WATER SCIENCE SERIES

Mapping Aquifer Stress, Groundwater Recharge, Groundwater Use, and the Contribution of Groundwater to Environmental Flows for Unconfined Aquifers across British Columbia

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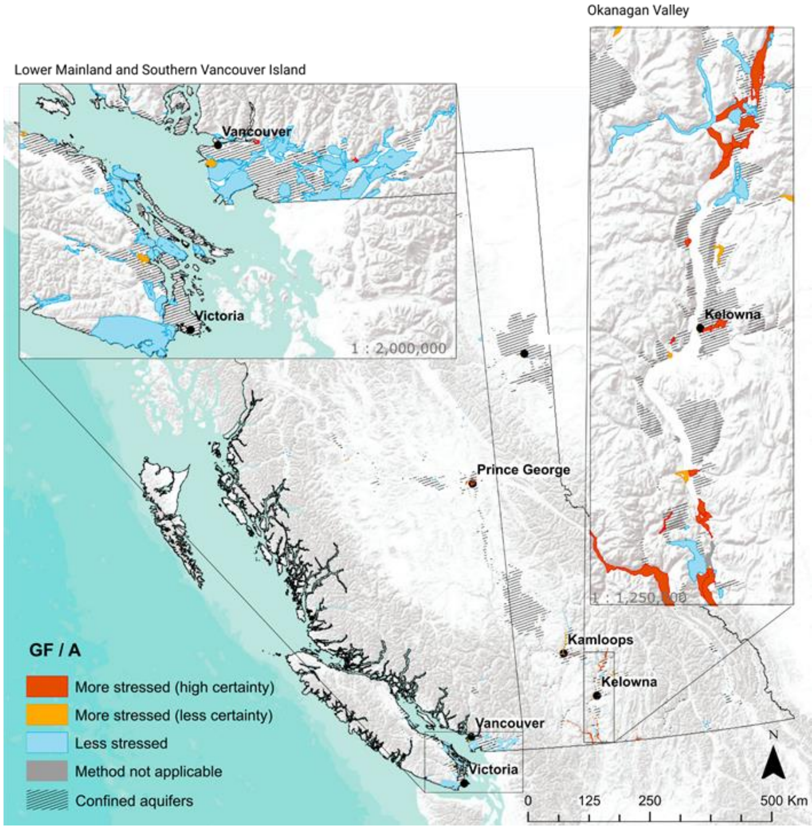

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Figure from report – aquifer stress for the Lower Mainland and Vancouver Island.

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EXECUTIVE SUMMARY

Key Finding:

One in every five unconfined aquifers in the province is likely stressed. Regions of priority for groundwater management include the Okanagan, the Lower Mainland and Vancouver Island, as well as isolated aquifers in other regions.

Need for this Study:

Groundwater is a critical source of freshwater supporting residential, commercial, industrial and agricultural sectors within British Columbia (B.C.). The Province has mapped and classified more than 1100 aquifers across B.C., 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 project focuses on the synthesis, spatial analysis and modelling of existing data to map stress for unconfined aquifers across the province and develop an aquifer-scale decision support tool to assist water managers in decision making, prioritization of high risk aquifers for detailed studies, promote awareness of groundwater resources across the province, and encourage the protection and management of this valuable freshwater resource. **The scope of this project is to derive aquifer-scale estimates of annual volumes for groundwater withdrawal, recharge, and groundwater's contribution to environmental flows as a means to provide screening level estimates of aquifer-scale stress using the groundwater footprint.**

Groundwater Use:

This report estimates groundwater use across B.C. 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, commercial, 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 B.C. 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.

Groundwater Recharge:

Recharge is estimated using two approaches; a generalized aquifer-scale method, using the Hydrologic Evaluation of Landfill Performance (HELP) and modelled recharge outputs from PCR-GLOBWB, a global hydrologic model. **Results show that generally recharge predictably varies with precipitation and that the average recharge is 462 mm (32% of precipitation) for the aquifer-scale HELP method and 393 mm (33%) for the global hydrologic model.** The generalized methodology results in annual recharge rates that are consistent with the more localized studies of the Abbotsford-Sumas aquifer in humid southwestern B.C. and the Grand Forks aquifer in semi-arid south-central B.C. Although the results are consistent with previous localized recharge modelling, as well as expected patterns of recharge across the province, these recharge estimates should only be used for regional to provincial scale groundwater resource management rather than localized analysis.

Groundwater's Contribution to Environmental Flows

This study estimates groundwater's contribution to environmental flows across the province for this first time using two separate approaches. The first approach uses the groundwater presumptive standard, which is a general standard for managing groundwater pumping. The second method introduces a novel approach for estimating the contribution of groundwater to environmental flows using the existing B.C. environmental flow needs framework and an understanding of low flow zone hydrology. **In general, both methods show larger contributions from groundwater to environmental flows in the Lower Mainland and southern Vancouver Island compared to the Interior.** As both methods rely on modelled baseflow and streamflow, respectively, uncertainties increase in mountainous terrain where the models may not fully represent local aquifer dynamics.

Aquifer Stress:

For each aquifer, the groundwater footprint (expressed as the unitless ratio of groundwater footprint to aquifer area or GF/A) is calculated four times; using results from each of the two methods used to estimate recharge and each of the two methods used to estimate the groundwater contribution to environmental flows. None of the methods can be categorically considered more scientifically robust, so all four of the calculated groundwater footprints are reported and combined into three mapped categories that also highlight the uncertainty of the results: (a) more stressed (highly certain) if all results suggest aquifer stress; (b) more stressed (less certain) if some results suggest aquifer stress; (c) less stressed if none of the results suggest aquifer stress. The groundwater footprint, which is an indicator of groundwater stress with a single cut-off: GF/A > 1 suggests an aquifer is more stressed, and GF/A < 1 suggests less stressed. There is no scientific basis to interpret the calculated values more finely. Given the significant limitations and uncertainties in the input parameters and single cut-off, the calculated values of the groundwater footprint should not be over-interpreted. For example, aquifers with GF/A of 2 or 10 should both be considered 'more stressed' and provoke similar management decisions. **Of the unconfined aquifers (n = 404) in the province, 43 aquifers (11%) are stressed with high certainty, 32 aquifers (8%) are stressed with low certainty, 296 aquifers (70%) are less stressed, and 29 aquifers (11%) were not included due to missing parameters or issues where modelled recharge was less than environmental flows.**

Recommendations:

We provide a number of recommendations that could significantly improve the conjunctive management of surface water and groundwater in the province including:

- establishing new systems for tracking groundwater use and linking this with aquifers;
- improving the observational well network to better quantify recharge;
- develop a new environmental flow regulation, incorporating many of the elements of the existing EFN policy, but more holistically incorporating the importance of groundwater;
- testing the new methods for quantifying the groundwater contribution to environmental flows to determine if they could be used in operational water management; and
- using the aquifer-scale decision support tool to assist water managers in decision making, prioritizing high risk aquifers for detailed studies, promoting awareness of groundwater resources, and encouraging the protection and management of this valuable resource.

CONTENTS

ACRONYMS

A	Aquifer area
AWS	Agricultural Water Survey
AWDM	Agricultural Water Demand Model
B.C.	British Columbia
BCOGC	British Columbia Oil and Gas Commission
BGCZ	Biogeoclimatic zone
C	Groundwater consumption, annual average
CN	Curve Number
DFO	Fisheries and Oceans Canada
E	Annual groundwater volume contribution to environmental streamflow
EFN	environmental flow needs
EPOI	Enhanced Points of Interest
GCWM	Global Crop Water Model
GF	Groundwater Footprint
GW	groundwater
HELP	Hydrologic Evaluation of Landfill Performance model
ID	identifier or identification number
IWS	Industrial Water Survey
LAI	leaf area index
MENV	Ministry of Environment and Climate Change Strategy
MFLNRORD	Ministry of Forests, Lands, Natural Resource Operations and Rural Development
MMF	mean monthly flow
MWDS	municipal water distribution systems
MWWS	Environment Canada’s Municipal Water and Wastewater Survey
NAICS	North American Industry Classification System
PCR-GLOBWB	PCRaster GLOBal Water Balance model
R	Annual groundwater recharge
SIC	standard industry classification codes
SLC	Soil Landscapes of Canada
SW	surface water
WDS	water distribution systems
WELLS	B.C. MENV Groundwater wells database
WGEN	Weather Generator
WSA	Water Sustainability Act

1. INTRODUCTION: STUDY AIMS, SCOPE AND RESEARCH QUESTIONS

Groundwater is a critical source of freshwater supporting residential, commercial, industrial and agricultural sectors within British Columbia (B.C.), accounting for approximately 23% of the national volume of water used (Rivera 2003; Hess 1986). The province of B.C. has mapped and classified more than 1000 aquifers but the level of development for each aquifer has always been subjectively based on well density or the mapper's knowledge of groundwater use (Berardinucci and Ronneseth 2002). This project focuses on the spatial and statistical analysis of existing data to map aquifer stress across the province, and develop an aquifer-scale decision support tool for water managers.

The B.C. Ministry of Environment and Climate Change Strategy (MENV) identified key questions that water managers were expected to ask and this research is motivated by some of these key questions:

- Given that the overlying stream already has a water allocation restriction that indicates the surface water supply is reaching its limit (e.g., fully recorded; fully recorded except for domestic; fully recorded except with storage), how much more can we allocate from the underlying aquifer, if it is connected? Where are those aquifers in the province?
- How much water is available from this specific aquifer? How firm or uncertain is that number? What are the indicators that availability limits for this specific aquifer has been reached? Which specific aquifers do we need to most work on?

The scope of this project is to derive aquifer-scale estimates of annual volumes for groundwater withdrawal, recharge, and groundwater's contribution to environmental flows as a means to provide screening level estimates of aquifer-scale stress quantified using the groundwater footprint. A major part of this project included a synthesis of varying scales of data. Where possible, local-scale data is used; however, in many cases, due to lack of spatially distributed data, national or global-scale data is used. This brings in inherent uncertainty and limitations considering the resolution of global models is approximately 100 km^2, whereas the average area of aquifers in B.C. is ~30 km^2. No new field data was collected, and deriving these parameters relies on data previously collected for this desktop data synthesis, analysis and modelling study. The main challenges in this study for deriving aquifer-scale estimates for all aquifers in B.C. include (i) spatial distribution of aquifers in a province of wide climatic and topographical variability, and (ii) local scale data sparsity and coverage.

In addition to addressing the urgent gaps in provincial groundwater knowledge, the following research questions and deliverables motivate this project:

1. What is the spatial distribution of groundwater use in B.C.?
    a) first spatially distributed map of groundwater use in B.C.; and
    b) develop methods for estimating groundwater use in data sparse regions.
2. What is the spatial distribution of aquifer recharge in B.C.?
    a) first provincial estimates of recharge for aquifers across B.C.
    b) comparison using two methods at different spatial scales for deriving recharge.
3. What is the contribution of groundwater to environmental flow needs (EFN) across B.C.?
    a) first provincial estimates of groundwater contribution to EFNs; and
    b) develop methods for estimating groundwater's contribution to EFN in data sparse regions.

2. BACKGROUND, THEORY AND DATA

Water stress studies provide a framework to understand the dynamics for evaluating changes in groundwater resources by directly comparing water availability to human water use (van Beek et al. 2011; Wada et al. 2011; Richey et al. 2015; Mehran et al. 2017). The Water Sustainability Act (WSA) was brought into force on February 29, 2016 to ensure a sustainable supply of fresh, clean water that meets the needs of B.C. today and in the future (Province of British Columbia 2016a). With the WSA, the strategy for protecting, managing and using water efficiently throughout the province has been modernized. For the first time in the province's history, groundwater is licensed for non-domestic use and anyone who diverts and uses groundwater for anything other than household use is required to obtain a water license and pay water fees and rentals. Quantifying aquifer stress is critical to support the sustainable development of aquifers in the province. Detailed scientific studies are often lengthy so a desktop method for quantifying aquifer stress at the regional scale provides a crucial placeholder until more detailed information on the development of aquifers becomes available.

It is commonly accepted that water stress can be defined by a ratio of water use to availability (Alcamo et al. 1997). Groundwater availability can be defined as the renewable water resource, whereas, use is the volume of water extracted form an aquifer.

$$Stress = \frac{Use}{Availability} \qquad \text{(Eq. 1)}$$

In an effort to quantify aquifer stress, the groundwater footprint provides an indication of area required to support known groundwater withdrawals and maintain environmental flow needs (Gleeson et al. 2012) (Figure 1). The groundwater footprint (GF) is defined as:

$$GF = \frac{C}{R - E} * A \qquad \text{(Eq. 2)}$$

where

GF is the area required to support known annual groundwater withdrawal and maintain environmental flows [L^2]

A is aquifer area [L^2]

C is area-averaged annual consumption of groundwater [$L^3 T^{-1}$]

R is annual recharge rate [$L^3 T^{-1}$]

E is the annual groundwater volume contribution to environmental streamflow [$L^3 T^{-1}$]

Groundwater consumption (C) is the "use" numerator and is defined as the volume of groundwater removed from an aquifer. Groundwater availability is represented as the difference between recharge (R), which represent the natural influx of groundwater into the aquifer, and groundwater's contribution to environmental flows (E), which is a proportion of natural discharge to streams in order to maintain high standards of hydrologic and ecological protection.

The GF was previously applied on a global-scale to major aquifers that are important to agriculture (Gleeson et al, 2012 - Figure 2). It has since been applied on various spatial scales in regions around the world (Gleeson and Wada 2013; Esnault et al. 2014; McDonald et al. 2014).

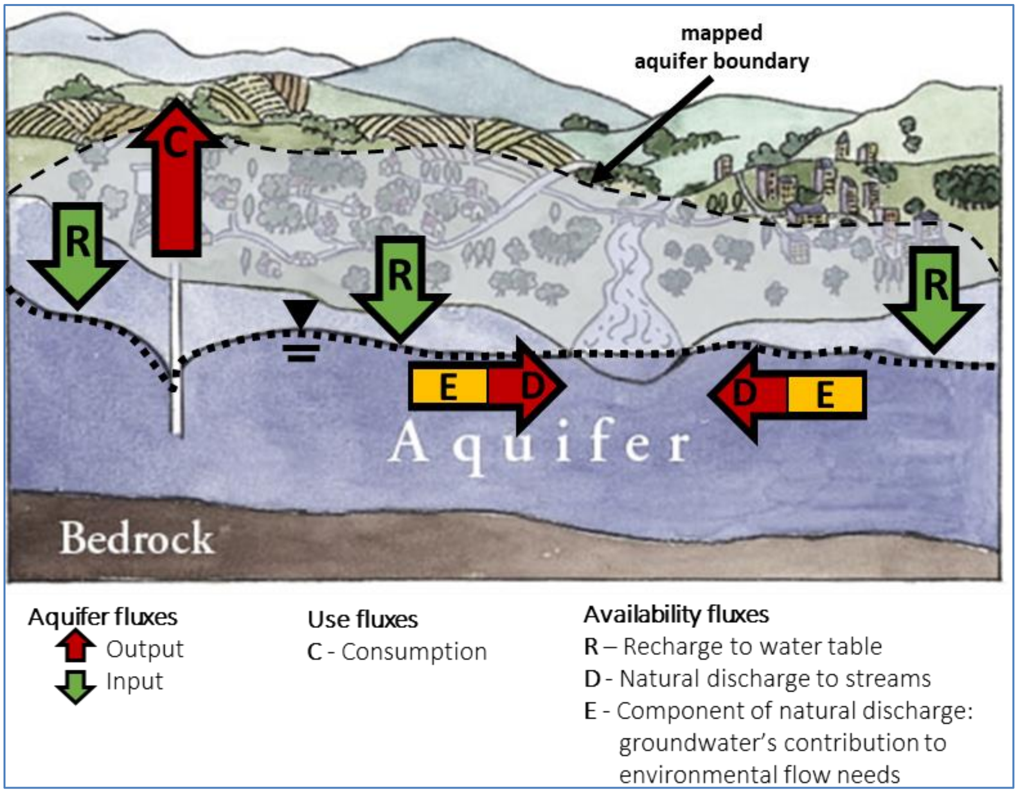

Figure 1: Conceptual model of fluxes for deriving the groundwater footprint (GF). The GF is based on the major annual aquifer fluxes of consumption from well withdrawal (C), recharge to the water table (R), and groundwater's contribution to environmental flows (E).

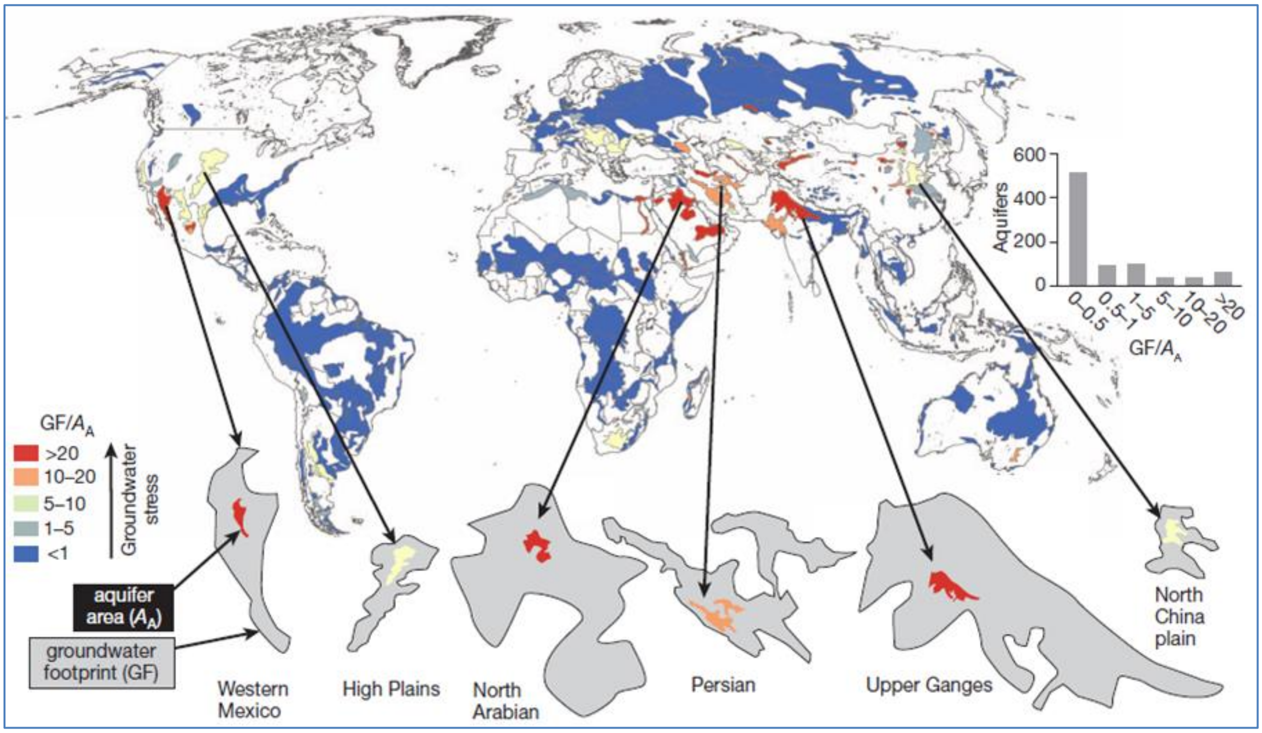

Figure 2: Groundwater footprint mapped for major aquifers. GF/A > 1 indicates aquifer stress. (Gleeson et al. 2012)

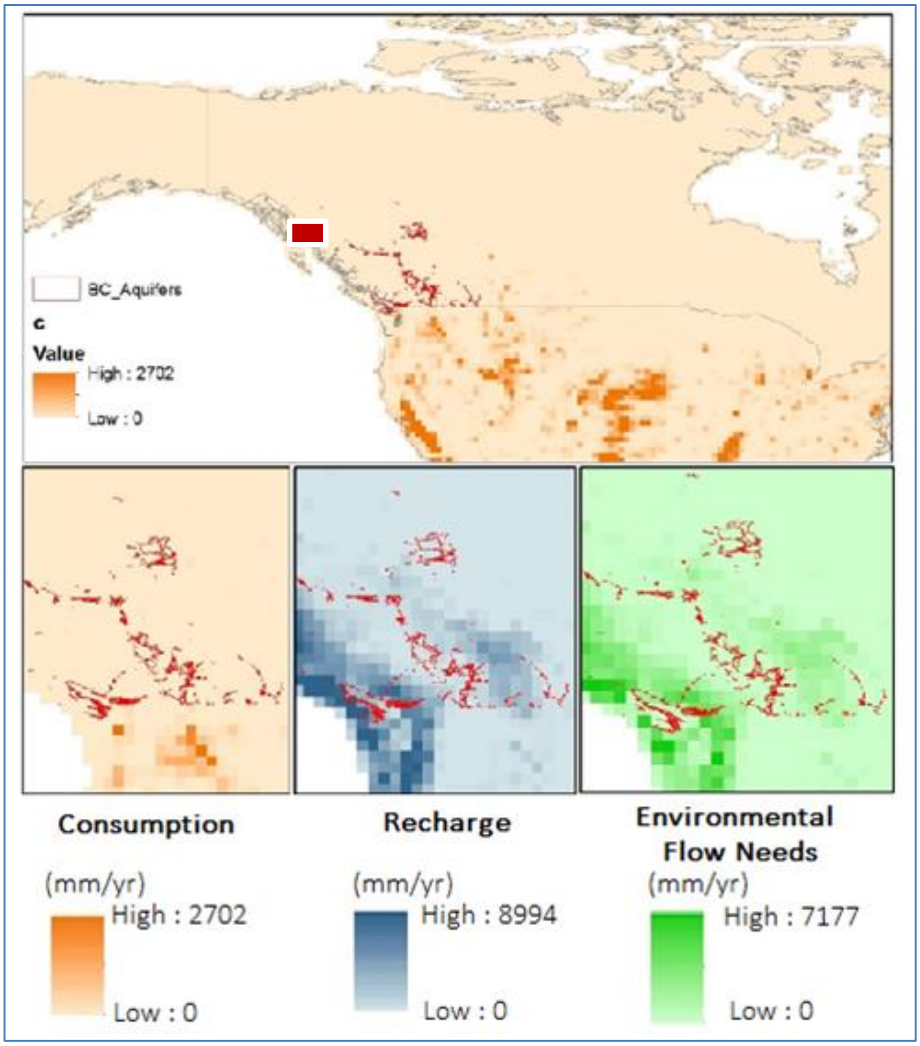

Figure 3: Global groundwater data for consumption, recharge and environmental streamflow. The current global groundwater consumption data indicates very low values for the province of B.C. However, based on national data, B.C. is a major groundwater user.

The GF was initially calculated for B.C. aquifers using globally available data to quantify aquifer stress on a global scale (Figure 3). The global groundwater consumption model was derived on national groundwater use data downscaled based on water consumption patterns (Wada et al. 2012), while recharge and environmental flows were based on a global hydrologic model, PCR-GLOBWB (PCRaster GLOBal Water Balance model) (Van Beek and Bierkens 2009). The global groundwater consumption data indicated zero consumption for B.C., likely because of the water use algorithm indicating that deriving local groundwater use data was essential for this study. By contrast to the global groundwater consumptive model, Environment and Climate Change Canada identifies B.C. as a major consumer of groundwater on a provincial scale highlighting the need for deriving the parameters of W, R, and E specifically for B.C. in order to make GF calculations. The complete methodologies, results and discussions of quantifying W, R, E and GF are included in the following sections of the report with a brief summary below.

Groundwater consumption (C) is commonly defined as the volume of groundwater removed from an aquifer; however, due to the lack of data on groundwater use in B.C., withdrawal (W) is used as a proxy for C in the equation to represent the availability in the GF calculation. National, regional, and local data was compiled to derive W from B.C. aquifers. W is derived based on the methodology in section 4.0, and represents a conservative approximation of groundwater use until additional data can be used to supplement or replace current derived sectoral groundwater volumes. An important differentiation between C and W in this study is that C represents the volume of water after return flows to an aquifer are accounted for from groundwater extracted volumes. For example, groundwater extracted for the purpose of irrigated agriculture is often in excess of the required amount and volumes of freshwater not consumed by the crops are returned to the aquifer. As data was unavailable to make consistent and scientifically sound approximation of C, W is used as a conservatively large approximation and accounts for the volume of groundwater removed from an aquifer via wells. Groundwater withdrawal is estimated for the domestic, municipal, commercial, industrial, agricultural, and finfish aquaculture sectors.

