the magnitude of groundwater abstraction fluxes were ≥1 m per year for some aquifers (Table 4). Average annual groundwater abstraction fluxes are 0.03, 0.02, 0.009, 0.005, and 0.003 m yr^{-1} for municipal water distribution systems, finfish aquaculture, irrigated agriculture, private domestic wells, and industrial use respectively (Figure S3a-f).

Most aquifers (n = 734) have abstraction from two or more major sectors. Aquifers dominated by one sector (defined as >50% of annual groundwater abstraction) are most prevalent for private domestic wells dominating 328 mapped aquifers, with the remaining sectors dominating ≤50 aquifers. This may be an artifact of aquifer mapping bias, where mapping was historically prioritized in regions of high groundwater well density (Berardinucci and Ronneseth 2002). However, it does highlight that the majority of aquifers are being abstracted by more than one sector, and therefore, estimates of irrigated agriculture alone would underestimate the annual groundwater flux.

Attribution of annual groundwater volumes to the aquifer were made via spatial relationships of point location or well location. Although, the well location at the land surface was relatively well known, the lack of aquifer data attributed to the locations provides uncertainty in accuracy of aquifer abstracted. For example, of the 91 municipalities identified as groundwater users, 60 municipalities overlie only one aquifer, 22 municipalities overlie two or more aquifers, and 9 municipalities do not overlie mapped aquifers. Where wells or locations do not overlie mapped aquifers, groundwater volumes were unattributed. With 22 municipalities overlying two or more aquifers, the volume attribution was divided equally among all underlying aquifers based on the methods outlined in Section 3.1. Therefore, the groundwater volume is in the approximate location but the exact aquifer abstracted still remains uncertain where both aquifers are unconsolidated. In the future, this problem will be minimized as licensable wells will be correlated to aquifers through the groundwater licencing process.

Unattributed volumes are concentrated in low population regions where aquifer mapping has not been prioritized. Finfish aquaculture has 32% of derived volume unattributed to aquifers, while industrial, private domestic wells, irrigated agriculture, and municipal water distribution systems have unattributed volumes of 31%, 26%, 10%, and 10% respectively. Finfish aquaculture has a large portion of derived groundwater volume unattributed due to high annual fluxes from few locations. In addition, finfish hatcheries, mining, oil and gas