Recharge (R) represents the natural influx of groundwater into the aquifer. One of the main challenges with this component is that aquifers in B.C. represent a large spatial distribution and diverse climate. Although many local studies exist in populated areas of B.C. (Zebarth et al. 1998; Allen et al. 2004; Scibek and Allen 2006a; Denny et al. 2007), in order to analyze the magnitude of aquifers in the province and make a comparative analysis, two approaches are used to identify recharge. A hydrologic modelling software HELP - Hydrologic Evaluation of Landfill Performance (Schroeder et al. 1994) is used to determine aquifer scale estimates of natural recharge (R_{HELP}). A new 'generalized' methodology is derived in this study which assigns aquifers into biogeoclimatic zones, maps soil and aquifer types, and then simulates R with the HELP model as was done in the localized modelling studies. HELP is a one-dimensional, water balance software that simulates vertical infiltration through multiple soil and aquifer layers within the vadose zone, and internally calculates evapotranspiration and runoff that may contribute to overland flow. The second approach uses spatially downscaled estimates of R_{PCR} derived from PCR-GLOBWB. As HELP and PCR-GLOBWB only simulate the vertical percolation from precipitation, confined aquifers are excluded from the recharge analysis.

Two approaches are taken in the assessment of groundwater's contribution to environmental flows (E) using methods that can be replicated in data scarce regions. The first approach uses baseflow outputs from a MODFLOW groundwater model coupled to PCR-GLOBWB (De Graaf et al. 2015), to derive E_{PS} using the groundwater presumptive standard, which states that high levels of ecological protection are maintained if 90% of baseflow is preserved. The second uses a novel approach to quantify E_{LF} from groundwater-dominated monthly low streamflow outputs from PCR-GLOBWB and a modified application of the B.C. EFN Policy (Province of British Columbia 2016b). Confined aquifers are excluded from this analysis as methods are not applicable.

Four calculations of GF were made based on data from W, R_{HELP}, R_{PCR}, E_{PS}, and E_{LF} all reported in $m^3\ yr^{-1}$ for an aquifer area:

$$GF_1 = \frac{W}{R_{HELP} - E_{PS}} * A \tag{Eq. 3}$$

$$GF_2 = \frac{W}{R_{PCR} - E_{PS}} * A \tag{Eq. 4}$$

$$GF_3 = \frac{W}{R_{HELP} - E_{LF}} * A \tag{Eq. 5}$$

$$GF_4 = \frac{W}{R_{PCR} - E_{LF}} * A \tag{Eq. 6}$$

where

$GF_{1\text{-}4}$	is the groundwater footprint derived with different combinations of input data $[L^2]$
W	is annual volume of groundwater use $[L^3\ T^{-1}]$
R_{HELP}	is annual volume of recharge modelled by HELP $[L^3\ T^{-1}]$
R_{PCR}	is annual volume of recharge modelled by PCR-GLOBWB $[L^3\ T^{-1}]$
E_{PS}	is annual volume of groundwater's contribution to environmental flows derived based on the groundwater presumptive standard $[L^3\ T^{-1}]$
E_{LF}	is annual volume of groundwater's contribution to environmental flows derived based on the Low Flows approach $[L^3\ T^{-1}]$
A	is aquifer area $[L^2]$.

2.1 Data used for Multiple Parameters

Data that is used for individual parameters such as W, R, or E is introduced in following sections; herein we introduce data used for multiple parameters.

A map-based aquifer classification system was developed by the Ministry of Environment, Lands and Parks (Berardinucci and Ronneseth 2002). To date, 1130 aquifers have been classified and added to a provincial inventory using this system as a means to prioritize aquifer planning, management and protection (Figure 4; Table 1). "UNK" aquifers are classified as unconsolidated unconfined (68/88) or bedrock (20/88) based on the aquifer material. Unconsolidated aquifers (703/1130) are classified as unconfined, Type 1-4a (316/703), or confined, Subtype 4b and 4c (387/703); however, bedrock aquifers (339/1130) lack this classification of confinement. For the purpose of this study, unconfined bedrock aquifers are determined based on a "High" vulnerability rating (68/339). Some aquifers (88/1130) are classified as "UNK", in which case, if the vulnerability rating is "High", aquifers are assumed unconfined (20/88). This resulted in 404 aquifers being considered unconfined in this study.

Table 1: Classification of unconfined and confined aquifers.

	Unconsolidated	**Bedrock**	**Unknown**		**Total**
B.C. aquifer types	1a, 1b, 1c, 2, 3, 4a, 4b, 4c	5a, 5b, 6a, 6b	UNK		
B.C. aquifer material	Sand and/or Gravel	Bedrock	Sand and/or Gravel	Bedrock	
Unconfined	316	68	18	2	404
Confined	387	271	50	18	726
Total	703	339	68	20	1130

Biogeoclimatic zone (BGCZ) data was extracted from a Microsoft Suite Access database contributed by Will MacKenzie, Provincial Research Ecologist from the B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development (MFLNRORD) based on ClimateBC version 5.10 with updated PRISM data (Figure 5). Within B.C., 82% of all mapped aquifers (924/1130) and 85% of unconfined aquifers are completely within a single BGCZ (Table 2). Only 3% of aquifers (30/1130) fall within more than two BGCZs, and aquifers that are not entirely within one BGCZ are generally spatially dominated (>50% coverage) by a single zone (1127/1130). Therefore, it seems reasonable to represent each aquifer as a single BGCZ - the spatially dominant BGCZ for aquifers with multiple BGCZs. In total there are 14 defined BGCZs across B.C.; however, only 11 contain mapped aquifers.

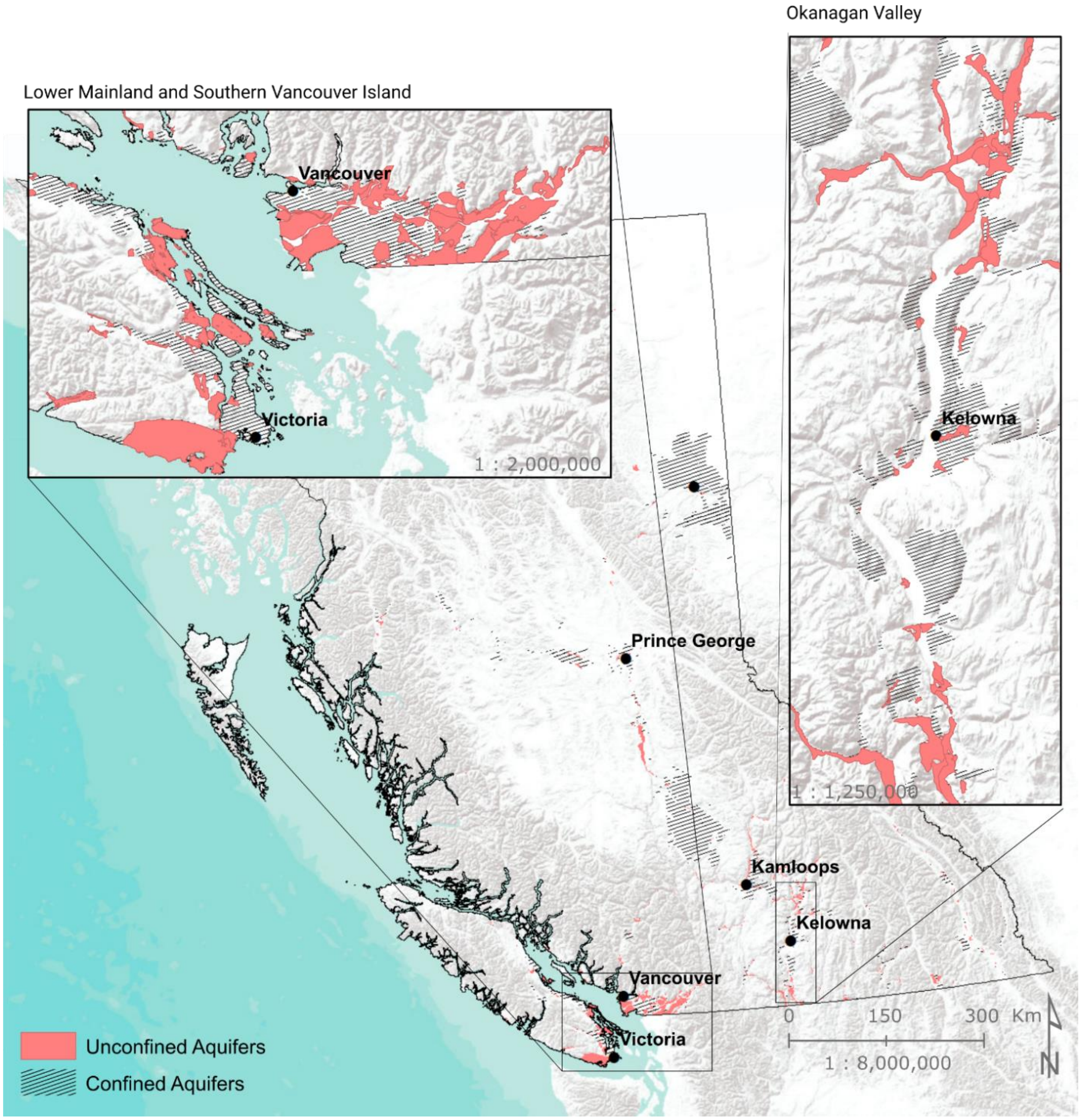

Figure 4: Status of mapped aquifers in B.C. (Dec. 2017).

PCR-GLOBWB is a large scale global hydrologic model developed at the Department of Physical Geography, Utrecht University (Netherlands) and has been used in several high impact global studies (Bierkens and Van Beek 2009; Wada et al. 2010, 2013; Gleeson et al. 2012; De Graaf et al. 2014). PCR-GLOBWB provides a grid-based representation of terrestrial hydrology with a typical spatial resolution of approximately 10x10 km in B.C. PCR-GLOBWB is similar to other large hydrologic models in that it is essentially a leaky bucket type model, but a certain consideration is given representing the groundwater reservoir (Figure 6). PCR-GLOBWB is forced with CRU TS 2.1 data set (New et al. 1999, 2000). For a full description of the conceptualization and parameterization of the model refer to Van Beek and Bierkens (2009), and for results on how modelled discharge and runoff compares to global observation see van Beek L. P. H. et al. (2011).

Table 2: Spatial join of BGCZs and aquifers. Aquifer areal coverage describes the percent of aquifer area within a BGCZ.

Biogeoclimatic Zone (BGCZ)	Abbr.	Aquifer count	Aquifer areal coverage		
			>80%	50-80%	<50%
Bunchgrass	BG	39	31	6	2
Ponderosa Pine	PP	79	61	18	-
Interior Douglas-fir	IDF	258	225	32	1
Sub-Boreal Pine—Spruce	SBPS	3	3	-	-
Sub-Boreal Spruce	SBS	142	139	3	-
Montane Spruce	MS	24	18	6	-
Boreal White and Black Spruce	BWBS	59	59	-	-
Interior Cedar—Hemlock	ICH	91	89	2	-
Coastal Douglas-fir	CDF	142	125	17	-
Engelmann Spruce—Subalpine Fir	ESSF	1	1	-	-
Coastal Western Hemlock	CWH	292	278	13	1
TOTAL		1130	1029	97	4

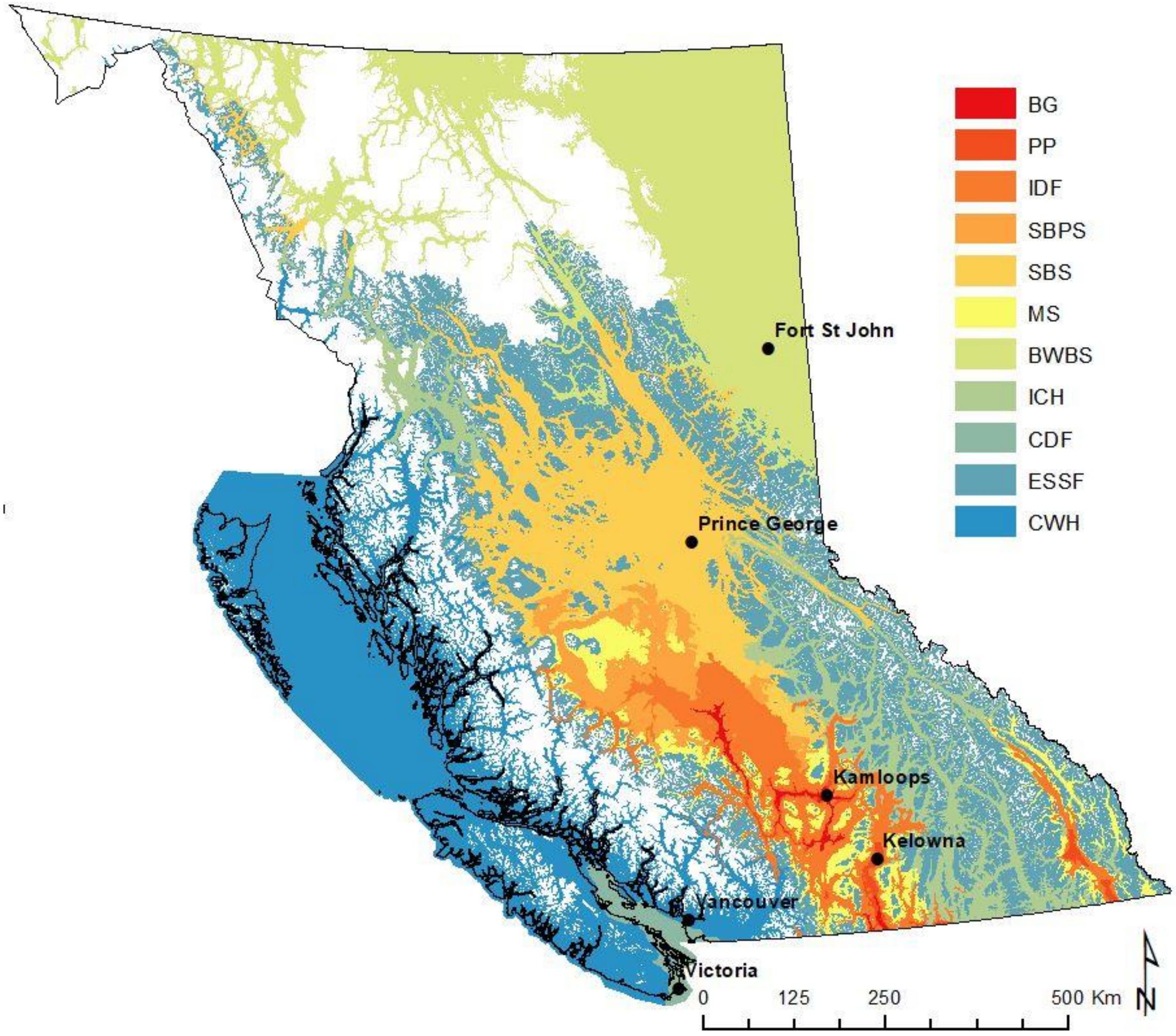

Figure 5: Biogeoclimatic zones overlapping aquifers in of British Columbia.

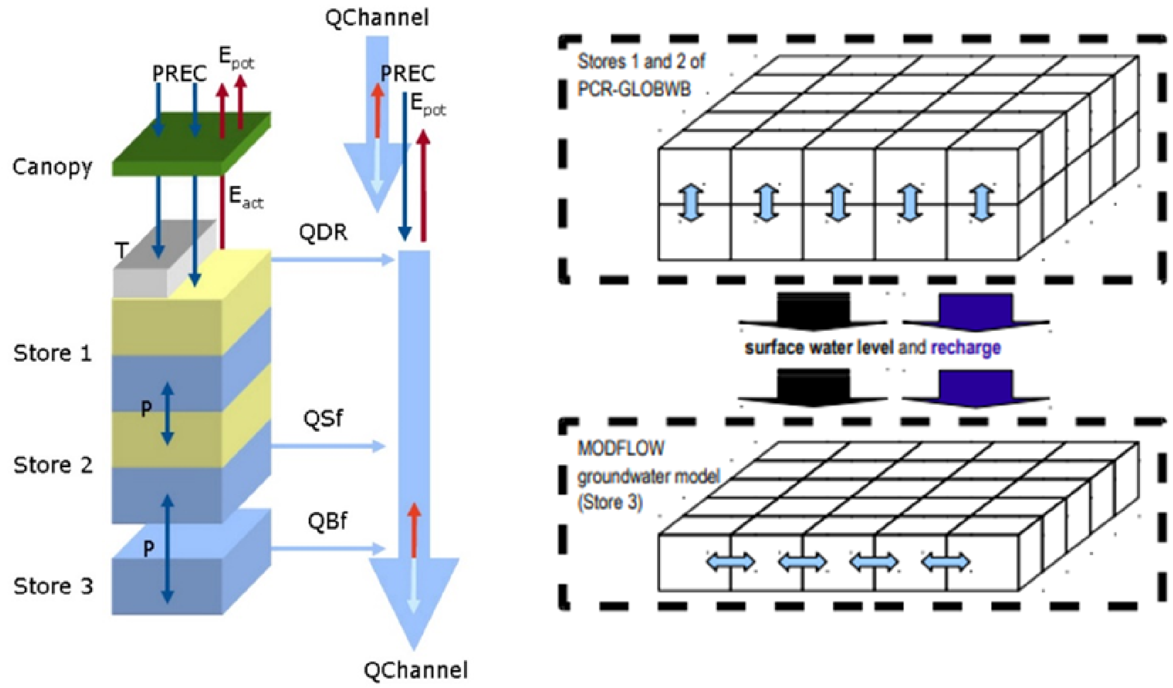

Figure 6: Conceptual model of PCR-GLOBWB. Store 1 and 2 represent soil compartments, whereas, store 3 represents the MODFLOW groundwater model. The total local gains (QDR, QSf, QBf) are routed along the local drainage direction to yield channel discharge (QChannel). Precipitation (PREC); potential evapotranspiration (Epot); actual evapotranspiration (Eact); snowpack (T); direct runoff (QDR); interflow (QSf); baseflow (Qbf); percolation (P). (right) The modelling strategy used to couple PCR-GLOBWB and MODFLOW. (Van Beek and Bierkens 2009; De Graaf et al. 2015)

Using process-based equations to compute moisture storage in two vertically stacked soil layers, the water exchanged between the soil and the atmosphere and the underlying groundwater reservoir can be seen in the conceptual model in Figure 6. Over each grid cell, precipitation (PREC) falls in the form of rain or snow, and based on temperature, can be stored in the snowpack (T) or melt added to the net liquid precipitation. Excess water from snowmelt or rainfall forms direct runoff (Q_{DR}) or infiltrates into the first soil layer (Store 1) if water storage is available. Percolation into the second soil layer (Store 2) and third groundwater reservoir (Store 3) are driven by effective degree of saturation in both layers. Simulated local direct runoff (Q_{DR}), interflow(Q_{Sf}), and baseflow(Q_{bf}) are routed along the river network based on the Simulated Topological Networks (Vörösmarty et al. 2000).

Recharge is the flux between Store 2 to 3, where the coupled MODFLOW groundwater model (run at a 6 ft. resolution) is used to simulate an equilibrium water table based on long-term climatic forcing. Aquifer properties are based on two data sets: (1) high resolution global lithology map (GLiM) of Hartmann and Moosdorf (2012), and (2) the global permeability estimates from Gleeson et al. (2011). Transmissivity data were estimated from derived aquifer thicknesses. Simulated groundwater heads were compared to peizometer observations, where the model best performs in large sedimentary basins, and groundwater depths are often overestimated compared to observations in higher steeper terrain. A few major limitations of the model: (1) model simulates a natural dynamic steady-state, (2) model contains only one single layer, whereas in reality likely many unconsolidated or consolidated layers, (3) capillary rise of the water table into the soil layer has not yet been implemented, and (4) no dynamic interaction between grondwater and surface water, as the drainage level of rivers does not change over time. For full details of the groundwater model see, De Graaf et al. (2015).

Spatially distributed estimates of baseflow were derived using a MODFLOW groundwater model (De Graaf et al. 2015) built at a 6 ft. resolution which is coupled with PCR-GLOBWB which outputs values at a resolution of 10x10km^2. The model uses MODFLOW river and drain packages to incorporate interactions between groundwater bodies and surface water. For large rivers (width >10m), interactions are governed by actual groundwater heads and surface water levels, and estimated with the RIV package in MODFLOW. To simulate small rivers (width <10m), the DRN package was used. Water can only leave the groundwater system through the drain when head rises above the drainage level which is taken equal to the surface elevation.

Sub grid variability is taken into account as follows:

- fraction of cell covered with short and tall vegetation;
- fraction covered with freshwater, being either a river, lake or reservoir;
- fraction glaciers;
- sub-grid elevation distribution determining the accumulation and melt rate of snow and ice as well as fraction of the river plain flooded (optional);
- soil type distribution and its effect on soil hydrological properties; and
- distribution of water-holding capacity of the soil resulting in variable saturation excess overland flow [Improved Arno Scheme, 2] as a result of variations in soil depth, effective porosity and elevation distribution.

3. WITHDRAWAL

3.1 Background

Several issues arise in deriving spatially distributed groundwater consumptive data for the province of B.C. The primary challenge in this study is the historical lack of reporting standards for groundwater consumption in the province mainly due to lack of provincial legislation under the Water Act. Most data on groundwater in B.C. is disseminated across many sources, and the data is often reported on a range of scales from municipal-scale data to single provincial values which require a secondary proxy in order to spatially distribute and downscale the volumes of groundwater consumed.

Groundwater and surface water are the primary sources of freshwater which are withdrawn and supplied to the population via water distribution systems (WDS) or self-supplied via private wells or diverted from streams. Major sectors were identified as domestic, commercial, industrial, irrigated agriculture, and finfish aquaculture based on previous classification of reported data (Hess 1986) and for ease of future comparison with other provincial values (Figure 7).

Municipal water distribution systems (MWDS) supply either groundwater, surface water or both sources to all major sectoral users connected to a network. As volumes reported for MWDS are rarely partitioned by sector, MWDS groundwater use accounts for its own section in this report. Self-supplied users obtain their own groundwater from private wells. Self-supplied commercial users were not included in this study as for a lack of data, although most major commercial users would be located in municipalities, and therefore volumes likely included in the MWDS users.

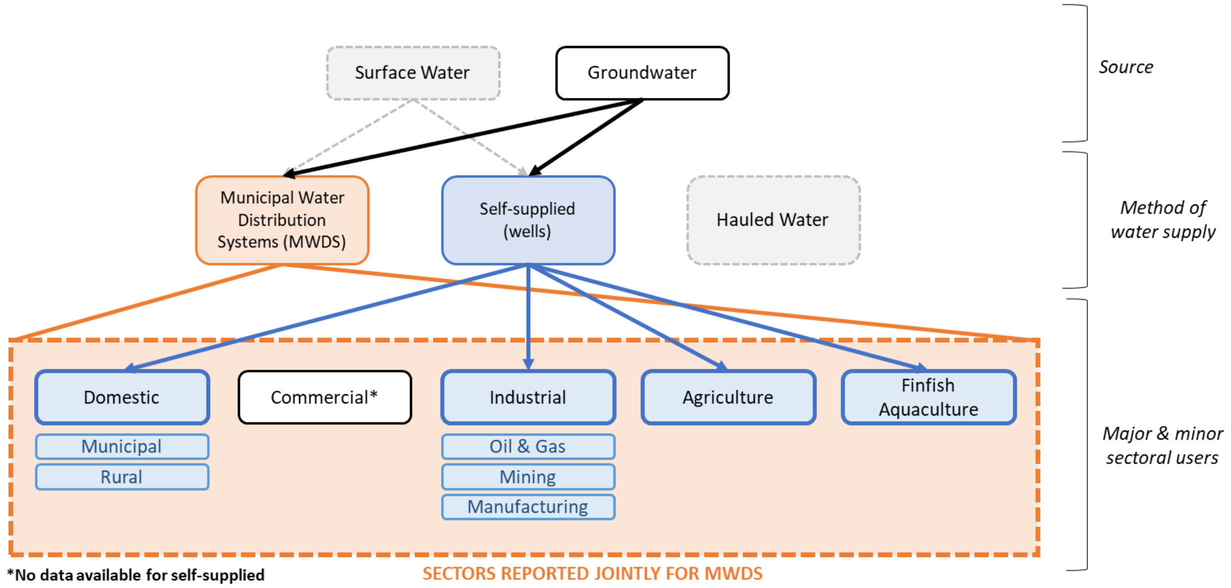

Figure 7: Classification scheme of source water, method of water supply, and the major sectoral users determined for the purpose of this study. Dashed boxes indicate sources or water supply methods not considered in this study. The domestic and commercial annual groundwater volumes are derived jointly analogous to provincial and national data sources.

3.2 Water Use Terminology

In 2016, B.C. modernized the previous Water Act, replacing it with the Water Sustainability Act (WSA). The definitions in this study differ from those found in the WSA, mainly in the water use and purposes terminology (Table 3). Where the WSA provides a more comprehensive list of water use purposes, this study classifies water use based on major sectors of use. This is done in part because most groundwater use data is collected by national surveys which have different classification schemes. Groundwater use is first classified based on method of distribution via either water distribution systems or self-supplied via private wells, and secondly via major sectors of use in B.C. namely, domestic, commercial, industrial, irrigated agriculture, and finfish agriculture. The purpose for this classification scheme is established so as to more readily make comparisons with previous studies and value obtained for other province.

Table 3. Comparison of groundwater use purposes as defined in this study and in the Water Sustainability Act. The major sectors of use defined in this study reflect the reporting of national surveys. This table highlights the water use purposes as defined by the WSA.

Major Sectors of Use	WSA water use purposes*
Municipal water distribution systems	Waterworks
Domestic	Domestic
Industrial	Industrial, Mining, Oil and Gas
Agriculture	Irrigation
Finfish aquaculture	Industrial, Conservation

* WSA Water Use Purposes not included this analysis included Land Improvement, Power, and Storage.

3.3 Data Sources

Water use data was collected from national and provincial surveys reporting on volumes, and a water use model. Spatial data consists of geographic information with or without accompanying annual groundwater volumetric data. National and provincial surveys are included as they are often the only sources of reported annual groundwater volumes. Water use models are used to calculate agricultural irrigation volume.

With the majority of volumetric data reported on national-scales, values are downscaled subjectively based on well locations, business locations, and populations. For example, Figure 8 illustrates how the volumetric data obtained from Statistics Canada, from sources such as the Agricultural Water Survey or the Industrial Water Survey, are categorized as national and provincial scale data as the values encompass the entire province, as opposed to reporting values per municipality or a finer point-scale resolution.

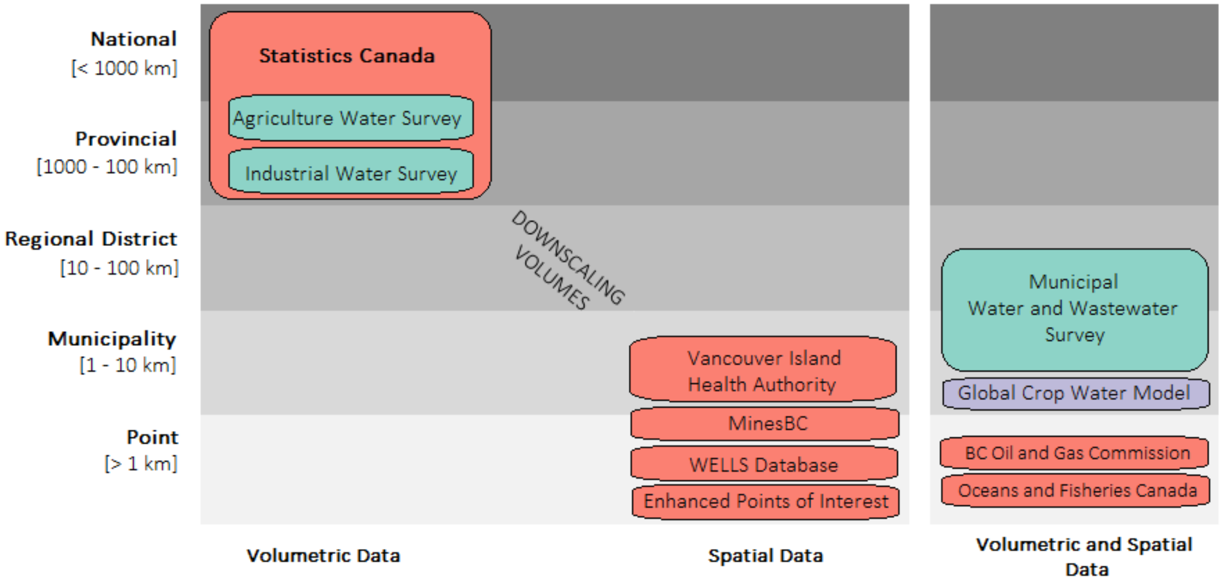

Figure 8: Scales of data. The majority of volumetric data is reported on the national and provincial scale. Spatial data on the scale of regional district, municipal, and point scale is used to downscale volumetric values.

3.3.1 Spatial Data

WELLS Database

The WELLS Database, managed by the MENV, is a publically accessible catalogue of all recorded water wells in the province. The well records include a unique record ID (well tag number), well location, well yield, driller reports and remarks, and water use (Figure 9). The submission of water well information was historically voluntary, and although the catalogue is populated with over 105,000 wells, many records are incomplete and existing wells remain unrecorded, and at least 50% are not paired to mapped aquifers (at the time of this study).

Well records include a "water use" categorization. This designation is based on the information supplied to the province. The categorization water use categories include:

- Private Domestic: single or multi-household wells for private supply; and
- Water Supply System: campgrounds, private or public water supply wells for municipalities; and
- Commercial & Industrial: manufacturing, quarrying, mining, oil and gas industries; and
- Irrigation: crop irrigation for farming.

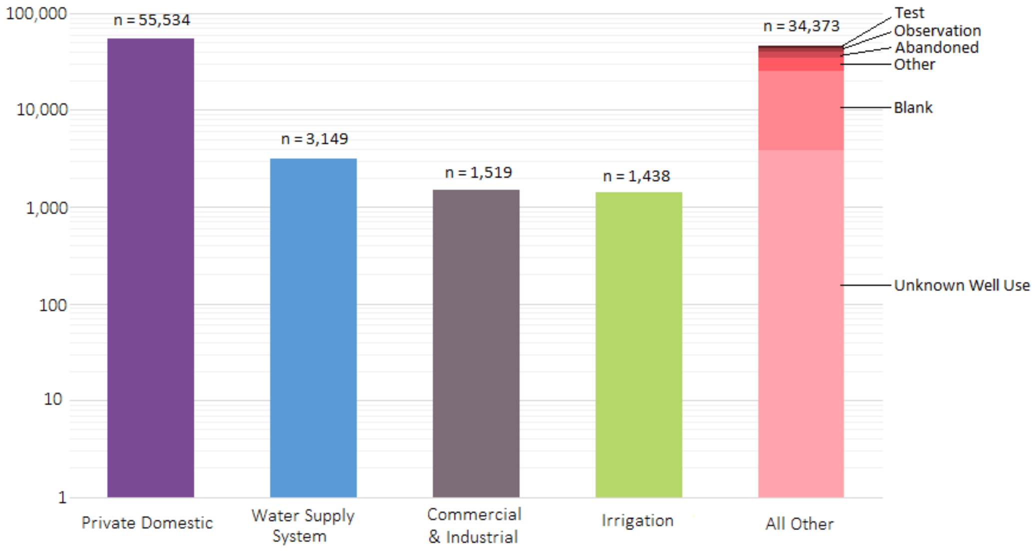

Figure 9: Distribution of "well use" in the WELLS Database. The graph above shows the classification of wells based on the purpose of the abstracted water use and the number of wells in each classification on a log scale.

Enhanced Points of Interest

The CanMap Suite 2015 (DMTI Spatial Inc. 2015) is a national database of over 1 million Canadian businesses and recreational points of interests. The most recent Enhanced Points of Interest (EPOI) file for 2015 contains over 100 unique layers of data across Canada. The important features include the location coordinates, standard industry classification codes (SIC), North American Industry Classification System (NAICS) codes, and business names and addresses.

DataBC

The B.C. government manages DataBC, providing easy access to the government's geospatial data holdings, as well as applications and web services. The municipalities, regional districts, and provincial shapefiles were downloaded from the DataBC Catalogue.

3.3.2 National Survey Data

Agricultural Water Survey

The Agricultural Water Survey (AWS) of 2014 (Statistics Canada, n.d.) was conducted to gather information on irrigation use, methods and practices, sources, and quality of water used for irrigation. This voluntary sample survey targeted populations of farms that use irrigation. Irrigation volumes are reported for April-May (combined), June, July, August, and September-October (combined), with the annual volume reported as the sum of irrigation volume for these periods. Irrigated area or volumes data are imputed using an automated nearest neighbor approach, for further details please see federal documentation of the Agricultural Water Survey. The total sample size was 2,486 farms.

Groups not included in this survey include:

- farms with sales less than $10,000;
- all institutional farms (government farms, university and prison farms);
- all units which reported nursery, sod, greenhouse, mushroom or Christmas tree operations on the last census;
- all units that belong to Statistics Canada's Large Agricultural Operations Statistics program;
- all units for which the 2011 Census of Agriculture irrigation data was completely imputed;

- all units which reported only irrigation area in the "Other" category on the last Census of Agriculture and did not report owning any irrigation equipment; and
- all (units) in the seven most northern of Canada's 25 drainage regions: Yukon (5), Peace-Athabasca (6), Lower Mackenzie (7), Arctic Coast-Islands (8), Keewatin-Southern Baffin Island (16), Northern Ontario (17) and Northern Quebec (18).

Industrial Water Survey

The Industrial Water Survey (IWS) of 2013 (Statistics Canada, n.d.) is a biennial survey conducted to gather information about the intake, costs, sources, treatments, and discharge of water used. The target population consists of locations primarily involved in manufacturing, coal mining, metal ore mining (excluding sand and gravel quarrying), and thermal-electric power production (fossil-fuel and nuclear electric power generation).

The survey was completed using different sampling strategies for each of the three industries:

- thermal-electric power plants: all 128 thermal electric power plants were included;
- mining: some industries, identified as large consumers of water were selected with certainty; and 378 of 869 mining locations were sampled; and
- manufacturing: some industries, identified as large consumers of water, were selected with certainty. 5037 of 123,397 manufacturing locations were sampled.

Municipal Water and Wastewater Survey

Environment Canada’s Municipal Water and Wastewater Survey (MWWS) (Environment Canada 2011) which reports on 2009 use statistics is a national survey conducted to gather information for provincial populations on water distribution systems, water use per capita, usage of water meters, water sources, water use by sector, and wastewater treatment levels. Water supply systems provide water to homes and businesses, as well as some industrial and agricultural operations that are connected to a WDS. The MWWS was sent out to all municipalities in Canada with a population greater than 1000, and to a sample of those municipalities under 1000, except municipalities on federal lands and First Nations. Initial survey responses were supplemented with call-backs and internet searches for readily available information. Some missing records were imputed from previous census years where information was available. A responding population is recorded for all statistics, and no statistical extrapolation techniques were used by Environment Canada. The population estimates for each municipality are based on Statistics Canada’s population estimates for census subdivisions on July 1, 2009.

The MWWS reports MWDS annual water consumption volumes and aggregates all volumes into allocation sectors. Below are the definitions used by this survey of allocation sectors:

- domestic: water used by residential sector (single family and multi-family homes); and
- commercial: commercial, institutional, and municipal sector (firefighting, street cleaning, park watering, etc.); and
- industrial: industrial (ex. manufacturing) and agricultural sector; and
- unaccounted: leakage, system flushing, unknown.

3.3.3 Water Use Models

Agricultural Water Demand Model

The Agricultural Water Demand Model (AWDM) was originally developed by the B.C. Ministry of Agriculture to predict water requirements for lands reserved for agriculture in the Okanagan, B.C. The model has been extended to include the Regional District of Central Kootenay, City of Kamloops, Fraser

Valley, Comox Valley Regional District, Bonaparte watershed, Kettle watershed, Nicola watershed, Similkameen watershed, Metro Vancouver, Cowichan Valley Regional District, Regional District of Nanaimo, North Thompson, Okanagan Basin, and Salt Spring Island. The model provides current and future estimates of water demand by calculating and field verifying water use on a property by property basis. Groundwater is assigned when no surface water licences exist on the property and there are no obvious surface water sources. Crop irrigation system type, soil type and climate data are used to calculate water demand. For the purpose of this study, groundwater volumes are derived from crop irrigation. Crops included in this model are categorized into the following crop groups: alfalfa, apple, berry, cherry, domestic outdoor, forage, fruit, and golf.

Global Crop Water Model

The Global Crop Water Model (GCWM) was developed to simulate consumptive crop water use and crop yields in rain-fed and irrigated agriculture (Siebert and Döll 2008). This dataset is based on the global land use data set MIRCA2000 (Portmann et al. 2010) which provides monthly growing patterns for 26 crop classes under rain-fed and irrigated conditions for the period of 1998-2002. By computing daily soil water balance, crop water use is partitioned into evapotranspiration stemming from irrigation or precipitation water for each crop and grid cell. The model has a spatial resolution of roughly 10 x 10 km^2 (5 arc minute) and considers 26 different crop classes for water consumption.

3.4 Groundwater Use by Sector

The following sections outline the data sources and methodology for deriving the spatially distributed annual abstracted volumes of groundwater in B.C. The volumes are calculated per major sector due to the various methodologies applied and the nature of the data sources readily available per sector.

3.4.1 Volume Attribution to Aquifers

Volume attribution to aquifers used a combination of wells and locations/facilities identified from NAICS where no specific well was identified.

The WELLS database currently stores aquifers as two dimensional entities; therefore, vertical interpretations of aquifer depths cannot be queried. Approximately, half of WELLS database wells have not been correlated to a particular aquifer unit. Where aquifers are vertically stratified, extractions in one aquifer may impact availability in underlying or overlapping units. The WELLS database cannot be queried for hydraulic connectivity between units; however, hydraulic connectivity between vertically stratified units is possible.

Volume attribution is done based on a few approaches based on availability of data. Groundwater volumes are derived and associated to a number of features namely either, (a) reported wells; (b) NAICS location; (c) directly to the reported aquifer, or (d) based on spatial coverage of model data. It is important to understand which method was used based on which sector dominates groundwater use.

When a volume is associated with a well, method of aquifer attribution is based on the following priorities:

1. Reported aquifer number associated with well.
2. If well only overlies one aquifer, volume is attributed to be diverting from this aquifer.
3. If well overlies overlapping aquifers and no aquifer number is reported with well, aquifer material reported with well is used to correlated which aquifer is associated with the well. For example, a well reporting an aquifer material of “Sand and Gravel” and then classified as “Unconsolidated” and volume is only attributed to overlapping unconsolidated aquifers. Where volumes are attributed to several aquifers, the volume is equally divided.

When a volume is associated with a location, such as with NAICS data or model output, the volume is equally attributed to each overlapping aquifer underlying the location (Figure 10). In reality, most often abstraction is likely focused in shallow aquifers but the current state of the provincial database precludes improving this methodology. Where aquifers are overlapping, volume attribution is more uncertain for non-stacked aquifers, assuming wells are diverting from mapped aquifers (Figure 11).

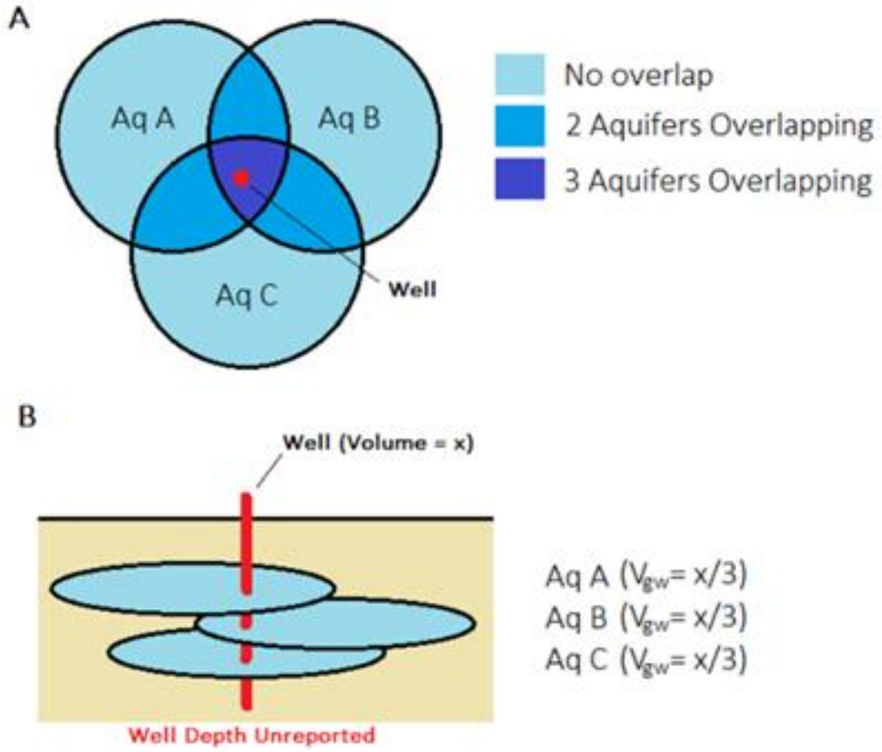

Figure 10: Methodology of assigning volume to an aquifer. a) Map view of a boundary containing a well (red), with overlapping several aquifers as seen in (b). b) Profile of overlapping aquifers showing Aquifer A is overlapping two other aquifers, B and C. The groundwater volume for the well (red) is then divided equally between all three aquifers since the aquifer being tapped is inconclusive based on the depth of the well.

3.4.2 Municipal Water Distribution Systems

Municipal water distribution system (MWDS) sector includes all users connected to a water distribution system operated by a municipality (see definition in glossary). Water facilities not operated by a municipal jurisdiction (ex. private water purveyors) are not included in this analysis for lack of readily available data.

MWDSs supply water to all major sectors: domestic, commercial, industrial, agriculture, and aquaculture. MWDSs are a key component of calculating groundwater use as they often supply large volumes of groundwater to meet the demands of municipal populations. These demands are often met from a limited number of high yield wells concentrating large volumes of withdrawal to few aquifers, as opposed to smaller volumes withdrawing from many wells over a distributed region, distributing the volumetric burden to many aquifers. Larger water distribution systems (Multi-MWDS) exist in B.C., such as the Metro Vancouver water supply system which distributes treated surface water wholesale to member municipalities. The larger MWDSs included in this study are the Greater Vancouver Water District, Greater Victoria Water Supply Systems, Comox Valley Regional District, Greater Vernon Water, and Regional District of Nanaimo.

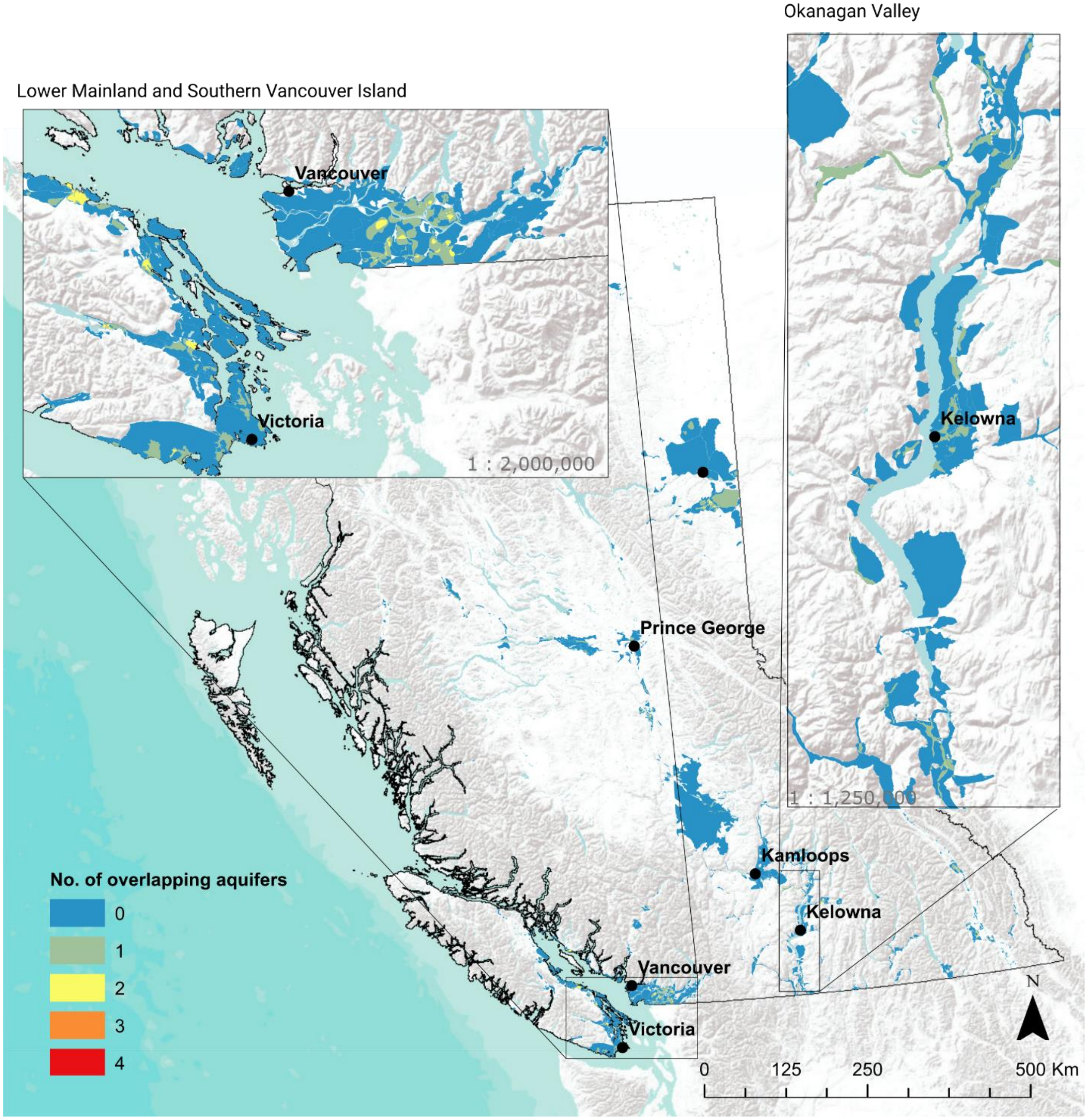

Figure 11: Map illustrating areas where overlapping aquifers exist.

The data sources used to determine MWDS groundwater use for this sector are the WELLS Database, MWWS (2011), DataBC and municipal surface water licenses. The WELLS database is used to determine location of municipal wells. The MWWS reports on percent population serviced water from a MWDS, percent population on wells, percent population on hauled water, annual volume distributed and percent population sourced water from a groundwater source. DataBC provided spatial files of municipalities, regional districts, and population statistics. Populations were taken from DataBC as the most accurate and representative of all municipalities included, whereas MWWS only provides data on municipalities included on the survey. The surface water license data is open-access and data was collected on existing municipal water licenses (as of July 18, 2017).

Methods

159 municipalities (n = 161) were analyzed in this study, excluding Jumbo Glacier and Sun Peaks due to negligible populations (<10). The following includes the steps in deriving annual groundwater volume withdrawn for the purpose of distributing to MWDSs:

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

Municipality data was collected from DataBC with population statistics from 2009 to correspond with the MWWS 2009 data set. The MWWS provides disparate sample data for 134 municipalities, with the remaining municipalities consolidated by regional district. If a municipality was not included in the MWWS, data from the regional district is used to infer percent population serviced by MWDS, wells, and hauled water, and the ratio of groundwater sourced for MWDS.