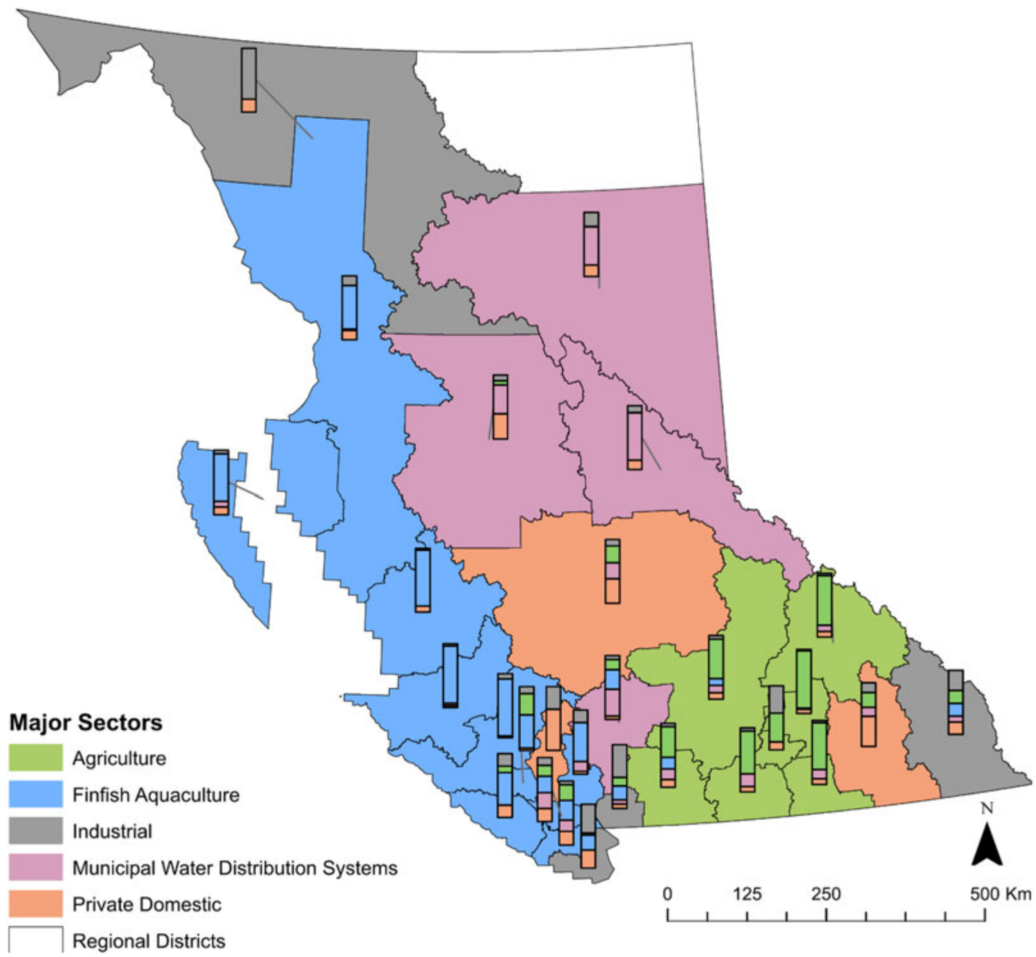

Figure 6. Derived dominant sectors per regional district. Stacked bar are representative of each regional district and represent the sectoral ratio of annual groundwater use.

operations, rural private domestic wells, and some agriculture tend to be in non-populous regions resulting in their high unattributed groundwater volume percentage. In the case of municipal water distribution systems, five municipalities had reported groundwater use; however, no water supply wells were returned in the well query.

Aquifers in BC are currently classified based on development and vulnerability (Berardinucci and Ronneseth 2002). Development is ideally classified based on detailed water balance; however, data are often unavailable, and classification is subjectively based on well density, known water use, aquifer productivity, and sources of recharge. Larger ratios of groundwater volume per aquifer area would be expected to classify as (I) High describing an aquifer with a high level of development; (II) Moderate for moderate groundwater use, and (III) Low for lower development aquifers. When results were compared to the provincial classification, high development aquifers with larger ratios of groundwater use per area were seen (Figure 4). Although, groundwater use estimates given here are also based on well data, these were derived based on several different sources of data and sectoral distribution.

5. Discussion

Multi-method approach to deriving groundwater use is critical to capture the regionally significant sectors of use. Many studies often only consider agricultural, industrial, and domestic groundwater use – which accounts for a substantial portion of groundwater use on a global-scale – however, this may misrepresent groundwater abstractions in regions significantly impacted by other sectors on a local-scale (Howard and Gelo 2002; Wada et al. 2010; Gleeson et al. 2012; Richey et al. 2015). Figure 6 highlights the diversity of sectoral groundwater use across the province and highlights the importance of spatially distributed sectoral estimates. In the coastal area of the province most groundwater use is attributed to finfish aquaculture, which is a regionally specific sector is importance. In