Population serviced by MWDS is derived for each municipality:

$$P_{MWDS} = p_{MWDS} \cdot P_{mun} \quad \text{(Eq. 7)}$$

where:

P_{MWDS} is population serviced by MWDS
P_{mun} is municipal population
p_{MWDS} is percent population serviced MWDS

If no data is reported on p_{MWDS}, the presence of existing municipal groundwater wells, reported MWDS volumes, existing municipal surface water licenses, or if the municipality is a member of a larger MWDS is taken as evidence of a municipal water system. Municipalities are then assumed to support 100% of the population with a MWDS. If no data exists for this municipality, manual investigation determined if this municipality operates a water supply system. No easily accessible data were available for nine municipalities, and therefore, manual investigations were completed for Bowen Island, Chase, Fort St. James, New Hazelton, Salmon Arm, Sechelt, Sicamous, West Kelowna, and Williams Lake.

The MWWS reports on total annual volume of water supplied by the MWDS, the total volume of groundwater sourced and the percent of population serviced MWDS water from a groundwater source.

Where total volume of groundwater sourced is not reported, percent of population serviced groundwater and population serviced by MWDS is used to derive total volume of groundwater for each municipality:

$$V_{GW,MWDS} = p_{GW,MWDS} \cdot P_{MWDS} \quad \text{(Eq. 8)}$$

where:

$V_{GW,MWDS}$ is total volume of groundwater serviced through a MWDS
$p_{GW,MWDS}$ is percent of population serviced MWDS from a groundwater source

If $p_{GW,MWDS}$ is unreported, surface water licenses are used to constrain the municipal volume of groundwater. Surface water licenses managed by the municipality are queried through the B.C. government data catalogue. The “Purpose of Use” variable is selected as “Waterworks: Local Provider” and the municipality is searched under the variable “Client Name”. The “Quantity” variable indicates the maximum allowable withdrawal volume in m^3 yr^{-1}. As many municipalities have several surface water licenses, the total annual volume of surface water ($V_{SW,MWDS}$) is derived by summing all surface water license volume allocations per municipality. Groundwater volumes can then be inferred to supplement the surface water allocations in order to meet the municipal need. As surface water allocations over represent actual surface water use, groundwater volumes derived by this method are underestimated.

For each municipality where $p_{GW,MWDS}$ is unreported, total volume of groundwater serviced through a MWDS is derived by:

$$V_{GW,MWDS} = V_T - V_{SW,MWDS} \qquad \text{(Eq. 9)}$$

where:

V_T is total volume used by a MWDS

$V_{SW,MWDS}$ is total volume of surface water license allocations for a municipality

For municipalities with unreported groundwater or surface water apportionment data, $p_{GW,MWDS}$ is assumed to be 100% as a conservative groundwater estimate, and $V_{GW,MWDS}$ can be calculated from equation 3. There were 53 municipalities, representing a reported population of 870,000, which were conservatively assumed to be 100% supported by groundwater.

Data on groundwater volumes withdrawn from specific wells is not readily available. Therefore, the WELLS Database is used to spatially distribute the groundwater volumes derived in the previous section. As the WELLS Database is comprised of voluntary well records, often multiple variables must be used to determine a specific wells purpose.

In the case of municipal groundwater volumes, the WELLS Database is 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”. The $V_{GW,MWDS}$ for the municipality is then equally distributed to the remaining list of wells. If the well query returns no results, a manual investigation is done to distribute the spatial location of groundwater use. Manual investigations were done for 11 municipalities (Bowen Island, Chase, Fort St. James, New Hazelton, Salmon Arm, Sechelt, Sicamous, West Kelowna, White Rock, Williams Lake, and Vernon).

Results

The MWWS provided data for 134 municipalities and 29 regional districts. Of the 161 municipalities in B.C., 25 municipalities were not included in the MWWS, in which case, regional districts data was used to infer percent population serviced by a MWDS or percent population serviced MWDS from a groundwater source. In addition, Fort St. James (280,000 m^3), New Hazelton (12,000 m^3), Sechelt (1,600,000 m^3), West Kelowna (2,900,000 m^3), and Vernon (550,000 m^3) groundwater volumes of MWDS were not included in the mapped results, as no municipal water supply wells were found within the municipal boundaries. The municipalities not included in the mapped results represent 6% of total provincial groundwater volume from MWDS, and 16% of the provincial population supported by MWDS sourced from groundwater. Appendix B contains resultant MWDS water sources and groundwater use volumes per municipality. The total annual groundwater volume used for MWDS sector is 84 Mm^3, of which 77 Mm^3 (94%) is attributed to municipal wells, and 74 Mm^3 (89%) is associated to mapped aquifers. Groundwater sourced for the purpose of MWDSs supports ~12% of B.C.’s municipal population.

Groundwater withdrawal volumes are concentrated in the municipalities of (1) Prince George (18Mm^3 yr^{-1}), (2) Chilliwack (11 M m^3 yr^{-1}), and (3) Williams Lake (4 Mm^3 yr^{-1}) and the regional districts (not including municipalities) of (1) Sunshine Coast (2.4 Mm^3 yr^{-1}), (2) Kitimat-Stikine (2.3 Mm^3 yr^{-1}), and (3)

Nanaimo (1.1 M m^3 yr^{-1}) (Table 4). However, 64% of regional districts and 47% of the municipalities did not report the percent of total water supply sourced from groundwater.

Table 4: Summary of municipalities with the greatest diversion from groundwater sources for the purpose of municipal water distribution systems.

Rank	Municipality	**MWWS Reported Data**			Estimated groundwater use $V_{SW,MWDS}$	No. MWDS wells
		% pop. MWDS p_{MWDS}	% pop. GW $p_{GW,MWDS}$	Total volume V_T		
		%	%	Mm^3	Mm^3	n
1	Prince George	85	100	17.8	17.8	25
2	Chilliwack	92	100	10.7	10.7	10
3	Williams Lake	99	0	4.0	4.0	3
4	Oliver	100	22	17.8	3.9	15
5	North Cowichan	80	-	-	3.8	19
6	Squamish	100	100	3.6	3.6	4
7	White Rock	100	-	-	3.4	8
8	Fort St John	100	100	3.2	3.2	7
9	Merritt	100	100	3.1	3.1	13
10	Parksville	73	99	-	2.2	25
11	Grand Forks	97	100	2.0	2.0	14
12	Qualicum Beach	73	99	-	1.6	17
13	Abbotsford	82	7	20.9	1.5	26
14	Elkford	100	100	1.4	1.4	8
15	Delta	100	5	27.0	1.4	1

Therefore, groundwater use volumes are conservative, as 100% of the water supply was assumed to be sourced from groundwater. Of the mapped aquifers in B.C. (n = 1128), 204 aquifers provide water supply for MWDS networks (Figure 12). The top five aquifers with the greatest volume of withdrawal are in the regions of Prince George (aquifer 92), Chilliwack (aquifer 8), Oliver (aquifer 254), Surrey/White Rock (aquifer 57), and Taylor (aquifer 442). The top five aquifers with the greatest withdrawal per aquifer area are in the regions of Squamish (aquifer 397), Williams Lake (aquifer 144), Taylor (aquifer 442), Montrose (aquifer 485), and Gibsons Landing (aquifer 554).

3.4.3 Domestic

Domestic users include all users self-supplying water for the purpose of domestic household use. The data sources used for this section are the 2009 MWWS and the WELLS Database. MWWS reports annual volumes for municipalities with a population greater than 1000 population and a sample of municipalities with a population less than 1000. The WELLS database provides well locations for private domestic use. For rural populations living outside municipal boundaries, per capita use statistics are used.

Methods

The methodology for deriving the distribution of annual groundwater volume withdrawn is 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, and attribute volumes to wells.

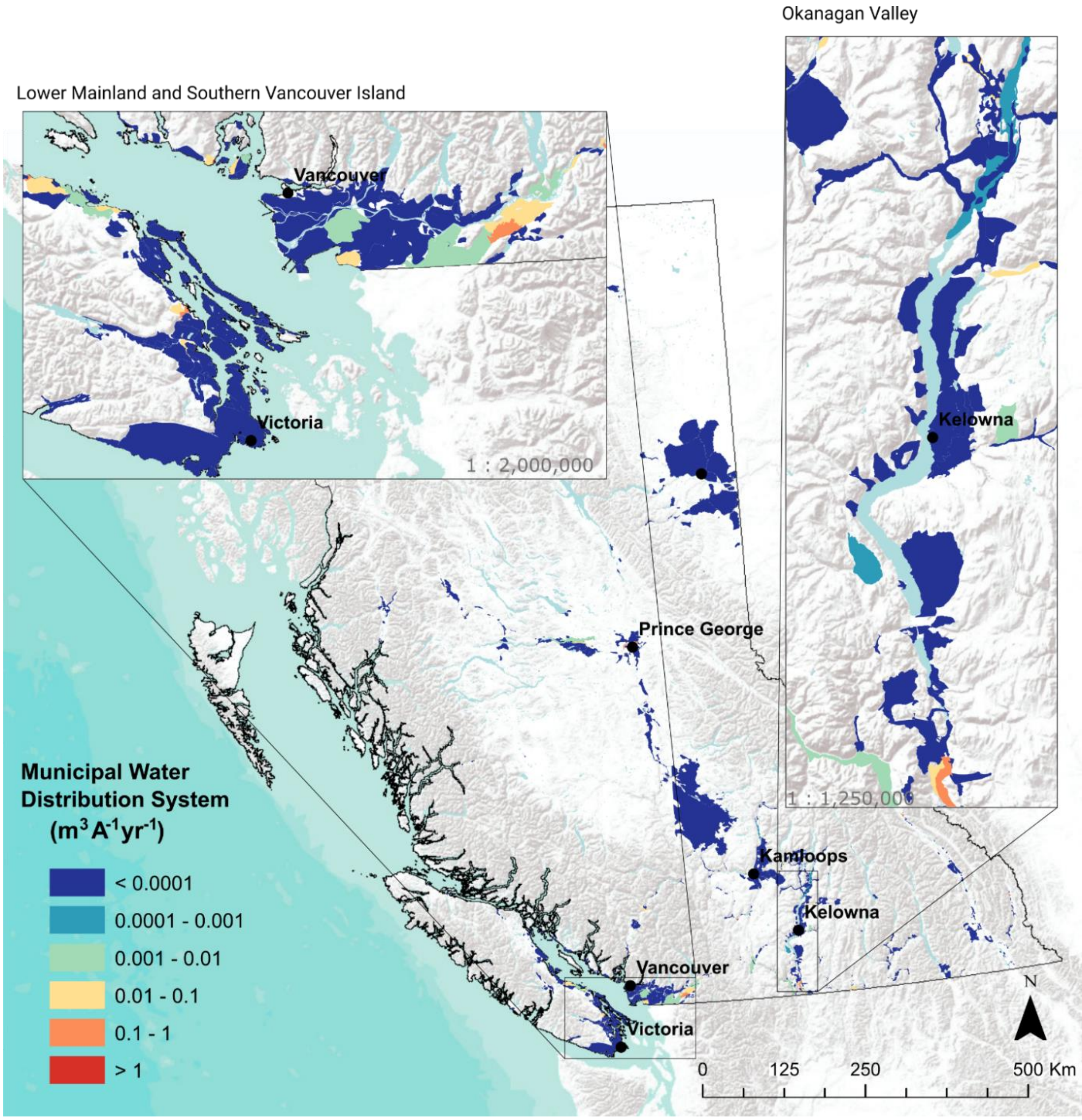

Figure 12: Results for annual groundwater use for municipal water distribution system (MWDS) users. The larger map on the bottom illustrates annual MWDS groundwater volumes normalized by aquifer area, with the inset of Lower Mainland and Southern Vancouver Island and the Okanagan Valley.

Populations using private wells are determined based on type of serviced water for municipalities (and regional districts) based on the MWWS. As discussed in the previous section (see Section 3.4.2), municipalities that did not report their type of serviced water or did not indicate they were supplied water via a MWDS, were assumed to be sourced 100% by private groundwater wells. Regional districts who did not report on type of serviced water were assumed to be supplied water by private wells.

The population on private domestic wells (P_{PDW}) for each municipality or regional district is derived using the percent population on wells (f_{PDW}) reported from the MWWS and the total population for a municipality (or regional district) (P_T):

$$P_{PDW} = P_T * f_{PDW} \qquad \text{(Eq. 10)}$$

Since the MWWS only reports on volumes related to municipal water distribution systems, annual groundwater volumes for populations using wells are inferred from the annual average residential usage (V_C) per capita (130 m^3 $person^{-1}$ yr^{-1}) in B.C. (Honey-Roses et al. 2016). Based on V_C, and the P_{PDW}, the total annual groundwater volume from wells (V_{PDW}) can be inferred:

$$V_{PDW} = V_C \; * \; P_{PDW} \qquad \text{(Eq. 11)}$$

Wells with the attribute of “Private Domestic” under the “Well Use” variable from the WELLS Database were used to distribute the municipal and regional district volumes.

The V_{PDW} is equally attributed to all private domestic wells inside the municipality or regional district boundary. Wells attributed as “Private Domestic” under the “Well Use” variable in WELLS Database are used to spatially distribute the volumes for domestic and commercial annual volumes. The volume per well, $V_{PDW,well}$ is derived based on V_{PDW}, and the number of private household wells within a municipal boundary (or regional district), n_{PDW}:

$$V_{PDW,well} = \frac{V_{PDW}}{n_{PDW}} \qquad \text{(Eq. 12)}$$

Results

The total annual groundwater volume abstracted for self-supplied domestic users is 84 Mm^3, of which 67 Mm^3 (80%) is attributed to mapped aquifers (Table 5). Municipalities account for 23 Mm^3 (27%), while rural areas account for 63 Mm^3 (75%) (Figure 13).

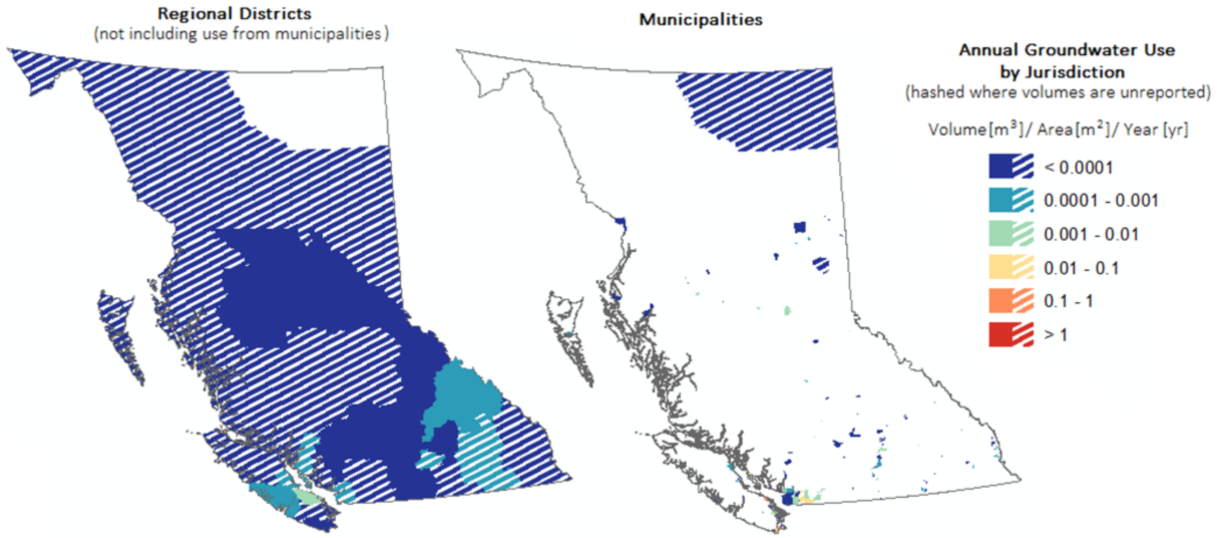

Figure 13: Annual groundwater withdrawal for self-supplied domestic and commercial users by jurisdiction for municipalities and regional districts (not including volumes from municipalities). Regions are hashed where groundwater volumes have been inferred based on either groundwater source or percent groundwater from the MWWS.

Table 5 and Table 6 highlight the top fifteen municipalities and regional districts with use from private domestic wells. Groundwater withdrawal volumes are concentrated in the municipalities of (1) Abbotsford (3.2 Mm^3 yr^{-1}), (2) Nanaimo (2.8 Mm^3 yr^{-1}), and (3) Maple Ridge (2.0 Mm^3 yr^{-1}) and the regional districts (not including municipalities) of (1) Cariboo (5.2 Mm^3 yr^{-1}), (2) Cowichan Valley (4.6

$Mm^3\ yr^{-1}$), and (3) Capital (3.2 $Mm^3\ yr^{-1}$). However, as mentioned in Section 3.4.2, 64% of regional districts and 47% of the municipalities did not report the percent sourced groundwater of the total water supplied within the MWDS, therefore, these values represent a conservative approach in estimations of groundwater use (Figure 13).

Table 5: Sumary of municipalities with the greatest diversion from groundwater sources for the purpose of private domestic use from household well.

Rank	Municipality	**MWWS Reported Data** % pop. PDW f_{PDW}	Pop. per well $V_{PDW,well}$	Estimated groundwater use V_{PDW}
		%	x 1000	Mm^3
1	Abbotsford	18	1090	3.2
2	Nanaimo	26	165	2.8
3	Maple Ridge	20	580	2.0
4	Prince George	15	377	1.4
5	Surrey	2	1060	1.2
6	Mission	20	504	1.0
7	Chilliwack	8	501	0.8
8	North Cowichan	20	824	0.8
9	NRRM	95	53	0.7
10	Kent	75	134	0.6
11	West Kelowna	10	204	0.3
12	Coldstream	14	52	0.2
13	Coquitlam	1	8	0.2
14	Kelowna	1	400	0.2
15	Vernon	3	252	0.2

Table 6: Summary of regional districts with the greatest diversion from groundwater sources for the purpose of private domestic use from household well.

Rank	Municipality	**MWWS Reported Data** % pop. PDW f_{PDW}	Pop. per well $V_{PDW,well}$	Estimated groundwater use V_{PDW}
		%	n	Mm^3
1	Cariboo	-	6	5.2
2	Cowichan Valley	-	10	4.6
3	Capital	-	7	3.2
4	Thompson-Nicola	-	10	3.1
5	Okanagan-Similkameen	-	12	3.1
6	Bulkley-Nechako	97	14	2.5
7	Columbia Shuswap	90	11	2.4
8	Central Kootenay	60	8	2.4
9	North Okanagan	91	12	2.2
10	Fraser Valley	-	34	2.2
11	East Kootenay	-	5	2.1
12	Fraser-Fort George	99	13	1.9
13	Peace River	49	8	1.4
14	Kootenay Boundary	-	10	1.3
15	Nanaimo	26	3	1.3

Of the mapped aquifers in B.C., 894 aquifers (n = 1128) are being sourced groundwater for the purpose of self-supplied domestic needs (Figure 14). The top five aquifers with the greatest volume of withdrawal are Wark-Colquitz (aquifer 680), Fraser Plateau Lava (aquifer 124), Abbotsford-Sumas (aquifer 15), South Vernon Confined Aquifer (aquifer 347), and Quesnel (aquifer 115). The top five aquifers with the greatest withdrawal per aquifer area are in the regions of Quesnel (aquifer 115), South Vernon Unconfined Aquifer (aquifer 346), South Vernon Confined Aquifer (aquifer 347), North Vancouver (aquifer 67) and Barnston Island (aquifer 40).

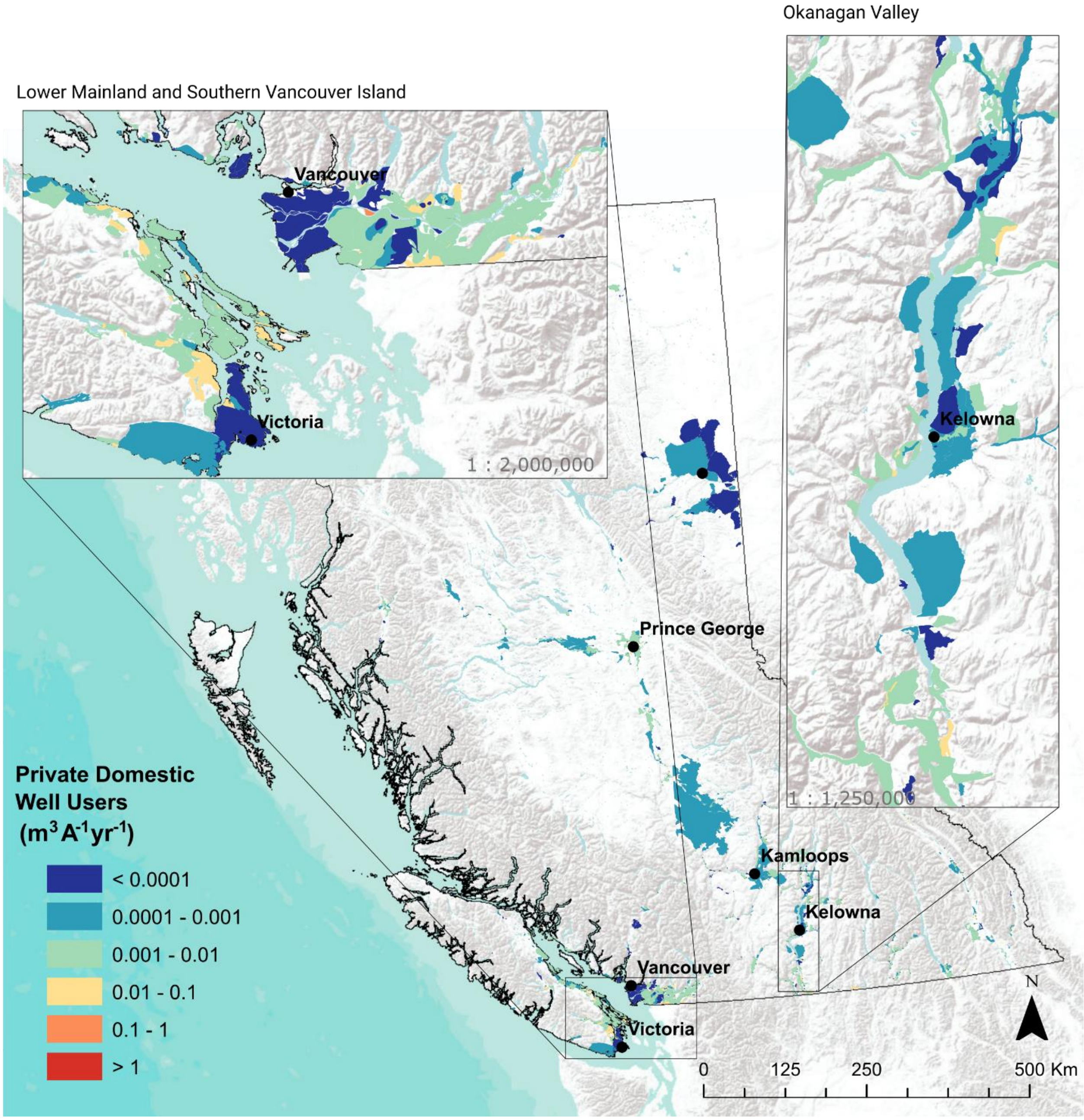

Figure 14: Results for annual groundwater use for private domestic well (PDW) users. The map illustrates annual self-supplied groundwater volumes normalized by aquifer area, with the inset of Lower Mainland and Vancouver Island and Okanagan Valley.

3.4.4 *Industrial*

The industrial sector represents self-supplied annual groundwater volumes for the purpose of manufacturing, mining, and oil and gas production.

Volumetric data for manufacturing and mining is provided from the national IWS, and spatial data is derived from the EPOI, which provides all business locations in 2016 by the NAICS designed by DMTI Spatial. Volumetric and spatial data are provided from the British Columbia Oil and Gas Commission's (BCOGC) for the years 2013-2015 (British Columbia Oil and Gas Commission, 2012 - 2015) (Figure 15).

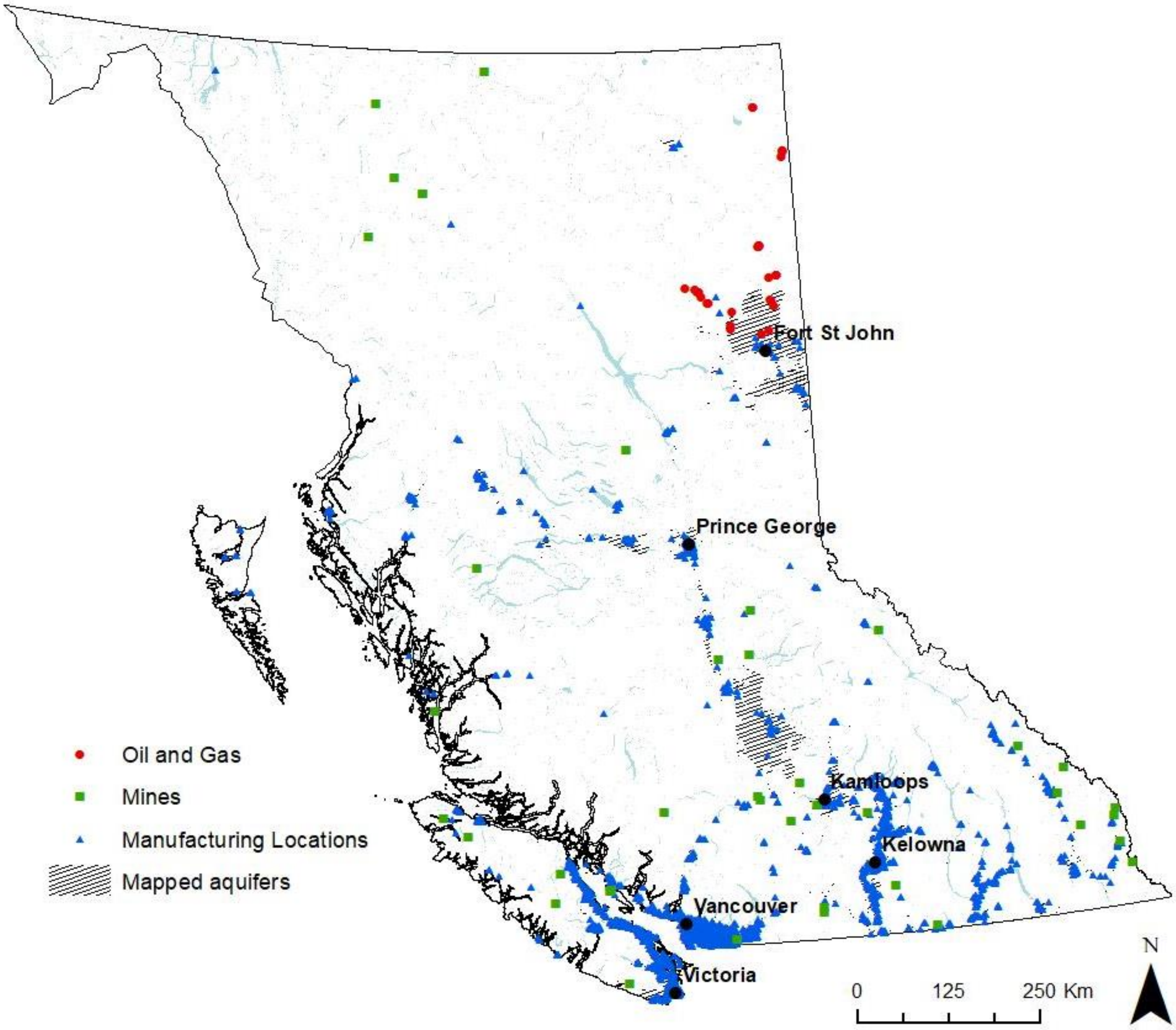

Figure 15: Spatial data for manufacturing (black), mining (orange), and oil and gas (red). Where points are filled, specific groundwater withdrawal volumes are available. Oil gas wells (red) are the only points where reported volumes are spatially distributed.

Methods

The methodology for oil and gas is separated from manufacturing and mining due to the difference in data sources. Annual groundwater water volumes and well extraction locations for oil and gas operations were reported by the BCOGC for 2013-2015 (BCOGC 2013, 2014, 2015) and averaged to represent groundwater use for the oil and gas sector (Table 7). Deep wells (>250 m) depth were not included as they are less likely to be drawing from any mapped freshwater aquifers.

Table 7: Annual groundwater volumes withdrawn from 2013 - 2015 (Source: B.C. Oil and Gas Commission)

Sub-Basin Name	Well Number	Company	Well Depth (m)	Water Withdrawal 2013 ($m^3 yr^{-1}$)	Water Withdrawal 2014 ($m^3 yr^{-1}$)	Water Withdrawal 2015 ($m^3 yr^{-1}$)	Average ($m^3 yr^{-1}$)
Upper Beatton River	26846	Progress Energy	80	17,667	26,926	23,674	22,756
Upper Beatton River	26848	Progress Energy	80	3,170	530	807	1,502
Upper Beatton River	26849	Progress Energy	80	3,287	1,616	-	1,634
Upper Beatton River	26864	Progress Energy	80	14,316	25,602	12,121	17,346
Upper Beatton River	27413	Progress Energy	80	18,665	45,855	15,654	26,725
Milligan Creek	25370	Canadian Natural Res.	91	17,635	13,419	22,872	17,975
Milligan Creek	25371	Canadian Natural Res.	91	25,568	33,323	35,751	31,547
Milligan Creek	25373	Canadian Natural Res.	91	35,786	23,651	15,286	24,908
Milligan Creek	26952	Canadian Natural Res.	91	6,953	5,338	8,113	6,801
Milligan Creek	27214	Canadian Natural Res.	91	26,536	12,580	21,313	20,143
Milligan Creek	27281	Canadian Natural Res.	91	19,487	11,393	17,790	16,223
Lower Beatton River	26962	Canadian Natural Res.	91	14,621	18,920	15,492	16,344
Lower Beatton River	16332	Canadian Natural Res.	91	39,756	26,545	23,496	29,932
Lower Beatton River	25556	Canadian Natural Res.	91	21,841	10,812	6,235	12,963
Cameron River	26240	Progress Energy	80	800	1,476	1,304	1,193
Cameron River	27142	Progress Energy	80	3,547	5,313	26,935	11,932
Cameron River	27813	Progress Energy	80	18,543	50,034	5,140	24,572
Hay River	12650	Harvest Operations	116	6,289	-	-	2,096
Hay River	12663	Harvest Operations	116	6,894	-	-	2,298
Hay River	25318	Harvest Operations	116	67,104	-	-	22,368
Hay River	25319	Harvest Operations	116	44,590	-	-	14,863
Lower Kiskatinaw River	7779	Shell Canada	1473	220	-	-	73
Cache Creek	3164	Harvest Operations	116	25,033	3,790	-	9,608
Pouce Coupe River	23533	Tourmaline Oil	2600	8,160	-	-	2,720
Sahdoanah River	14893	Ish Energy	232	61,381	65,386	57,913	61,560
Sahdoanah River	17557	Ish Energy	232	2,368	1,091	364	1,274
Tsea River	25945	Nexen	749	2,111	132,271	143	44,842
Lower Sikanni Chief River	11449	Canadian Natural Res.	91	14,322	13,141	16,806	14,756
Lower Sikanni Chief River	11499	Canadian Natural Res.	91	67,485	59,933	36,115	54,511
Lower Sikanni Chief River	11500	Canadian Natural Res.	91	47,537	19,863	34,252	33,884
Lower Sikanni Chief River	14995	Canadian Natural Res.	91	41,857	36,853	-	26,237
Blueberry River	27364	Artek Exploration	254	-	10,841	-	3,614
Middle Kiskatinaw	29739	Encana	995	-	14,182	-	4,727
Middle Kiskatinaw	29740	Encana	995	-	11,088	28,308	13,132
Lower Kiskatinaw	28495	Encana	995	-	30,826	42,742	24,523
Lower Kiskatinaw	28496	Encana	995	-	30,026	40,868	23,631
Cache Creek	29801	Canadian Natural Res.	91	-	42,657	-	14,219
Lower Kiskatinaw	26471	Encana	985	-	-	13,046	4,349
Lower Sikanni Chief River	1499	Canadian Natural Res.	91	-	-	52,894	17,631

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

1. manufacturing locations were derived using EPOI and the British Columbia Geological Survey open file contained locations of operating mines in B.C. for 2015 (Arnold 2016);
2. volumes were derived based on water intensity and production ratios; where this data was not available, provincial scale volumes were distributed based the ratio of manufacturing location counts in Canada and B.C.; and
3. aquifer attribution inferred based on point location of each industry.

Manufacturing locations were based on EPOI of the NAICS codes. Statistics Canada reports total annual water volumes on a national scale for each manufacturing type based on a unique NAICS code. Therefore, using the unique NAICS codes, locations of each manufacturing type could be derived. 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 B.C.” by the British Columbia Geological Survey (accessed November 2016).

The total annual groundwater volumes for B.C. were derived for manufacturing and mining industries from 2005-2011 IWS. Mining water use does not include water extracted for mine dewatering, but rather focuses on the water used in ore production. Annual groundwater withdrawal was reported per manufacturing type on a provincial-scale for all of Canada, and provincial annual groundwater volumes for total manufacturing industries in B.C.

Some sub-sector manufacturing types are highlighted as being larger consumers of water (Renzetti 1992). Several economic studies have been conducted on estimation techniques for industrial water demand (Mercer and Morgan 1974; Arbués et al. 2003; Reynaud 2003; Worthington 2010); however, many require data unavailable for the province, and therefore, a simpler analysis was conducted herein as a first order estimate.

For the subsectors of wood and paper manufacturing and mining (coal, metal, and non-metal sub-sectors), production volumes are used as a proxy to distribute national values to location points in B.C. based on a method by Vassolo and Döll (2005). The following equation is used to calculate total volume, V_i (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}).

$$V_i = PV_i \cdot WI_i \tag{Eq. 13}$$

WI_i values are calculated based on average production. Wood product manufacturing and paper manufacturing values are averaged over 2008 – 2012 (Table 8). The mining sub-sectors are averaged based on biannual reports over 2005 – 2013 (Table 9). This method assumes that the water intensity values are the same for Canada and B.C.

Table 8: Calculation of average water intensity for Canadian manufacturing industries and sub-industries based on annual production and water intake biannual data collected through 2008-2012 (Source: Statistics Canada).

Manufacturing Industry (sub-industry)	**Average production in Canada** (tonnes)	**Average total water used** (m^3)	**Average water intensity** (m^3 tonne^{-1})
Paper Manufacturing Total Production	30,314,400	1,837,640,000	61
Newsprint	5,428,400		
Printing and writing paper	4,864,600		
Wood pulp	20,021,400		
	(m^3)	(m^3)	(m^3 m^{-3})
Wood product manufacturing Total	70,896,939	58,000,000	0.73
Hardwood lumber	1,590,540		
Softwood lumber	61,073,820		
Structural panels	8,232,579		

Table 9: Calculation of average water intensity for Canadian mining industries based on annual production and water intake biannual data collected through 2005-2013 (Source: Statistics Canada).

Sub-Industry	**Average production in Canada** (tonnes)	**Average total water withdrawn** (m^3)	**Average water intensity** (m^3 $tonne^{-1}$)
Metallic	36,005,954	324,120,000	9.1
Industrial Mineral	336,652,753	69,600,000	0.21
Coal*	66,655,000	33,450,000	0.49

*Total water intake was not reported for 2005, therefore the average total water intake was averaged over 2007-2013

Where production volumes are not readily available, annual groundwater volume per sub-sector are calculated based on location [m^3/location/yr]. There is a statistically significant correlation between business counts in Canada and B.C.; therefore, we infer that volumes of water used follow this trend (Figure 16).

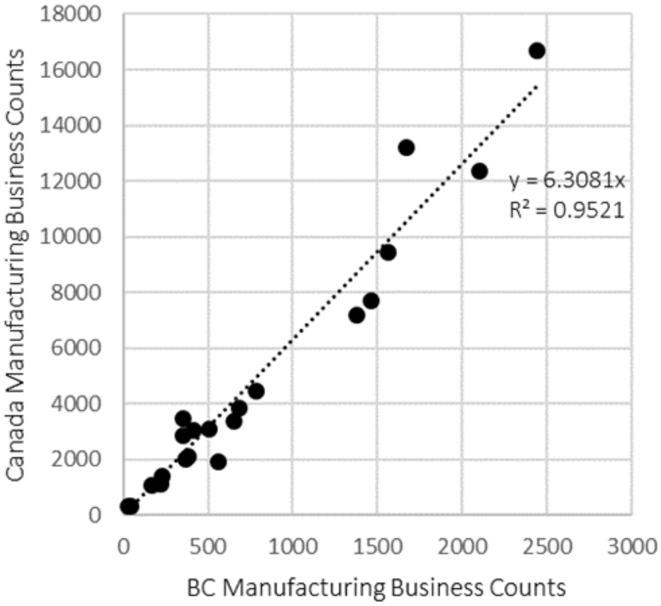

Figure 16: Relationship between manufacturing business counts in Canada and B.C. Each point represents a different subsector of manufacturing.

Location counts ($n_{CAN,i}$) are derived from EPOI, and total annual water volumes ($n_{CAN,i}$) from Statistics Canada.

$$V_i = \frac{V_{CAN,i}}{n_{CAN,i}} \quad \text{(Eq. 14)}$$

To calculate annual groundwater volume per sub-sector, the groundwater coefficient (f_{gw}) is derived from Statistics Canada tables reporting provincial volumes of groundwater ($V_{BC,gw}$) to total water (V_{BC}) (Table 10 and Table 11).

$$f_{gw,i} = \frac{V_{BC,gw,i}}{V_{BC,i}} \quad \text{(Eq. 15)}$$

Table 10: Calculation of groundwater coefficient for B.C. manufacturing industries based on average values through 2005-2013 (Source: Statistics Canada).

Type of water source for manufacturing industries	**Average total water intake** (m^3)	**Derived GW coefficient** (%)
Freshwater source, public supplied, municipal	35,575,000	
Freshwater source, self-supplied, surface water bodies	628,240,000	
Freshwater source, self-supplied, groundwater	**76,650,000**	**9.6**
Freshwater source, self-supplied, other	29,150,000	
Saline water source, self-supplied, groundwater	-	
Saline water source, self-supplied, tidewater	52,100,000	
Saline water source, self-supplied, other	-	
Percent GW Usage to total volume	-	
Total water intake, all sources*	796,740,000	
* Total may not add up to 100% of all sources as based on averages		

Table 11: Calculation of groundwater coefficient for B.C. and territories mining industries based on average values through 2005-2013 (Source: Statistics Canada).

Type of water source for mining industries	**Average total water intake*** (m^3)	**Derived GW coefficient** (%)
Freshwater source, public supplied, municipal	-	
Freshwater source, self-supplied, surface water bodies	399,000,000	
Freshwater source, self-supplied, groundwater	**218,500,000**	**35**
Freshwater source, self-supplied, other	-	
Saline water source, self-supplied, groundwater	-	
Saline water source, self-supplied, tidewater	-	
Saline water source, self-supplied, other	-	
Total water intake, all sources	617,500,000	
*Data from 2009 had suppressed or unreliable data to calculate averages		

Total groundwater volume per sub-sector ($V_{gw,i}$) is then calculated (Table 12 and Table 13):

$$V_{gw,i} = f_{gw,i} \cdot V_i \qquad \text{(Eq. 16)}$$

The total annual groundwater volume per sub-sector is then equally distributed among all locations of that subsector based on location points from EPOI.

Table 12: Annual groundwater volume withdrawn for wood and paper manufacturing in B.C.

Manufacturing Industry (sub-industry)	**Average production in B.C. 2008 - 2012 (biannual)** (tonne^{-1})	**Average water intensity (Canadian production)** (m^3 tonne^{-1})	**Total Water** (m^3)	**Groundwater Factor** (%)	**Total Groundwater** (m^3)
Paper Manufacturing	6,038,000	61	65,000,000	9.2	34,000,000
Pulp and paper shipments	6,038,000				
	(m^3)	(m^3 m^{-3})	(m^3)	(%)	(m^3)
Wood Product Manufacturing	89,071,871	0.73	370,000,000	9.2	6,000,000
Timber scaled	61,974,891				
Lumber	27,096,980				
Total					40,000,000

Table 13: Annual groundwater volume withdrawn for mining in B.C.

Manufacturing Industry	Average production in B.C. 2008 - 2012 (biannual) (tonne^{-1})	Average water intensity (Canadian production) (m^3 tonne^{-1})	Total Water (m^3)	Groundwater Factor (%)	Total Groundwater (m^3)
Metallic	335,794	9.1	3,100,000	0.35	1,100,000
Industrial Mineral	35,161,200	0.21	7,500,000	0.35	2,700,000
Coal	26,210,400	0.49	13,000,000	0.35	4,600,000
Total Mining					8,400,000

Results

The total annual groundwater volume abstracted for self-supplied industrial users is 89 Mm^3, of which 62 Mm^3 (70%) is attributed to mapped aquifers, and the remaining in regions of unmapped aquifers (Figure 17). Manufacturing, mining, and oil and gas industries account for 81 Mm^3 (89%), 8.3 Mm^3 (9%), and 0.56 Mm^3 (1%) total groundwater withdrawal respectively. Table 14 highlights the results from derived groundwater volumes using the water intensity formulae for paper manufacturing and wood products.

Of the mapped aquifers in B.C., 477 aquifers (n = 1128) provide source water for industrial needs. The top five aquifers with the greatest volume of withdrawal are in the regions of Vancouver (aquifer 49), Richmond (aquifer 44), Nicomekl-Serpentine (aquifer 58), Victoria (aquifer 680), and Surrey (aquifer 61). The top five aquifers with the greatest withdrawal per aquifer area are in the regions of Mitchell Island (aquifer 64), Chetwynd (aquifer 628), Port Moody (aquifer 69), Capilano River (aquifer 66), and North Arm Delta (aquifer 45).

Table 14: Annual groundwater volumes derived for the following major manufacturing industries.

	Reported				Derived			
						Groundwater volume per business location		
Manufacturing Industries	Average total water use in Canada from 2005 - 2013 (m^3)	NAICS code	Ratio of number of business in B.C. to Canada	Number of businesses in B.C. (m^3)	Average total water use in B.C. (m^3)	From ratio of B.C .to Canada business counts	From production water intensity	Total groundwater (m^3)
Beverage and tobacco product manufacturing	54,800,000	312	0.29	560	16,000,000	2,700		1,500,000
Chemical manufacturing	436,560,000	325	0.18	362	77,000,000	20,000		7,300,000
Computer and electronic product manufacturing	5,450,000	334	0.13	1,665	690,000	40		66,000
Electrical equipment, appliance and component manufacturing	2,733,333	335	0.13	415	370,000	85		35,000
Fabricated metal product manufacturing	17,960,000	332	0.17	2,098	3,000,000	140		290,000
Food manufacturing	323,420,000	311	0.19	1,459	61,000,000	4,000		5,900,000
Machinery manufacturing	4,240,000	333	0.15	2,441	620,000	24		60,000
Miscellaneous manufacturing	2,860,000	339	0.16	1,558	470,000	29		45,000
Non-metallic mineral product manufacturing	50,720,000	327	0.19	1,372	9,600,000	680		930,000
Paper manufacturing	1,837,640,000	322	0.15	165	280,000,000	160,000	200,000	34,000,000
Petroleum and coal product manufacturing	319,540,000	324	0.10	348	32,000,000	8,700		3,000,000
Plastics and rubber products manufacturing	27,800,000	326	0.18	380	5,000,000	1,300		480,000
Primary metal manufacturing	1,208,280,000	331	0.18	683	210,000,000	30,000		21,000,000
Textile mills	5,040,000	313	0.07	25	350,000	1,400		34,000
Textile product mills	2,820,000	314	0.19	220	540,000	240		52,000
Transportation equipment manufacturing	27,040,000	336	0.19	652	5,200,000	770		500,000
Wood product manufacturing	58,000,000	321	0.17	778	10,000,000	1,200	7,700	6,700,000
Total	4,384,903,333			15,181	710,000,000			82,000,000

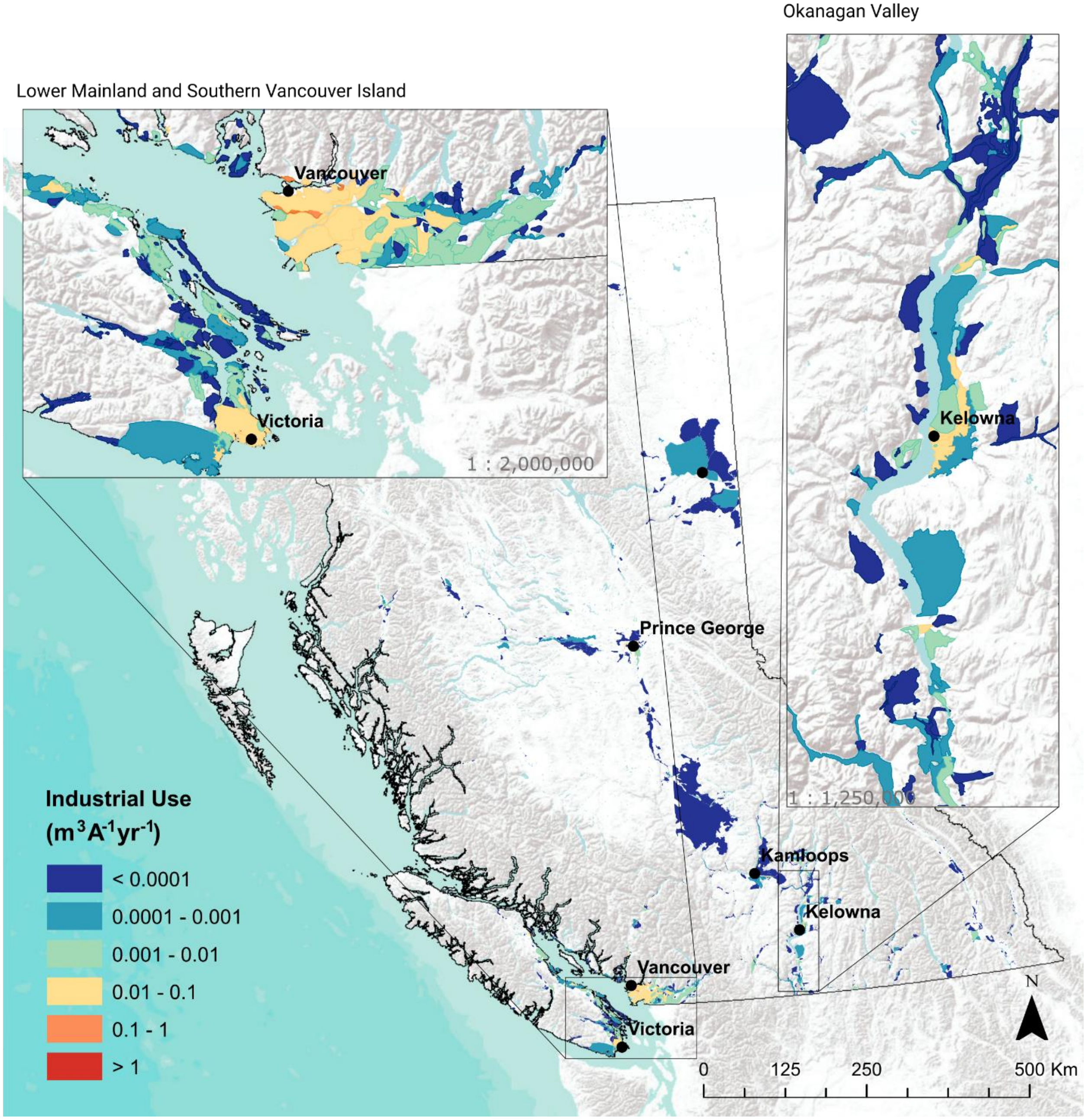

Figure 17: Results for annual groundwater use for self-supplied industrial users. The map illustrates annual self-supplied groundwater volumes normalized by aquifer area, with the inset of Lower Mainland and Vancouver Island and Okanagan Valley.