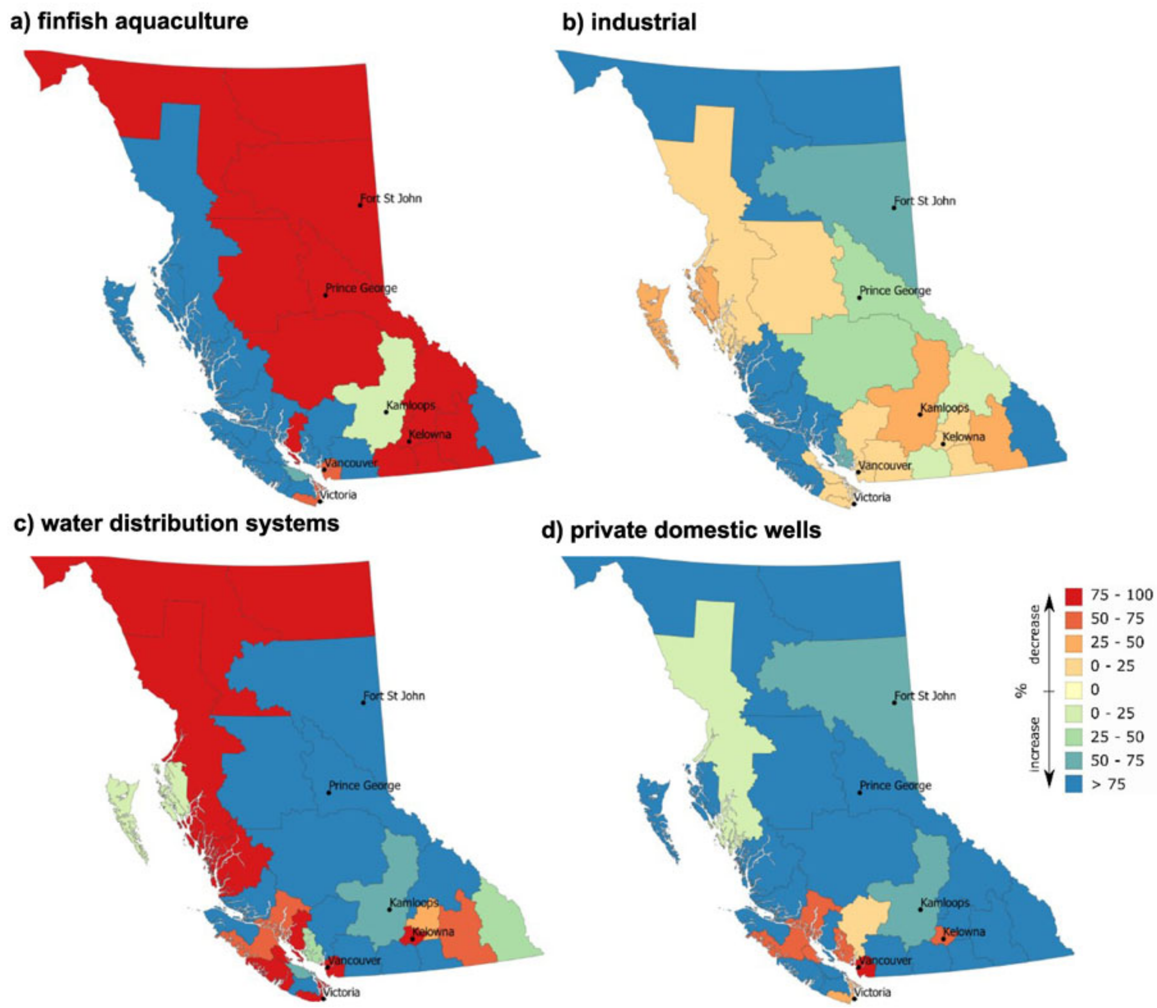

Figure 7. Percent change in per capita groundwater use compared to provincial average value for a) finfish aquaculture, b) industrial, c) municipal water distribution systems, and d) private domestic wells. An increase in per capita groundwater use as illustrated highlights areas where regional average per capita groundwater use is greater than the provincial average.

addition, agriculture is only a significant user of groundwater in the southern and central regions.

Lumping municipal water distribution systems and private domestic use from wells into a single domestic sector can lead to poor management strategies. Private domestic wells often have a low abstraction rates per aquifer compare to municipal water distributions which often lead to high abstraction rates.

As water withdrawal rates are often reported on national or provincial scale, methods of disaggregating often require secondary proxies (Alcamo et al. 1997; Vorosmarty et al. 2000; Wada et al. 2010). Methods for estimating water use often rely on per capita statistics (Alcamo et al. 1997; Vorosmarty et al. 2000; Richey et al. 2015); however, due to the disproportional use of groundwater in the population, this assumption could lead to misrepresentative values of groundwater use. For example, Richey et al. (2015) estimate groundwater use from national groundwater withdrawal statistics based on Vorosmarty et al. (2000). Vorosmarty et al. (2000) develops methods to estimate total water use for domestic and industrial groundwater use based on national per capita statistics, and spatial disaggregation of industrial use in proportion to urban populations. By disaggregating groundwater rates based on population, the inherent assumption is that groundwater use is proportional to population (essentially a per capita statistic). However, Figure 7 illustrates the percent difference in using the provincial per capita value (total sectoral groundwater use divided by the total population) and the regional district per capita (regional district sectoral groundwater use divided by regional district population). In addition, due to local-scale data scarcity, global-scale groundwater use estimates are often used in groundwater stress studies (Wada et al. 2010; Gleeson et al. 2012). Using downscaled values of groundwater use from global datasets can be misleading in regions where groundwater use is unregulated/newly regulated, as is the case in BC. Wada et al (2010) estimated groundwater abstraction based on country statistics of abstraction rates; however, this method reported zero groundwater consumption for BC, which these results show is misrepresentative of local scale values.

5.1. Limitations & method uncertainty by major sector

The largest uncertainties in this study are associated with unavailable data or unreported values in provincial and national surveys. The following sections highlight the uncertainties and limitations by major sector. One of the primary challenges in this analysis was the lack of high resolution point-based volumetric data in order to spatially distribute the groundwater withdrawals. For the majority of derived groundwater volumes per sector, large uncertainty was introduced due to unreported values which required extensive interpolation from large scale volumes (reported on the provincial scale) to proxy point (such as business locations, or type of wells) to distribute the values to aquifer-scale. Due to the nature of many of the dataset, groundwater use was often based on single values, and uncertainty was impossible to adequately quantify. For this reason, this analysis should be considered a first order estimate of groundwater withdrawals in BC; however, this analysis should be refined and updated once measured data are available.

5.1.1. Municipal water distribution systems and private domestic wells

The MWDS and private domestic wells (PDW) groundwater volumes are derived from data in the MWWS (Environment Canada 2011). Approximately one quarter (24%) of the BC population – 24% of municipalities and 43% of regional districts – did not report on type of serviced water. Based on the MWWS, total annual water use for MWDS was only reported for 39% of municipalities (n= 98) and 36% of regional districts (n = 18). The regional districts and municipalities with unreported total MWDS volumes were attributed a volume based on total water use per capita (180 m^3 yr^{-1}). Calculations for MWDS users relied on source water data and percent groundwater from the MWWS, as well as, surface water license data from municipal waterworks to derive annual groundwater withdrawals. Subsequently, 14% of municipalities (n = 23) were inferred as groundwater users due to lack of source water data supplying the MWDS.

Compared to annual groundwater use volumes derived by Hess (1986), municipal and rural groundwater use have increased 66% and 111% respectively based on the findings of this study. However, based on population statistics, municipalities have seen a 78% increase and rural population have seen a 0.5% decline since 1981 (Statistics Canada 2011). The methodology for deriving municipal and rural groundwater volumes assumes a conservative approximation of groundwater use by defaulting unknown source of freshwater to groundwater use. Therefore, it is likely the rural volumes have been overestimated. Alternatively, municipal water distribution systems have seen a decline in water use compared to population increase. Surface water licences represent a maximum allowable diversion, where the actual surface water diversion is often less than the licensed volume. As groundwater volumes were taken as the difference between total water use and surface water allocations, groundwater volumes may have been underestimated where municipal water distribution systems did not divert their total annual allocation from surface water sources. Another possible reason for the decrease in municipal water use compared to population increase could be due to water use trends, such as per capita water use or a switch from groundwater to surface water sources, however, due to lack of reported data, these are no more than speculations.

5.1.2. Industrial

Groundwater abstraction data are most accurate for the oil and gas sector, as these are reported values attributed to wells. The manufacturing and mining groundwater abstraction data was only provided at a provincial-scale. Derived groundwater volumes for manufacturing industries had an average total annual water intake calculated at 715 Mm^3 yr^{-1}, which is comparable to the provincial average of 796 Mm^3 yr^{-1} reported by Statistics Canada in the Industrial Water Survey. Although derived total provincial abstracted groundwater volumes fell close to the expected value reported by the Industrial Water Survey, the largest uncertainty for manufacturing and mining industries is the spatial distribution of derived groundwater abstraction. Spatial variability is masked as it assumes 1) all locations supply a portion of their groundwater through self-supplied private wells, as no data exists as to which locations are connected to a MWDS, 2) all locations use some volume of groundwater based on the groundwater coefficient, and 3) all locations of the same sub-industry withdraw the same volume of groundwater as volumes are distributed using North American Industrial Classification System.

5.1.3. Irrigated agriculture

Where the AWDM reported groundwater volumes are unavailable for an aquifer, the GCWM is used to estimate groundwater volumes based on regional statistics of water use. As a result, the estimate volumes using the GCWM are more uncertain than the more locally representative volumes form the AWDM. The AWDM reported agricultural use for 422 aquifers in BC, as opposed to the GCWM reported for 653 aquifers; however, the AWDM accounts for 99% of the attributed volume of groundwater use compared to the GCWM since the AWDM has focused on the areas of most intense irrigation. Since only total annual irrigation volume is included, the groundwater coefficient had to be inferred from provincial statistics. This assumes all farms are groundwater users, therefore presenting a high uncertainty of groundwater volume location accuracy. As irrigation was determined to be the major contributor of annual groundwater withdrawal, livestock was not included and will need to be added at a later date.