3.4.5 Agriculture

Agricultural water use includes all self-supplied groundwater for the purpose of crop irrigation. Groundwater for irrigation obtained from all off-farm sources (tap water, treated wastewater, provincial sources, private sources, and other) is not included in this section. Volumes of groundwater sourced from municipal water, and treated wastewater for the purpose of irrigation are reported in the municipal water distribution system sector (see Section 3.4.2).

The main sources of data on irrigation volumes are derived from the Agricultural Water Demand Model (AWDM), the Global Crop Water Model (GCWM – Figure 18), and provincial statistics reported in the Agricultural Water Survey (AWS).

The AWS was conducted biannually from 2010 to 2013 by Statistics Canada to gather information on irrigation use, methods, and practices. Provincial off-farm, on-farm, and sources of water are reported on a provincial scale (Table 15).

Table 15: Calculation of groundwater coefficient based on groundwater irrigation water source data collected through 2010 - 2013 (Source: Statistics Canada).

Water source for irrigating farms in B.C. (off-farm sources)	**Number of farms** (n = 3,142)	**Average percent irrigation** (%)
On-farm groundwater	818	26
On-farm surface water	992	32
Off-farm water	1332	42
Tap water (drinking water or municipal water)	272	21
Treated wastewater	43	5
Provincial sources	870	66
Private sources	68	5
Other sources	85	7
Other water sources	0	0

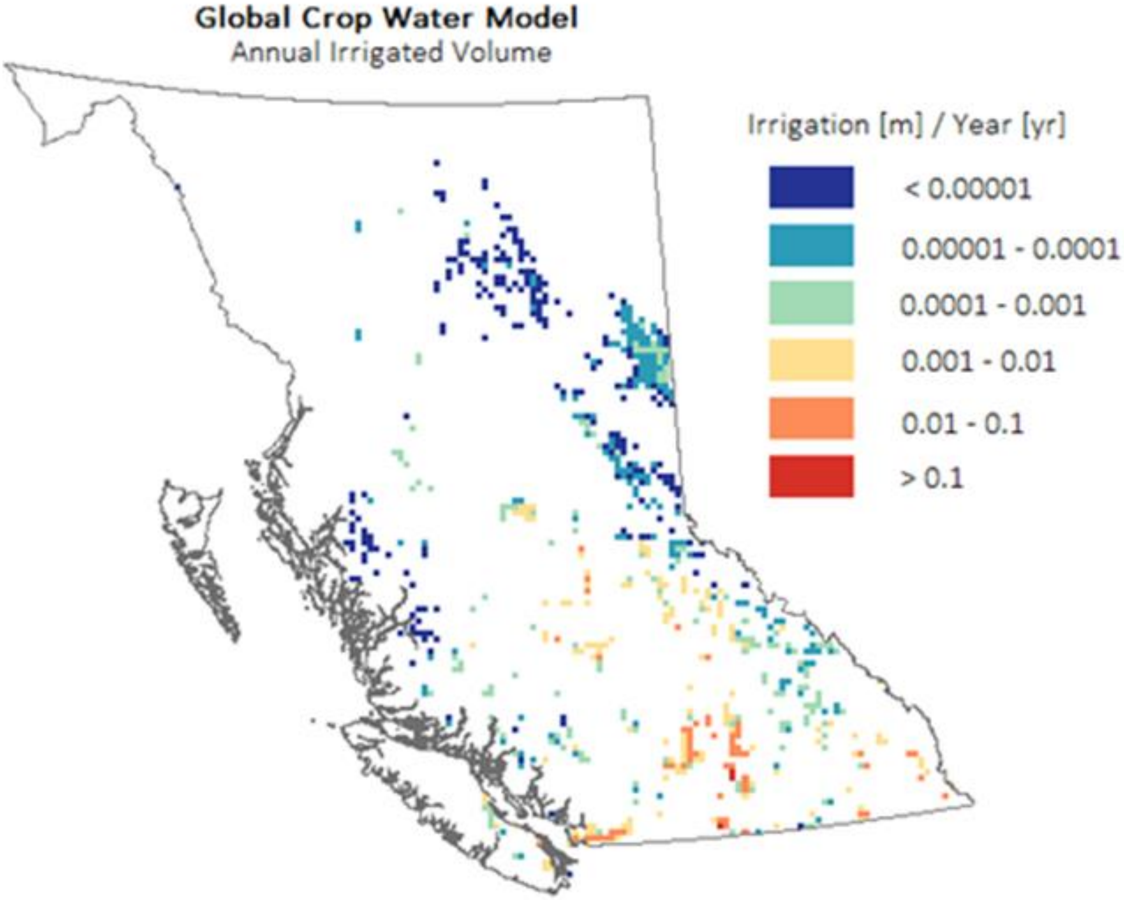

Figure 18: Coverage for irrigated agriculture based on the Global Crop Water Model.

Methods

The methodology for deriving the distribution of annual groundwater volumes is based on the following steps:

1. using the GCWM, calculate total irrigation volume per cell using all 26 crop raster sets;
2. prioritize attribution of groundwater volume to aquifers based on AWDM; where data is unavailable, the GCWM is used to derive volume; and apply groundwater coefficient derived from AWS statistics to calculated total groundwater irrigation volume per cell.

The GCWM provides values for total annual volume of irrigation [mm/yr] required for each of the 26 modelled crops ($V_{irr,c}$). The data is in the form of a raster (cell i), which is summarized to obtain the total volume of irrigation (V_{irr}) [m^3 yr^{-1}].

$$V_{irr} = \sum V_{irr,c} \qquad \text{(Eq. 17)}$$

In order to determine the total annual groundwater volume from the GCWM values of total irrigation volume, a groundwater coefficient is applied based on the method from Esnault et al. (2014).

The total volume of irrigation can be partitioned into self-supplied groundwater volume based on a groundwater coefficient (f_{gw}). The AWS reports on B.C.'s irrigation water by source based on a sample number of farms. Percent irrigation water from self-supplied on-farm groundwater is used as the groundwater coefficient. To calculate the groundwater volume per raster cell:

$$V_{gw} = [V_{irr} \cdot Area] * f_{gw} \qquad \text{(Eq. 18)}$$

where $V_{gw,}$ is the volume of irrigated groundwater required per cell area, $V_{irr}$is the total irrigated water requirement per cell area, and f_{gw} is the groundwater coefficient.

Results

The total annual groundwater volume based on the GCWM abstracted for self-supplied irrigated agriculture is 186 Mm^3. The AWDM reports a total annual groundwater volume for 438 aquifers of 188 Mm^3 yr^{-1} (Figure 19). When the GCWM is used to supplement the areas of limited data in the AWDM, the total groundwater volume is 190 Mm^3 yr^{-1}.

Compared to the AWDM, the GCWM and the Agricultural Water Survey appear to overestimate and underestimate total irrigation volumes, respectfully (Table 16).

Table 16: Comparison of total annual irrigated water use for province of B.C. from the Agricultural Water Survey, Agricultural Water Demand Model, and Global Crop Water Model.

Data set (Source) [Averaged Years]	**Irrigated Volume** **Total** (m^3)
Agriculture Water Survey (Stats Canada) [2010 – 2012]	234,032,000
Agricultural Water Demand Model [2010 - 2015]	586,912,022
Global Crop Water Model (Seibert and Doll, 2008) [1998 – 2002]	715,317,727

The distribution of irrigated agriculture is concentrated in the regional districts of (1) Central Okanagan, (2) Fraser Valley, and (3) Greater Vancouver. Of the mapped aquifers in B.C., 513 aquifers are being sourced for groundwater for the purpose of self-supplied irrigated agricultural needs. The top five aquifers with the greatest volume of withdrawal are in the regions of Lower Shuswap River valley (aquifer 111), Princeton (aquifer 259), Sumas-Prairie (aquifer 21), Grand Forks (aquifer 158) and Chilliwack-Rosedale (aquifer 6). The top five aquifers with the greatest withdrawal per aquifer area are in the regions of Armstrong (aquifer 355), Lower Clapperton Creek (aquifer 79), Mouth of Deep Creek (aquifer 356), Parkinsons Lake (aquifer 103) and Osoyoos East (aquifer 195).

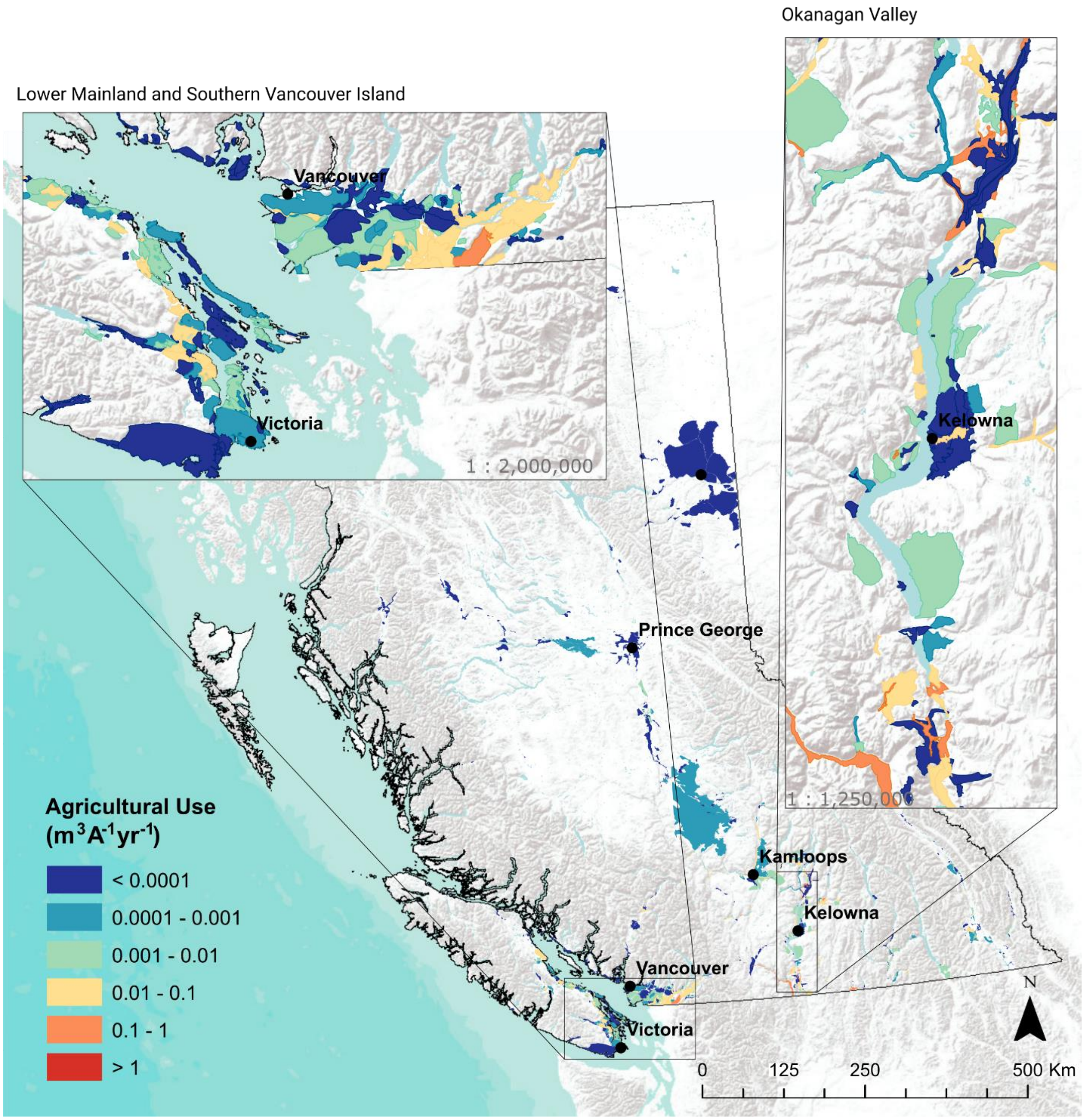

Figure 19: Results for annual groundwater use for agricultural users. The map shows annual groundwater use per aquifer normalized by aquifer area.

3.4.6 *Finfish Aquaculture*

Finfish aquaculture use represents self-supplied groundwater volumes for the purpose of conservation and industrial finfish freshwater fisheries/hatcheries.

Location data was derived from the EPOI, WELLS database for location of wells near industrial hatcheries, and Fisheries and Oceans Canada (DFO) (Government of Canada, n.d.) to derive location of government hatcheries (Figure 20). Volumetric data is based on reported flow rates from the DFO (MacKinlay and Howard 2004).

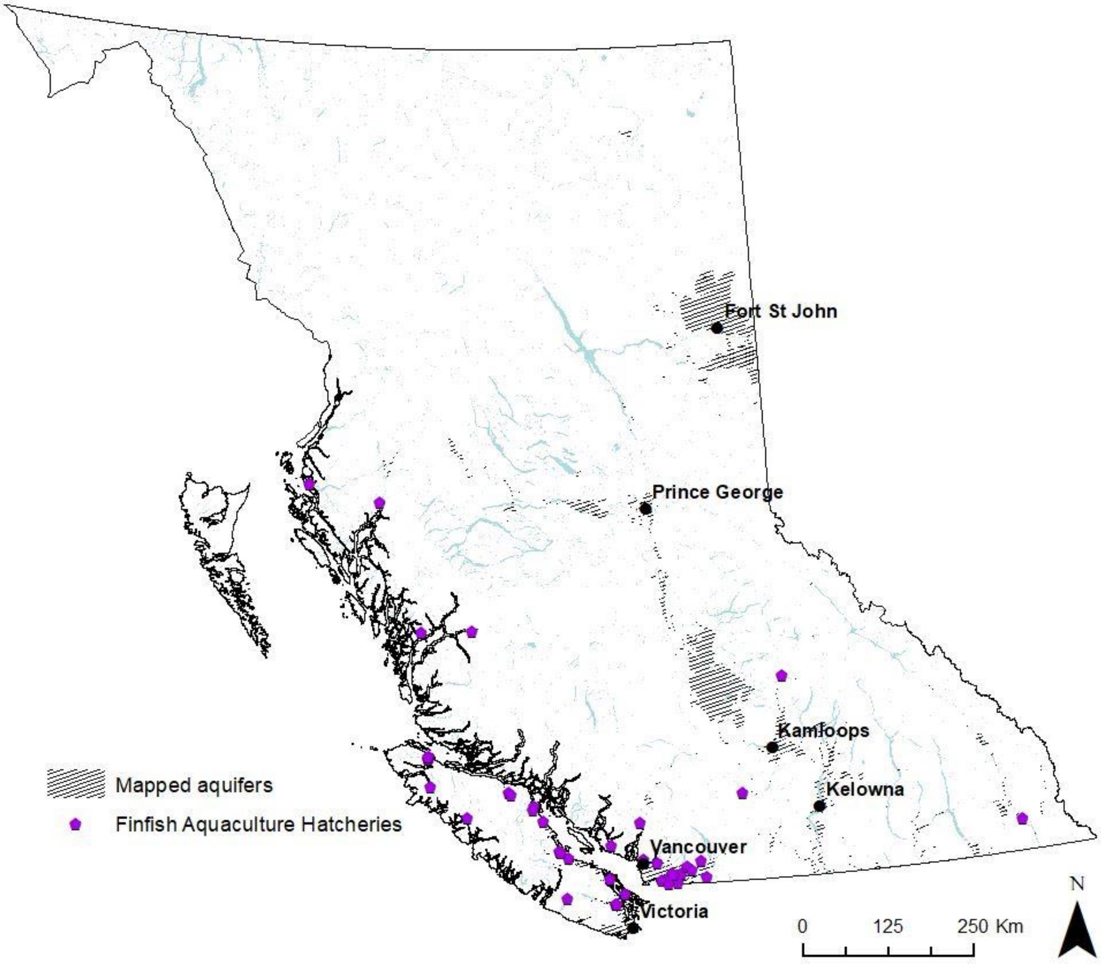

Figure 20: Spatial data for finfish hatcheries. Where points are filled (blue), specific groundwater withdrawal volumes are available.

<u>Methods</u>

The methodology for deriving the annual groundwater withdrawal volume is based on the following steps:

1. locate hatcheries from EPOI and Government Canada;
2. infer groundwater volume from the DFO (MacKinlay and Howard 2004); and
3. attributions to groundwater/surface water based on WELLS and DFO.

Hatchery location data is available from DataBC, EPOI, and online through the Department of Fisheries Canada (Table 17).

Table 17: Summary of data sources for finfish aquaculture in B.C.

	Salmon hatcheries	**Freshwater finfish hatcheries**	**NAICS finfish aquaculture**	**Salmonid enhancement facilities**
Data Source	DataBC	DataBC	EPOI 2016	Department of Fisheries Canada
Number of locations	35	63	62	16
Water source reported	no	no	no	yes
Groundwater flow rate reported	no	no	no	yes

As the data is derived from several different sources, duplicate values are possible. For example, the Freshwater Finfish Hatcheries (Ministry of Forests, Lands and Natural Resource Operations - GeoB.C. 2011) do not report any company owners, simply locations, which could be counted in the EPOI. Therefore, if any locations are within 100 m of the Finfish Hatcheries, it is assumed to be a duplicate. Finfish Hatcheries is the primary data source since it contains the largest number of locations. Salmon hatcheries (Ministry of Forests, Lands and Natural Resource Operations - GeoB.C., 2013) are categorized by culture type of either tank, hatchery, or net cage. Net cages are often used in the latter stages of salmon development and are kept in the ocean; therefore, these locations have been removed from this analysis. The EPOI reports on 2016 locations categorized as Aquaculture (North American Industrial Classification System (NAICS code:112511 Finfish Farming and Fish Hatcheries). Since the culture type is unidentified, every location is assumed to be a freshwater facility. The Salmonid Enhancement Facilities (MacKinlay and Howard 2004) was prepared by the DFO Canada and highlights all government hatcheries and information on water sources and flow rates.

Hatcheries rely on freshwater supply from either rivers and streams or groundwater. Groundwater can be favorable due to the minimal variation in temperatures year-round. The apportionment of groundwater and surface water is only reported in the DFO hatcheries. Therefore, groundwater or surface water supply source is inferred for the remaining hatcheries. If there is a well (tagged "Commercial and Industrial", "Unknown", or blank) within 100 m of the facility, the location is inferred as a potential groundwater user for the purpose of hatchery operation. Annual 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". However, based on personal communication with the DFO's Capilano Hatchery, some hatcheries only rely on groundwater seasonally. Therefore, total groundwater volumes were inferred based on continuous flow (based on reported daily flow rates) for 4 months. If no daily flow was reported, the modal value of 0.283 cubic meters per second (10 cubic feet per second) for activity for 4 months annually was assumed based on personal communication with personnel from Capilano Hatchery.

Results

The total annual groundwater volume abstracted for self-supplied finfish aquaculture users is 116 Mm^3, of which 79 Mm^3 (68%) is attributed to mapped aquifers, and the remaining in regions of unmapped aquifers (Figure 21).

Of the mapped aquifers in B.C., 32 aquifers are being sourced groundwater for the purpose of self-supplied finfish aquaculture needs. The top five aquifers with the greatest volume of withdrawal are in the regions of Beaver River (aquifer 32), Duncan (aquifer 186, 187), Port Hardy (aquifer 904), and Chehalis (aquifer 5). The top five aquifers with the greatest withdrawal per aquifer area are in the regions of Port Hardy (aquifer 904), Rosewall Creek (aquifer 414), Whiterock (aquifer 56), Kitimat (aquifer 1085), and Salmon River (aquifer 1096).

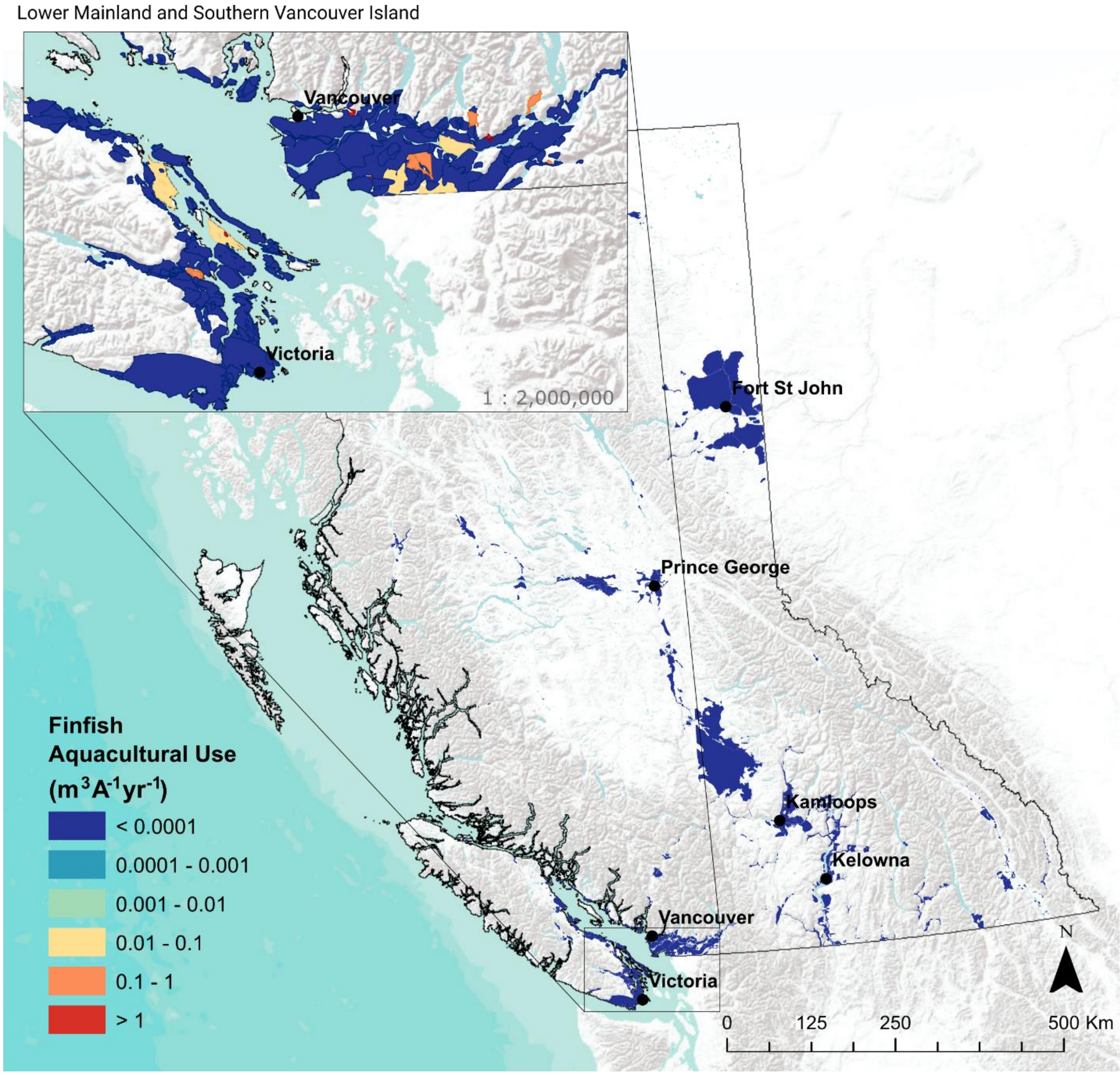

Figure 21: Results for annual groundwater use for Finfish Aquacultural users. The map shows the distribution of annual groundwater use per aquifer normalized by aquifer area.

3.5 Discussion

The results from this study provide the current best estimate of annual groundwater withdrawals in B.C. based on readily available data from identified major sectors. The purpose of this study is to provide an updated estimate of groundwater withdrawal by sector provincially, in addition to generating two of the first spatially distributed maps of groundwater withdrawal from mapped aquifers and total annual groundwater withdrawal.