5.1.4. Finfish aquaculture

Based on the major sectoral annual groundwater volumes from this study, finfish aquaculture is the second largest user of groundwater, after agriculture, accounting for 116 Mm^3 of total annual groundwater use in BC This value has large uncertainty since conservative inferences were made on groundwater flow rates, seasonal operation, and groundwater user locations. However, it is apparent that all aquifers being abstracted for the purpose of finfish aquaculture do have large withdrawal compared to aquifer area even at a conservative 4 months seasonal usage. These values should be verified with local studies to determine actual groundwater diversion to better constrain these volumes.

6. Recommendations & conclusions

Groundwater is a critical source of freshwater supporting residential, commercial, industrial and agricultural sectors within BC. The Province has mapped and classified more than 1100 aquifers across BC, but the level of development for each aquifer has always been subjectively based on well density or the mapper's knowledge of groundwater use.

This paper estimates groundwater use across BC for all the major groundwater use sectors and maps this groundwater use for each aquifer in the province for the first time. Data on major sectors of use was synthesized from provincial and national sources and spatially downscaled and interpolated to derive groundwater use volumes for currently mapped aquifers. Groundwater use was first classified based on means of distribution either through a municipal water distribution systems or self-supplied through private wells, and secondly, by major groundwater use sectors namely, domestic, industrial, irrigated agriculture, and finfish aquaculture. The methodologies used in deriving the spatially distributed groundwater use volumes are different for each sector based on the data availability and scale of reporting. Results suggest that BC uses a total of ∼562 million cubic metres of groundwater annually. The largest annual groundwater use by major sectors is agriculture (38%), finfish aquaculture (21%), industrial (16%), municipal water distribution systems (15%), and domestic private well users (11%). This study is a preliminary assessment, as the majority of the groundwater volumes were unreported per sector, and therefore, different methodologies are used to interpolate available data.

Sectoral groundwater use is useful for local regions and aquifer-scale groundwater stress studies which are significantly impacted by changes in the groundwater use. Based on the results from this study, the importance of regionally important sectors, such as finfish aquaculture in the coastal regions, has been identified.

The methods herein presented can be useful for regional scale estimates of groundwater use in data scarce regions and could be modified for application in other regions. In particular, one of the major limitations is the lack of pumping data; however, the location of wells can be used to spatially distribute groundwater volumes instead of population of area based assumptions. In addition, estimating municipal water distribution systems, which account for a large majority compared to self-supplied users, is a critical component of total groundwater use.

A few detailed recommendations derived from the results as well as challenges encountered during this analysis include:

- Identify local sectors which may be critically impacting the abstraction of groundwater within the study area.
- Compare annual groundwater volumes to results from local or regional studies which could help determine the accuracy of estimates in different regions.

- Create and provide public access to data on regional groundwater sources and volumes of use. The largest uncertainty in this groundwater use analysis was due to a lack of available data.
- Water meters should be encouraged for all well users to improve estimates of water use.

Acknowlegements

This project was funded by the Ministry of Environment and Climate Change of British Columbia in a provincial scale aquifer-stress study.

Funding

BC Ministry of Environment and Climate Change.

References

Aeschbach-Hertig, W., and T. Gleeson. 2012. "Regional Strategies for the Accelerating Global Problem of Groundwater Depletion." *Nature Geoscience* 5 (12): 853. doi:10.1038/ngeo1617.

Alcamo, J., P. Döll, F. Kaspar, and S. Siebert. 1997. "Global Change and Global Scenarios of Water Use and Availability: An Application of WaterGAP1.0." https://www.researchgate.net/profile/Stefan_Siebert2/publication/251427736_Global_change_and_global_scenarios_of_water_use_and_availability_An_Application_of_WaterGAP10/links/5b9b78cc45851574f7c72e77/Global-change-and-global-scenarios-of-water-use-and-availability-An-Application-of-WaterGAP10.pdf

Alley, W. M., B. R. Clark, D. M. Ely, and C. C. Faunt. 2018. "Groundwater Development Stress: Global-Scale Indices Compared to Regional Modeling." *Groundwater* 56 (2): 266–275. doi:10.1111/gwat.12578.

Arnold, H. 2016. Selected Exploration Projects and Operating Mines in British Columbia, 2015. British Columbia Geologcal Survey. http://webmap.em.gov.bc.ca/mapplace/DL/web/OF2016-1_42x28_HiRes.pdf.

Barlow, P. M., and S. A. Leake. 2012. *Streamflow depletion by wells–understanding and managing the effects of groundwater pumping on streamflow*. Reston, USA: US Geological Survey.

BC Oil & Gas Commission. 2013. *2013 Annual Report on Water Use for Oil and Gas Activity*. https://www.bcogc.ca/node/11263/download.

BC Oil & Gas Commission. 2014. *2014 Annual Report on Water Use for Oil and Gas Activity*. https://www.bcogc.ca/node/12676/download.

BC Oil & Gas Commission. 2015. *2015 Annual Report on Water Management for Oil and Gas Activity*. https://www.bcogc.ca/node/13261/download.

Berardinucci, J., and K. Ronneseth. 2002. *Guide to using the BC aquifer classification maps for the protection and management of groundwater*. Victoria, B.C.: Ministry of Water, Land and Air Protection. http://www.llbc.leg.bc.ca/public/PubDocs/bcdocs/357172/aquifer_maps.pdf.

Bredehoeft, J. D., and R. A. Young. 1983. "Conjunctive Use of Groundwater and Surface Water for Irrigated Agriculture: Risk Aversion." *Water Resources Research* 19 (5): 1111–1121. doi:10.1029/WR019i005p01111.

Castaño, S., D. Sanz, and J. J. Gómez-Alday. 2010. "Methodology for Quantifying Groundwater Abstractions for Agriculture via Remote Sensing and GIS." *Water Resources Management* 24 (4): 795–814. doi:10.1007/s11269-009-9473-7.

Changming, L., Y. Jingjie, and E. Kendy. 2001. "Groundwater Exploitation and Its Impact on the Environment in the North China Plain." *Water International* 26 (2): 265–272. doi:10.1080/02508060108686913.

Dalin, C., Y. Wada, T. Kastner, and M. J. Puma. 2017. "Groundwater Depletion Embedded in International Food Trade." *Nature* 543 (7647): 700. doi:10.1038/nature21403.

DMTI Spatial Inc. 2015. CanMap Content Suite, V2015.3. DMTI Spatial Inc. http://dvn.library.ubc.ca.ezproxy.library.uvic.ca/dvn/dv/UVICLDS/faces/study/StudyPage.xhtml?globalId=hdl:11272/P66YQ&studyListingIndex=6_095f14dea734a9285a4df275892f.

Environment Canada. 2011. "Municipal Water Use Report: Municipal Water Use 2009 Statistics."

Esnault, L., T. Gleeson, Y. Wada, J. Heinke, D. Gerten, E. Flanary, M. F. Bierkens, and L. P. van Beek. 2014. "Linking Groundwater Use and Stress to Specific Crops Using the Groundwater Footprint in the Central Valley and High Plains Aquifer Systems, US." *Water Resources Research* 50 (6): 4953–4973. doi:10.1002/2013WR014792.

Famiglietti, J.S. 2014. "The Global Groundwater Crisis." *Nature Climate Change* 4 (11): 945. doi:10.1038/nclimate2425.

Gleeson, T., and Y. Wada. 2013. "Assessing Regional Groundwater Stress for Nations Using Multiple Data Sources with the Groundwater Footprint." *Environmental Research Letters* 8 (4): 044010. doi:10.1088/1748-9326/8/4/044010.

Gleeson, T., Y. Wada, M. F. Bierkens, and L. P. van Beek. 2012. "Water Balance of Global Aquifers Revealed by Groundwater Footprint." *Nature* 488 (7410): 197–200. doi:10.1038/nature11295.

Hess, P. J. 1986. "Ground-Water Use in Canada, 1981." In *IWD technical bulletin*. Vol. 140. Environment Canada. http://bases.bireme.br/cgi-bin/wxislind.exe/iah/online/?IsisScript=iah/iah.xis&src=google&base=REPIDISCA&lang=p&nextAction=lnk&exprSearch=115114&indexSearch=ID.

Honey-Roses, J., D. Gill, and C. Pareja. 2016. "BC Municipal Water Survey 2016." *School of community and regional planning, university of British Columbia*. Ottawa, Canada: Water Planning Lab (March 3). Online URL: http://hdl.handle.net/2429/57077.

Howard, K. W. F., and K. K. Gelo. 2002. "Intensive Groundwater Use in Urban Areas: The Case of Megacities." *Intensive Use of Groundwater: Challenges and Opportunities* : 484.