The total annual diverted groundwater volume is the sum of groundwater diverted from all sectors, and is 562 Mm^3, of which 451 Mm^3 (80%) is attributed to mapped aquifers (Figure 22), and the remaining in regions of unmapped aquifers or from unreported wells. Of the mapped aquifers in B.C., 1031 aquifers are being sourced for some quantity of groundwater. The five largest absolute volumes of withdrawal are from the Spallumcheen Unconfined Aquifer (aquifer 111), Lower Nechako River Aquifer (aquifer 92), Similkameen River Aquifer (aquifer 259), Vedder River Fan Aquifer (aquifer 8) and Sumas Prairie Aquifer (aquifer 21) (Table 18). The top five aquifers with the greatest withdrawal per aquifer area are from the Squamish region (aquifer 397), 100 Mile House region (aquifer 144), Port Hardy region (aquifer 904), Parksville (aquifer 414), and south Surrey region (aquifer 56) (Table 19).

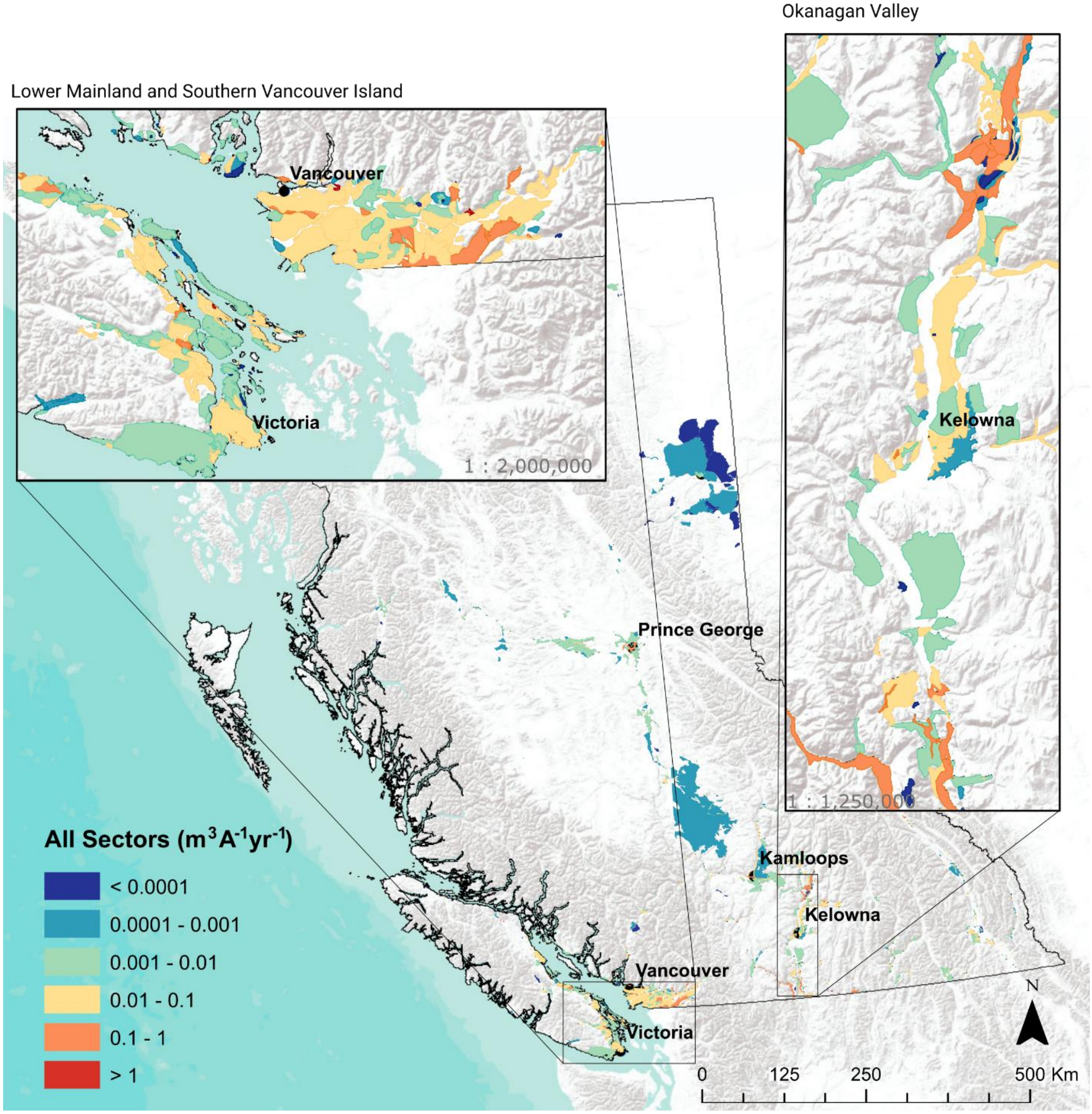

Figure 22: Results for total annual groundwater use for all major users in B.C. The larger map shows the distribution of annual groundwater use per aquifer normalized by aquifer area.

Table 18: The top 15 aquifers diverting absolute annual groundwater volumes and the sectoral distribution of diverted volumes.

Aquifer Number	**Total derived groundwater withdrawal**	**Sectoral Diversions (Percent of Total)**				
		MWDS	PDW	IND	AGR	FIN
	Mm^3	%	%	%	%	%
111	22	> 1%	> 1%	1%	98%	-
92	20	89%	3%	8%	0%	-
259	15	3%	3%	1%	94%	-
8	11	77%	2%	1%	20%	-
21	11	1%	4%	2%	93%	-
158	11	18%	4%	1%	77%	-
6	11	20%	4%	9%	67%	-
15	10	9%	13%	6%	41%	31%
254	7	54%	2%	1%	43%	-
49	7	-	-	99%	1%	-
355	6	-	-	-	100%	-
32	6	-	> 1%	3%	3%	93%
4	6	3%	8%	1%	88%	-
61	6	22%	10%	68%	-	-
44	6	-	-	94%	6%	-

Table 19: The top 15 aquifers diverting annual groundwater normalized by aquifer area with sectoral distribution of diverted volumes.

Aquifer Number	**Aquifer Area** m^2	**Total groundwater withdrawal** m^3	Sectoral Diversions (Percent of Total)					**Groundwater withdrawal per aquifer area** m^3/m^2
			MWDS	PDW	IND	AGR	FIN	
397	176,548	2,710,843	100%	-	-	-	-	15.4
144	356,437	1,346,222	100%	< 1%	-	-	-	3.8
904	949,885	2,997,542	-	-	1%	-	99%	3.2
414	1,454,354	2,982,314	-	< 1%	< 1%	-	100%	2.1
56	1,657,809	3,030,757	-	1%	1%	0%	98%	1.8
485	94,299	159,230	100%	-	-	< 1%	-	1.7
309	305,998	477,337	100%	-	-	-	-	1.6
1085	1,060,462	1,590,356	-	-	6%	-	94%	1.5
442	1,889,931	2,784,429	100%	-	-	< 1%	-	1.5
1096	2,157,353	2,976,662	-	-	-	-	100%	1.4
13	2,334,426	2,983,090	-	0%	-	< 1%	100%	1.3
155	1,238,579	1,505,054	-	1%	-	-	99%	1.2
69	2,811,467	3,354,898	-	-	11%	-	89%	1.2
554	467,503	510,688	98%	< 1%	2%	< 1%	-	1.1
831	1,115,247	1,071,600	-	-	-	< 1%	100%	1.0

The importance of spatially distributed groundwater use is illustrated by the resulting volumes and the sectoral distribution among aquifers. The largest annual withdrawal of groundwater by major sectors are self-supplied irrigated agriculture (42%), self-supplied finfish aquaculture (18%), self-supplied industrial use (14%), self-supplied private commercial and domestic wells (10%), and municipal water distribution systems (17%). The sectors that withdraw from the greatest number of aquifers are the self-supplied domestic and commercial (80% total aquifers), water distribution systems (7% total aquifers), industrial (42% total aquifers), irrigated agriculture (45% total aquifers), and finfish aquaculture (3% total aquifers). For example, both the MWDS and PDW groundwater volumes are comparable annually, however, the MWDS volumes are concentrated in a few aquifers with high withdrawals, which could have more severe impacts on the aquifer due to depletion (see Table 19 and Figure 24).

Aquifers in B.C. are currently classified based on development and vulnerability. Given the lack of historic reporting on groundwater withdrawals and few regionally comprehensive estimates of recharge, development classification has been highly uncertain. Development is ideally classified based on detailed water balance, however data is often not available, 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 our results were compared to the B.C. MENV classification, we see high development aquifers plotting with larger ratios of groundwater use per unit (Figure 23). Although, our groundwater use estimates are also based on well data, we derived our estimates based on several different sources of data and sectoral distribution.

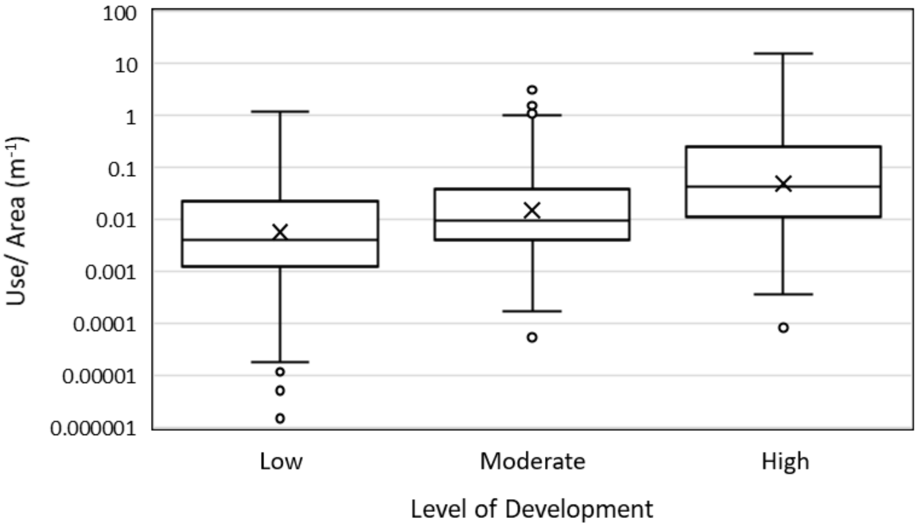

Figure 23: Illustrating the B.C. MENV classification of development compared to the normalized groundwater use to aquifer area.

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. For this reason, this analysis should be considered a first order estimate of groundwater withdrawals in B.C., however, we recommend this analysis be refined and updated once measured data is available.

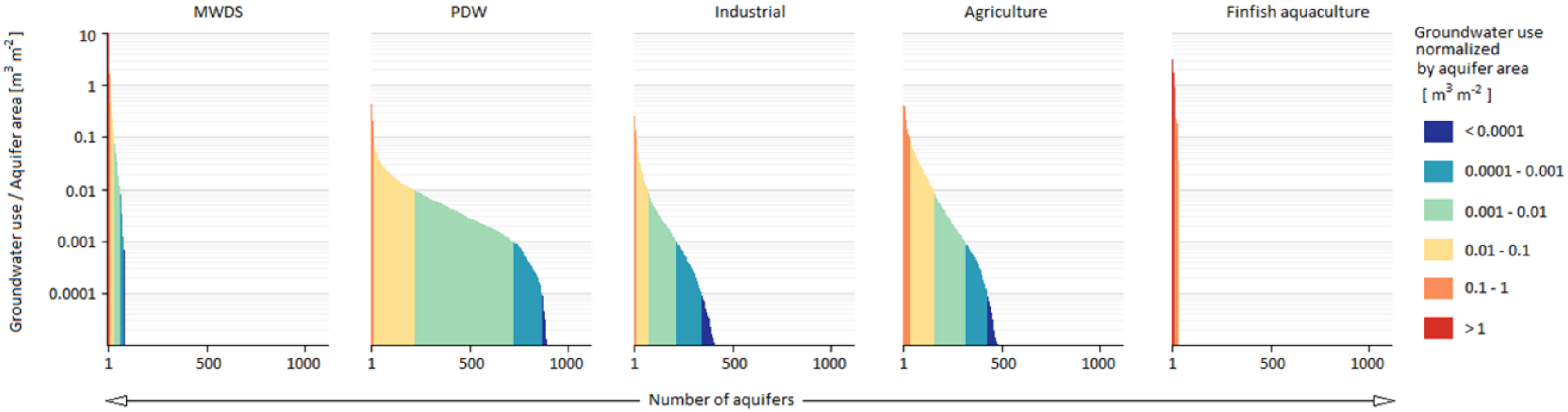

Figure 24: Groundwater use by sector normalized by aquifer area plotted per major sector illustrating the magnitude of use from individual aquifers and the distribution of use across the number of aquifers.

Table 20: Comparison of results to Hess (1986) the last major report of groundwater use by sector in B.C.

Sector	**Annual Groundwater Volume** (Mm^3)			
	This Study, 2017		Hess, 1986	
(sub-sector)	Sector	Sub-Sector	Sector	Sub-Sector
Municipal Water Distribution Systems	83.7		60.5*	
Self-supplied:				
Domestic and Commercial	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.

3.5.1 Spatial Uncertainty

In all sections, attribution of annual groundwater volumes to the aquifer was made via spatial relationships of point location or well location. Although, the well location at the land surface is 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 1 aquifer, 22 municipalities overlie 2 or more aquifers, and 9 municipalities overlie unmapped aquifers. With 22 municipalities overlying 2 or more aquifers, the volume attribution is divided equally among all underlying aquifers. Therefore, although the groundwater volume is in the approximate location, the exact aquifer abstracted is uncertain. In the future, this problem will be minimized as licensable wells will be correlated to aquifers through the groundwater licencing process.

3.5.2 Volume Uncertainty

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 sector.

MWDS and Domestic Users

The MWDS (Section 3.4.2) and self-supplied domestic and commercial user (Section 3.4.3) volumes are derived from data in the MWWS (2009). Approximately a quarter (24%) of the B.C. population – 24% of municipalities and 43% of regional districts – did not report on type of serviced water. The approach taken in this analysis is to determine a conservatively large volume of groundwater withdrawal.

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 and for all volumes derived for self-supplied domestic and commercial users were attributed a volume based on total water use per capita (180 m^3 yr^{-1} and 130 m^3 yr^{-1}) respectively and population.

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. This analysis may overestimate groundwater use in municipalities that simply rely on groundwater abstractions for emergency or backup needs.

Additional analysis should be completed to compare derived groundwater use values for municipalities and local reported groundwater volumes. Due to the lack of consistent reporting for groundwater use volumes per municipality, this was considered out of scope for the purpose of this project, but should be considered in the future.

Industrial Users

Within the manufacturing and mining industries, only provincial-scale values of groundwater use were reported. Therefore, using business count ratios of Canada to B.C., and Canadian water use per subsector of manufacturing, total water intake was calculated. Based on this methodology, manufacturing in B.C. had an average total annual water intake calculated at 715 Mm^3 yr^{-1} compared to the average reported value of 796 Mm^3 yr^{-1} reported for the province by Statistics Canada in the Industrial Water Survey. For oil and gas industries, volumes are of a higher certainty since they are reported annually by the BCOGC and associated directly with a well ID. For manufacturing and mining industries, the percent groundwater of total water intake was unreported for each sub-sector. Therefore, the groundwater coefficient was derived from the provincial statistics and groundwater withdrawal volumes could be calculated for each manufacturing and mining subsector. The groundwater volume is subsequently divided equally to all business locations classified under North American Industrial Classification System. This assumes all businesses are groundwater users and equally distributed an average groundwater volume to all locations. This is a major assumption for this sector, 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 groundwater, and 3) all locations of the same sub-industry withdraw the same volume of groundwater.

Agricultural Users

The main uncertainties in calculating groundwater volumes in the agricultural sector are in regions where the AWDM is unavailable as the GCWM uses a provincial scale groundwater coefficient to constrain groundwater volume. The AWDM reported agricultural use for 422 aquifers in B.C., as opposed to the GCWM reported for 653 aquifers, however the AWDM accounts for 99% of the attributed volumes compared to the GCWM. 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 the major contributor of annual groundwater withdrawal, livestock was not included and will need to be added at a later date.

Finfish Aquacultural Users

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 B.C. 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.

4. RECHARGE

4.1 Background

Quantifying aquifer recharge remains difficult, however using multiple estimation methods helps constrain recharge estimates and decreases uncertainty (Scanlon et al. 2002). Due to the large spatial distribution of aquifers, two methods are used and compared to derive recharge (R): HELP and PCR-GLOBWB modelling. The HELP method is designed to provide aquifer-scale estimates by generalization of the major parameters of climate based on BGCZs, saturated hydraulic conductivity for soil (Soil Landscapes of Canada Working Group 2010), aquifer mapping (Berardinucci and Ronneseth 2002), permeability (Gleeson et al. 2011), and mean water table depth (Fan et al. 2013). These estimates are then compared to a more complex global hydrological model, PCR-GLOBWB (Van Beek and Bierkens 2009) which provides recharge outputs on a regional scale at a resolution of ~100 km^2. Both methods estimate direct, natural vertical recharge from precipitation, and are not applicable to confined aquifers. Daily HELP results are summarized as mean annual averages, whereas PCR-GLOBWB outputs steady state recharge fluxes, therefore, this study does not capture seasonal variability.

The first approach determines aquifer recharge for unconfined aquifers across the province as is termed the generalized approach. This involved: (1) assigning aquifers to BGCZs based on the aquifer's location, (2) developing a soil and aquifer properties system, (3) attributing each aquifer with the appropriate soil, climate and water table depth data, (4) simulating recharge for 53 different parameter combinations in the simulation software (HELP) and (5) graphically representing results and comparing results to similar local research projects.

In the second approach, recharge is output from the global-scale groundwater model using MODFLOW and is forced from the land-surface PCR-GLOBWB model. Recharge is simulated as the downward percolating flux to the single unconfined groundwater store from Store 2 to Store 3 in PCR-GLOBWB (see Figure 6). Appendix C compares in greater detail the generalized (this study) and localized (previous studies) recharge modelling.

4.2 HELP Modelling

The HELP (Hydrologic Evaluation of Landfill Performance – Schroeder et al. 1994) software used in this study is implemented in Unsat Suite Plus 2.2 (Waterloo Hydrogeologic Inc. 2004). HELP is a one-dimensional (1D) water balance software that simulates vertical infiltration through multiple soil layers and internally calculates evapotranspiration and overland flow (Figure 25). Required inputs include daily climate, soil and aquifer material properties, and various surface settings. Aquifer recharge, the parameter of interest, is the vertical flux of water that passes through the percolation profile, exiting at the bottom as recharge. The bottom of the model coincides with the average annual water table depth.

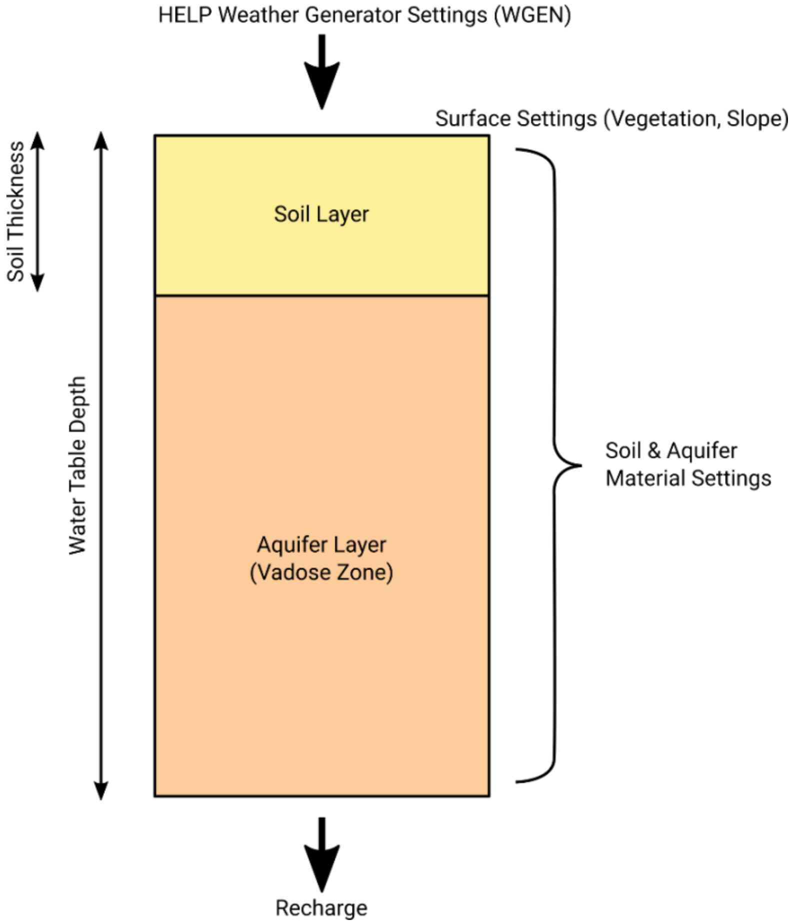

Figure 25: Conceptual model of a typical HELP profile.

Localized recharge modelling was carried out previously in the Grand Forks aquifer (Scibek and Allen 2004) and the Abbotsford-Sumas aquifer (Scibek and Allen 2006b). The localized recharge modelling results suggest the parameters with the greatest impacts on recharge include soil parameters, precipitation data, hydraulic conductivity of the aquifer and the thickness of unsaturated zone (Scibek and Allen 2006c). Parameters with moderate effect include soil thickness, and soil and vadose zone porosity. Low sensitivity parameters with no noticeable change or very small (<5% change) include the vegetation type, wilting point, field capacity and the initial moisture content of the profile. Taking these results into consideration, data was collected and analyzed so that aquifers could be categorized into characteristic climate, soil, aquifer types, and modeled in HELP (Figure 26).

HELP has proven to be a viable method of recharge modelling; however, it is not without limitations. First, HELP often underestimates evapotranspiration in semi-arid areas, and thus, overestimates recharge (Liggett and Allen, 2010). Second, the simple, homogeneous model structure cannot represent recharge processes in complex subsurface environments such as fractured bedrock or sloped terrain. Third, the water table in the model does not fluctuate and therefore, in areas where the water table may rise or lower, HELP assumes a continuous amount of recharge without raising the water table thereby creating higher than reasonable values as it does not account for limits of infiltration (i.e. flooding or pooling).

To generate recharge, HELP requires inputs grouped into case settings (Section 4.2.1), surface water settings (Section 4.2.2), weather generator settings (Section 4.2.3) and, soil and aquifer material properties (Section 4.2.4). In each section, we describe how the parameter is defined in HELP and quantified for this study. For input parameters with more detailed methodologies (soil, water table depth, aquifer and weather), we elaborate on the methods in subsequent sections.

4.2.1 Case Settings

Case settings describe parameters that are used to set the major functions of the model and characteristics of the one dimensional (1D) simulation. For recharge modelling, runoff and initial moisture settings are the key variables.

Runoff is calculated through the Curve Number (CN), which describes the runoff vs. infiltration behavior of water on the profile surface. HELP takes into account the surface slope, soil texture, and vegetation class to determine the value of CN. In this study, the default option to automatically calculate the CN was selected (it can also be user specified). The surface slope was set to zero for all profiles to minimize the amount of surface runoff generated because this water cannot be routed. When HELP predicts frozen conditions to exist, the value of CN is increased, resulting in a higher calculated runoff. This value was used for the Grand Forks, Abbotsford-Sumas and province wide investigation, which maximizes the amount of recharge calculated.

The initial moisture content for the model was model-generated (it can also be user specified). HELP calculates this value by estimating the initial moisture settings for each storage layer, and running a simulation for one year.

4.2.2 Surface Water Settings

The surface water settings are user specified; including the runoff area and vegetation class that control how the water on the surface of the profile behaves.

Runoff area defines the percent of area on the surface of the profile for which runoff is possible. Given that the Grand Forks and Abbotsford-Sumas studies both used 100%, this value was also used for the provincial wide study.