Ireson, A., C. Makropoulos, and C. Maksimovic. 2006. "Water Resources Modelling under Data Scarcity: Coupling MIKE BASIN and ASM Groundwater Model." *Water Resources Management* 20 (4): 567–590. doi:10.1007/s11269-006-3085-2.

Konikow, L. F., and E. Kendy. 2005. "Groundwater Depletion: A Global Problem." *Hydrogeology Journal* 13 (1): 317–320. doi:10.1007/s10040-004-0411-8.

Kundzewicz, ZBIGNIEW W., and PETRA. Döll. 2009. "Will Groundwater Ease Freshwater Stress under Climate Change?" *Hydrological Sciences Journal* 54 (4): 665–675. doi:10.1623/hysj.54.4.665.

Lapworth, D. J., A. M. MacDonald, M. N. Tijani, W. G. Darling, D. C. Gooddy, H. C. Bonsor, and L. J. Araguás-Araguás. 2013. "Residence Times of Shallow Groundwater in West Africa: Implications for Hydrogeology and Resilience to Future Changes in Climate." *Hydrogeology Journal* 21 (3): 673–686. doi:10.1007/s10040-012-0925-4.

Llamas, M. R. 1998. Groundwater Overexploitation. In *Proceeding of the UNESCO Congress on "Water in the 21st Century: A Looming Crisis.*

MacIsaac, E. A. 2010. "Salmonids and the Hydrologic and Geomorphic Features of Their Spawning Streams in British Columbia." In *Compendium of Forest hydrology and geomorphology in British Columbia. Land management handbook.* British Columbia: Ministry of Forests and Range.

MacKinlay, D., and K. Howard. 2004. "Fish Health Management Plan for All Major Salmonid Enhancement Facilities." https://docplayer.net/19080619-Fish-health-management-plan-for-all-major-salmonid-enhancement-facilities.html

Manga, M. 1999. "On the Timescales Characterizing Groundwater Discharge at Springs." *Journal of Hydrology* 219 (1-2): 56–69. no.doi:10.1016/S0022-1694(99)00044-X.

Mercer, L. J., and W. D. Morgan. 1974. *Estimation of commercial, industrial and governmental water use for local areas1. Journal of American Water Resources Association* 10 (4): 794–801. Wiley Online Library. http://onlinelibrary.wiley.com/doi/10.1111/j.1752-1688.1974.tb05640.x/abstract.

Pavelic, P.,. U. Patankar, S. Acharya, K. Jella, and M. K. Gumma. 2012. "Role of Groundwater in Buffering Irrigation Production against Climate Variability at the Basin Scale in South-West India." *Agricultural Water Management* 103: 78–87. doi:10.1016/j.agwat.2011.10.019.

Portmann, F. T., S. Siebert, and P. Döll. 2010. "MIRCA2000—Global Monthly Irrigated and Rainfed Crop Areas around the Year 2000: A New High-Resolution Data Set for Agricultural and Hydrological Modeling." *Global Biogeochemical Cycles* 24 (1): n/a. no. http://onlinelibrary.wiley.com/doi/10.1029/2008GB003435/full. doi:10.1029/2008GB003435.

Province of British Columbia. 1909. *Water Act.* http://www.bclaws.ca/civix/document/id/92consol16/92consol16/79429.

Province of British Columbia. 2016. *Water Sustainability Act.* http://www.bclaws.ca/civix/document/id/complete/statreg/14015.

Renzetti, S. 1992. "Estimating the Structure of Industrial Water Demands: The Case of Canadian Manufacturing." *Land Economics* 68 (4): 396–404. doi:10.2307/3146696.

Reynaud, A. 2003. "An Econometric Estimation of Industrial Water Demand in France." *Environmental and Resource Economics* 25 (2): 213–232. no.

Richey, A. S., B. F. Thomas, M.-H. Lo, J. T. Reager, J. S. Famiglietti, K. Voss, S. Swenson, and M. Rodell. 2015. "Quantifying Renewable Groundwater Stress with GRACE." *Water Resources Research* 51 (7): 5217–5238. doi:10.1002/2015WR017349.

Rutherford, S. 2004. Groundwater Use in Canada. West Coast Environmental Law. http://www.wcel.org/sites/default/files/publications/Groundwater%20Use%20in%20Canada.pdf.

Rutulis, M. 1989. "Groundwater Drought Sensitivity of Southern Manitoba." *Canadian Water Resources Journal* 14 (1): 18–33. doi:10.4296/cwrj1401018.

Scanlon, B. R., C. C. Faunt, L. Longuevergne, R. C. Reedy, W. M. Alley, V. L. McGuire, and P. B. McMahon. 2012. "Groundwater Depletion and Sustainability of Irrigation in the US High Plains and Central Valley."*Proceedings of the National Academy of Sciences* 109, no. 24: 9320−−9325. doi:10.1073/pnas.1200311109.

Siebert, S.,. J. Burke, J.-M. Faures, K. Frenken, J. Hoogeveen, P. Döll, and F. T. Portmann. 2010. "Groundwater Use for Irrigation–a Global Inventory." *Hydrology and Earth System Sciences* 14 (10): 1863–1880. doi:10.5194/hess-14-1863-2010.

Siebert, S., and P. Döll. 2008. The Global Crop Water Model (GCWM): Documentation and First Results for Irrigated Crops. https://www.mysciencework.com/publication/show/c32205cec4e69a100a36d39897f41470.

Srinivasan, V., S. Thompson, K. Madhyastha, G. Penny, K. Jeremiah, and S. Lele. 2015. "Why Is the Arkavathy River Drying? a Multiple-Hypothesis Approach in a Data-Scarce Region." *Hydrology and Earth System Sciences* 19 (4): 1905–1917. doi:10.5194/hess-19-1905-2015.

Statistics Canada. 2013. Industrial Water Survey http://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&SDDS=5120.

Statistics Canada. 2014. Agricultural Water Survey http://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&SDDS=5145.

Statistics Canada. 2011. "Canada's Rural Population since 1851."https://www12.statcan.gc.ca/census-recensement/2011/as-sa/98-310-x/98-310-x2011003_2-eng.cfm

Tsur, Y. 1990. "The Stabilization Role of Groundwater When Surface Water Supplies Are Uncertain: The Implications for Groundwater Development." *Water Resources Research* 26 (5): 811–818. doi:10.1029/WR026i005p00811.

Vassolo, S., and P. Döll. 2005. "Global-Scale Gridded Estimates of Thermoelectric Power and Manufacturing Water Use." *Water Resources Research* 41 (4): 1–11. http://onlinelibrary.wiley.com/doi/10.1029/2004WR003360/full. doi:10.1029/2004WR003360.

Vorosmarty, C. J., P. Green, J. Salisbury, and R. B. Lammers. 2000. "Global Water Resources: Vulnerability from Climate Change and Population Growth." *Science* 289 (5477): 284–288. no. July 14): doi:10.1126/science.289.5477.284.

Wada, Y., D. Wisser, and M. F. P. Bierkens. 2014. "Global Modeling of Withdrawal, Allocation and Consumptive Use of Surface Water and Groundwater Resources." *Earth System Dynamics Discussions* 5 (1): 15–40. doi:10.5194/esdd-4-355-2013.

Wada, Yoshihide, L. P. van Beek, C. M. van Kempen, J. W. Reckman, S. Vasak, and M. F. Bierkens. 2010. "Global

Depletion of Groundwater Resources." *Geophysical Research Letters* 37 (20): n/a. doi:10.1029/2010GL044571.
Wei, M., K. Ronneseth, D. Allen, A. P. Kohut, B. Turner, and S. Grasby. 2007. "Types and General Characteristics of Aquifers in the Canadian Cordillera Hydrogeologic Region." In *Proceedings 8th Annual Canadian Geotechnical Society-International Association of Hydrogeologists Joint Conference, OttawaGeo2007: The Diamond Jubilee Conference,* Ottawa.
Wei, M., K. Ronneseth, D. M. Allen, A. P. Kohut, S. E. Grasby, and B. Turner. 2014. "Cordilleran hydrogeological region". In Canada's Groundwater Resources, edited by A. Rivera, 804 p. Markham, Canada: Fitzhenry & Whiteside.
Welch, L. A., and D. M. Allen. 2014. "Hydraulic Conductivity Characteristics in Mountains and Implications for Conceptualizing Bedrock Groundwater Flow." *Hydrogeology Journal* 22 (5): 1003. https://link-springer-com.ezproxy.library.uvic.ca/article/10.1007/s10040-014-1121-5. doi:10.1007/s10040-014-1121-5.
Worthington, A. C. 2010. "Commercial and Industrial Water Demand Estimation: Theoretical and Methodological Guidelines for Applied Economics Research." *Estudios de Economía Aplicada* 28no. (2): 237–258.