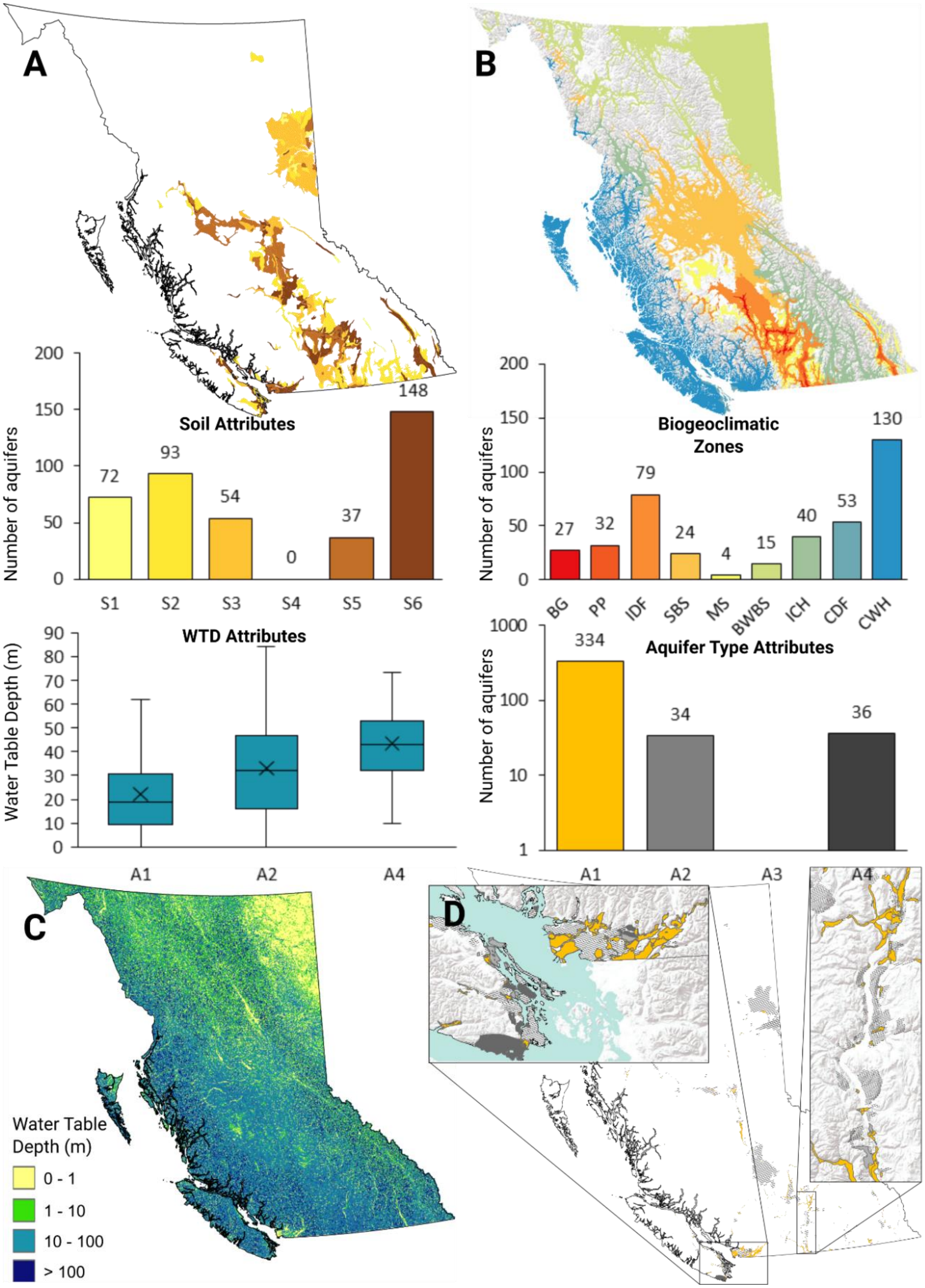

Figure 26: Overview of attributes used to generalize mapped aquifers. A. Soil attributes; B. Biogeoclimatic Zones; C. Water table depth – here water table depth distribution is categorized by aquifer type; however in this study, combinations of BGCZ, Soil and Aquifer type were used to derive an average water table depth value; C. Aquifer type.

The vegetation class defines the class of vegetation on the surface which controls the amount of evapotranspiration. Vegetation class represents the leaf area index (LAI). The options in HELP are limited because the software was developed for modelling infiltration of water in a landfill. We consistently used a ‘Good Stand of Grass’, the highest value of 5, across British Columbia which leads to lower recharge than the other vegetation classes (such as bare soil). Values higher than 5 are common for treed areas (e.g. 18 for conifers); therefore, recharge values may be overestimated in treed areas of B.C.

4.2.3 Weather Generator Settings

A Weather Generator (WGEN) is available for use with HELP in Unsat Suite Plus. WGEN generates a stochastic daily weather series of specified length for input to the model. Within WGEN, the station of preference can be selected and the climate statistical parameters accepted or edited, or a new station can be created. The statistical parameters within the WGEN climate station database include total precipitation for each month, mean daily temperature for each month, and a variety of other climate parameters that are used to generate the stochastic weather series. WGEN also requires evaporative zone depth, maximum leaf area index, growing season start and end date, average wind speed, and relative humidity for calculation of evapotranspiration.

Maximum leaf area index defines the density of trees and vegetation in the area. As described above, the value used consistently across the province was 4, to be consistent with the Grand Forks model.

Evaporative depth describes the maximum depth at which water can be lost from recharge to satisfy evapotranspiration demand. The depth is a function of soil properties and vegetation. Within HELP, the possible values include 20 cm, 51 cm and 91 cm. The minimum value allows for maximum evapotranspiration, minimizing recharge, which was conservatively and consistently used across the province.

Each of the aquifers across the province was sorted into a singular BGCZ (Figure 26b). Biogeoclimatic zones define the different ecosystems, climate and flora that exist in the different zones across B.C. Representative climate station and biogeoclimatic zone climate data was obtained from Will MacKenzie of the Ministry of Forest, Lands, Natural Resource Operations, and Rural Development (MFLNRORD) (See Table 21).

Table 21: Representative station reported per BGCZ. HELP has an internal database of separate climate stations which represent the representative location.

	Representative Station*	Closest HELP climate station
BG	Kamloops	Kamloops
BWBS	Fort Nelson A	Smithers
CDF	Victoria Int'l A	Victoria
CWH	Haney UBC	Vancouver
ICH	Revelstoke	Cranbrook
IDF	150 Mile House	Williams Lake
MS	Peachland	Peachland
PP	Kelowna	Penticton
SBS	Prince George A	Prince George

**B.C. Ministry of Forests, Lands, Natural Resource Operation and Rural Development*

Table 22 contains the input variables for growing season start and end date, quarterly relative humidity, precipitation, temperature, and wind speed were generalized for each BGCZ based on climate normals from 1960-1990.

Table 22: Input variables per BGCZ for WGEN in HELP.

	units	BG	BWBS	CDF	CWH	ICH	IDF	MS	PP	SBS
Growing season §										
start	day	132	161	97	129	150	148	167	126	161
end	day	272	248	308	287	261	261	250	278	251
Relative Humidity*										
Q1 - Jan, Feb, Mar	%	68	61	81	78	69	66	64	72	63
Q2 - April, May, Jun	%	58	59	71	69	61	58	60	60	57
Q3 - July, Aug, Sept	%	55	63	68	68	59	55	59	58	58
Q4 - Oct, Nov, Dec	%	63	68	75	76	69	64	65	66	67
Precipitation*										
January	mm	31.9	68.8	160.4	290.8	99.8	59.6	93.0	44.2	74.2
February	mm	19.4	47.4	122.9	229.7	69.4	39.1	62.3	27.0	49.3
March	mm	14.6	44.7	98.9	195.5	56.7	29.8	52.7	17.5	42.2
April	mm	20.2	34.3	56.3	148.5	47.7	30.1	41.4	21.9	33.4
May	mm	26.2	55.5	44.7	101.8	54.8	37.3	45.3	26.1	44.5
June	mm	29.1	77.4	33.6	80.9	62.4	39.9	48.8	24.3	57.9
July	mm	30.4	87.9	25.1	66.1	62.9	36.7	44.5	26.0	58.9
August	mm	32.0	74.9	33.9	84.7	63.3	39.6	47.1	30.8	57.8
September	mm	26.6	74.3	53.8	147.1	64.3	36.2	47.5	27.7	58.8
October	mm	22.4	80.9	107.8	298.4	81.7	41.1	71.9	25.4	69.4
November	mm	28.5	67.6	167.5	322.7	93.3	56.4	95.3	36.5	69.4
December	mm	40.8	68.6	183.3	311.1	109.7	66.3	98.2	50.0	76.1
Temperature*										
January	C°	-5.9	-14.1	2.8	-1.6	-8.0	-7.0	-8.2	-4.7	-10.5
February	C°	-1.9	-10.6	4.3	0.4	-4.5	-3.5	-5.4	-1.1	-6.6
March	C°	2.8	-6.1	5.8	2.4	-0.8	0.5	-2.6	3.1	-2.5
April	C°	7.4	1.0	8.3	5.3	3.9	5.0	1.6	7.6	2.7
May	C°	11.9	6.6	11.6	8.8	8.5	9.5	6.1	12.1	7.5
June	C°	15.9	11.0	14.6	12.0	12.4	13.4	9.9	16.2	11.4
July	C°	18.5	13.2	16.9	14.4	15.0	16.1	12.5	18.9	13.8
August	C°	18.1	12.2	17.0	14.6	14.7	15.8	12.4	18.5	13.2
September	C°	13.3	7.6	14.1	11.6	10.1	11.2	8.4	13.7	8.8
October	C°	7.4	2.1	9.6	6.9	4.2	5.4	3.0	7.6	3.6
November	C°	0.2	-7.7	5.4	1.8	-2.5	-1.6	-3.9	0.8	-4.2
December	C°	-5.0	-12.4	3.1	-1.2	-7.2	-6.5	-8.1	-4.0	-9.4
Average Wind Speed °	km hr^{-1}	11.0	7.0	10.0	12.0	5.2†	10.0	12.0	5.4†	10.0

§ Frost free start and end as a close approximation to growing season start and end.
**Average data from 1960-1990 for biogeoclimatic ecosystem zones by B.C. Ministry of Forests, Lands, and Natural Resource Operations*
° Climate normal data from 1960-1990 from Representative Climate Station data from Environment Canada
†Climate normal data from 1971-2000 from Representative climate stations (Environment Canada)

Growing season was determined by first frost free day and last frost free day, which is a common climatological meteorological definition (Brown 1976; Menzel et al. 2003). Average annual wind speed was obtained from Environment Canada's climate normals website for a representative station from each biogeoclimatic zone.

4.2.4 Soil & Aquifer Properties

In HELP, a vertical profile is created to represent the soil and aquifer materials. In this study, each vertical profile had two layers: a soil layer and underlying aquifer layer (Figure 25). The base of the vertical profile represents the average water table depth.

Soil materials were categorized using the British Columbia soils maps (https://governmentofbc.maps.arcgis.com/apps/MapSeries/index.html?appid=cc25e43525c5471ca7b13d639bbcd7aa) and the Soil Landscapes of Canada (SLC) version 3.2

(http://sis.agr.gc.ca/cansis/nsdb/slc/v3.2/index.html). The B.C. soils map data are at higher resolution, but data quality and availability are extremely heterogeneous. In contrast, the SLC data is at coarser resolution but is consistently mapped and has reasonable values of saturated hydraulic conductivity (K_{sat}) data for the soils overlying most aquifers in B.C. For this reason, we pair the SLC data (Figure 26a) with soil types from HELP using the expected K_{sat} as mapped. In order to transfer these values into HELP, the K_{sat} values were matched with existing HELP materials and given a soil type, S1-S6 (Table 23).

Table 23: Defining HELP soils based on SLC 3.2.

HELP Soil Class	SLC 3.2 K_{sat} cm hr^{-1}	HELP default input values HELP Soil Type	HELP default input values K_{sat} cm hr^{-1}
S1	33.0 30.0	Coarse Sand	33.0
S2	21.0 17.4	Sand	21.0
S3	10.0	Fine Sand	10.0
S4	5.20	Loamy Sand	5.20
S5	3.00	Sandy Loam	3.00
S6	1.00 0.300 0.200	Silty Loam	0.684

*When SLC returns a K_{sat} of 0, soil class is assumed to be S1.

Aquifer parameters (primarily K_{sat}) were derived from Gleeson et al. (2011) since the MENV data for aquifers only includes transmissivity and it is difficult to translate transmissivity into hydraulic conductivity when aquifer thickness is variable and often not readily available (Table 24). Calculating aquifer thickness for every aquifer across the province was beyond the scope of this project. Gleeson et al. (2011) compiled permeability values for different hydrolithologies from calibrated regional-scale groundwater models. Hydrolithologies from Gleeson et al (2011) are paired directly with aquifer types (1 - 6) to derive expected hydraulic conductivity values for aquifer sub-types (Wei et al. 2014) (Figure 26c&d). The recent MENV connectivity policy suggests transmissivities for aquifer types 1, 2, 3 and 4 are within an order of magnitude and are consistent with the proposed hydraulic conductivities, drawn from Gleeson et al (2011). We therefore model four aquifer types (A1 – 4) with characteristic K_{sat} values. There is one single aquifer code for all unconsolidated aquifers (A1) and three aquifer codes for bedrock aquifers (sedimentary – A2; carbonate – A3; and crystalline/volcanic – A4).

Drainage layer orientation is a selection between two drainage method profiles in HELP. Any given layer of a profile may be selected as either vertical or horizontal. Horizontal orientation is used in landfill or drainage design as it allows for input of a specified lateral flow into or out of the layer. The layers created in HELP for the province wide report were created as vertical drainage layers given that vertical drainage (i.e. recharge) was the parameter of interest in this study.

Slope defines the angle at which the surface of the soil and aquifer align. For simplicity, the slope used for all of these profiles is zero across the province, which maximizes the recharge calculated.

The soil layer thickness defines the depth of soil modelled from the profile surface down to the start of the aquifer material. For consistency across the province, soil thickness was assumed to be 1m, which is consistent with previous modelling for both Abbotsford-Sumas and Grand Forks models.

Table 24: Defining aquifer types for HELP analysis.

HELP Soil Class	B.C. aquifer classification	(Gleeson et al. 2011)	HELP default input values	
	Sub-type*	Aquifer material	HELP Soil Type	K_{sat} cm hr^{-1}
A1	1a; 1b; 2; 3; 4a	coarse grained unconsolidated	coarse sand	45.3
A2	5a; 6a	coarse grained siliciclastic sedimentary	silty loam	1.1
A3	5b	carbonate	loamy sand	5.7
A4	6b	crystalline; volcanic	silty loam	0.029

*when sub-type of aquifer is "UNK", aquifer material is used to determine HELP aquifer type. If aquifer material is sand or gravel, aquifer type is "A1", if bedrock material, aquifer type is "A2".

The vertical profile thickness is the distance from the top of the soil profile to the base of the profile. For recharge modelling studies, the profile represents the vadose zone with the water table forming the lower bounds. The average annual water table depth is used to define the thickness (Allen et al. 2004) (Figure 26c). Water passing through the base of the profile represents recharge. Whereas in reality the water table moves up and down seasonally, in HELP, the thickness remains fixed for the duration of the simulation. Soil morphology and precipitation have been shown to have significant effect on shallow water table depths (Calzolari and Ungaro 2012; Ghose et al. 2018). Therefore, water table depth is averaged per unique derived HELP code combination of soil and aquifer type (Table 25). For this study, the mean water table depth for each aquifer across B.C. was derived from Fan et al. (2013) as shown in Figure 26c. Mapping the mean depth for all the aquifers across the province based on well data was beyond the scope of this project.

4.3 Results

4.3.1 HELP Input Data for Recharge Models Categorized by Aquifer

Representative soil and aquifer hydraulic conductivities, precipitation determined by biogeoclimatic zone, and water table depth were varied for each aquifer.

Based on a global, 1-km resolution model of water table depth from Fan et al. (2013), aquifer types (A1 – A4) within biogeoclimatic zones generally have characteristic depth to water table with small ranges for each aquifer type, so water table depth is assumed to be consistent. Therefore, the input data that was varied for each aquifer was the soil hydraulic conductivity, aquifer hydraulic conductivity and weather, with the mean water table depth being assigned to each aquifer type (A1 – A4).

A histogram of the frequency soil types overlying aquifers across B.C. shows that soil types S2, S3, S5 and S6 are most common, while soil type S4 is absent (Figure 27). Soil types for each aquifer are explicitly linked to the soil hydraulic conductivity for each aquifer given that the soils derive from weathering of local materials. The distribution of unconfined aquifer types shows that type A1 (unconsolidated sand and gravel) is most common, A2 (sedimentary bedrock) and A4 (crystalline and volcanic bedrock) being moderately common, and A3 (carbonate bedrock) is uncommon (Figure 27).

Aquifers are commonly found in a variety of different BGCZs and aquifers are found in nine of the fourteen BGCZs in B.C: Bunchgrass (BG), Boreal White and Black Spruce (BWBS), Coastal Douglas-fir (CDF), Coastal Western Hemlock (CWH), Interior Cedar—Hemlock (ICH), Interior Douglas-fir (IDF), Montane Spruce (MS), Ponderosa Pine (PP), and Sub-Boreal Spruce (SBS). The BGCZs define the monthly climate parameters that are input into the weather generator in HELP.

Table 25: Average water table depths used for the HELP modelling based on unique combinations of biogeoclimatic zones, soil and aquifer type. Blank cells indicate no aquifers with these combinations. μ = mean, σ = standard deveiation.

Soil & Aquifer	Water table depth (m)																	
	BG		**PP**		**IDF**		**SBS**		**MS**		**BWBS**		**ICH**		**CDF**		**CWH**	
	μ	*σ*	*μ*	*σ*	*μ*	*σ*	*μ*	*σ*	*μ*	*σ*	*μ*	*σ*	*μ*	*σ*	*μ*	*σ*	*μ*	*σ*
S1_A1					27.7	23.3	17.8	4.9			8.5	1.6	12.3	12.6	24.1	0.1	26.6	26.3
S1_A2					84.4	0.0									15.7	15.2	20.2	26.2
S1_A4																	45.0	20.0
S2_A1			38.2	32.1	31.2	13.2	8.1	0.0			11.6	2.2	33.4	15.9	14.3	0.0	22.8	17.4
S2_A2			59.6	1.0											37.8	14.7		
S2_A4			52.8	0.0									31.2	0.0	44.4	6.9	45.2	14.4
S3_A1	33.8	19.4	26.4	13.4	44.4	23.9	12.5	8.0			21.6	15.8	22.9	0.0	19.3	17.3	19.5	15.3
S3_A2											14.4	0.0					47.6	0.0
S3_A4					37.0	0.0												
S5_A1	29.5	14.1	24.6	8.4	26.0	11.8	17.2	6.9					5.3	0.0	24.9	21.6	7.9	8.8
S6_A1	33.9	16.8	18.8	10.5	20.2	13.4	10.3	11.9	9.2	6.6			22.0	19.0	9.1	9.4	13.4	12.7
S6_A2															25.9	9.3	22.9	0.0
S6_A4															28.8	10.8	43.2	24.7

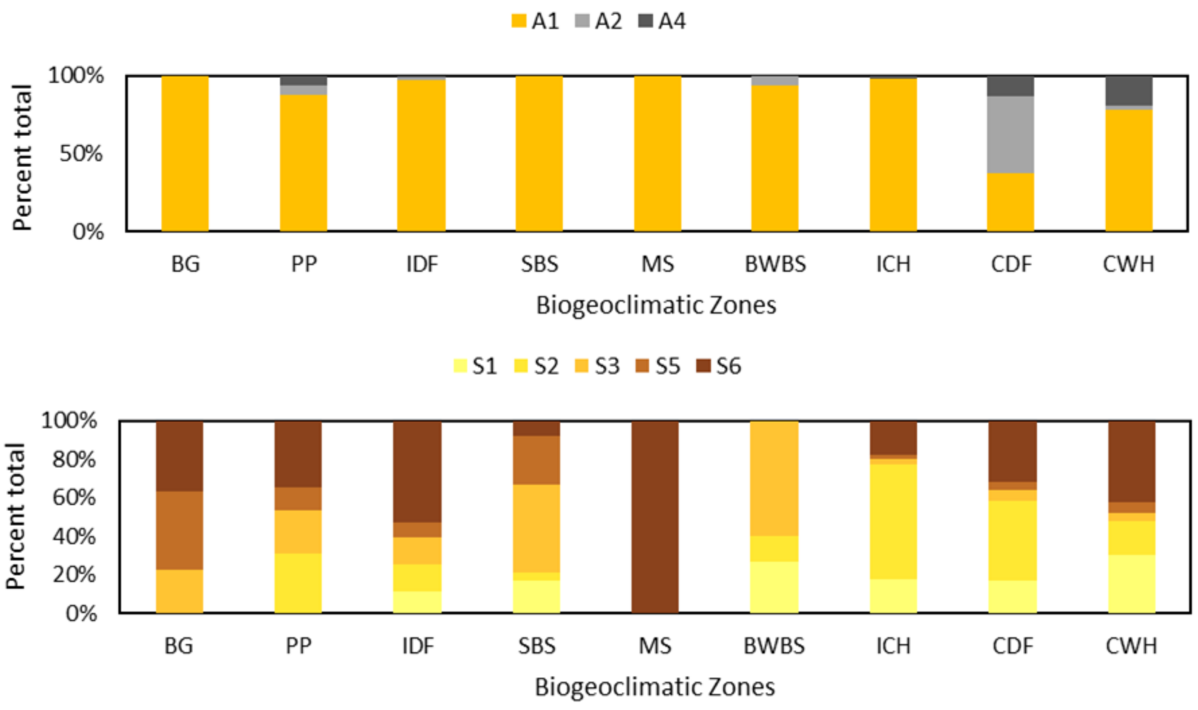

Figure 27: Distribution of type of aquifer types (above) and soil types (below) per BGCZ.

4.3.2 Recharge to Aquifers

Spatially, the results of this study varied across the province with a generally higher recharge along coastal regions and lower recharge in mid-southern regions of the province (Figure 28). Coastal regions have lower R_{HELP} values relative to modelled R_{PCR} values, whereas Interior regions have less difference between modelled R values (Figure 29).

Generally, BGCZs with lower precipitation rates have lower relative recharge rates (Figure 30). The mean R_{HELP} of all BGCZs was 329 mm/year with a median of 145 mm/year, and the mean R_{PCR} was 392 mm/year with a median of 229 mm/year. Average and median values of R have a greater correlation in the arid regions (BG, PP, IDF, SBS, MS, BWBS).

In general, we see a greater distribution in R_{PCR} values relative to R_{HELP} values in all zones, with increasing R_{PCR} distribution in zones of greater precipitation. PCR-GLOBWB calculates a recharge value per aquifer as opposed to HELP which assigns a value to the aquifer based on methodology of generalizing attributes.

Modelled recharge as a ratio of precipitation (R/P) falls within the range of 0-90% for most aquifers. Commonly, R_{PCR} values are greater than R_{HELP} values, with the exception of BWBS and CWH, where there is greater average modelled R_{HELP} compared to R_{PCR}.

Coastal Douglas-fir (CDF) had very high absolute and relative recharge rates (exceeding 100% of annual precipitation), which led to significant additional analysis. Firstly, we examined the relative recharge rates, expressed as R/P, at a monthly time scale (Figure 31). Most of the biogeoclimatic zones had monthly relative recharge rates <30% but Coastal Douglas Fir (CDF) and Coastal Western Hemlock (CWH) had much higher monthly results in excess of 100%. In these regions, high seasonal precipitation rates and low soil hydraulic conductivities lead to lags in the recharge in the soil above the aquifer, which then manifest as suspiciously high relative recharge rates in the dry summer months. Since the R_{HELP} values are derived from 100 years of simulations, profiles in CDF fluctuated drastically in modelled recharge

(<500mm - >1000mm). When coupled with lag time, the average modelled recharge appears greater than the average precipitation. The results of a simple sensitivity analysis varying soil hydraulic conductivities, which modified the timing and magnitude of this lag in recharge, and thus the monthly relative recharge rates, are given in Appendix C.

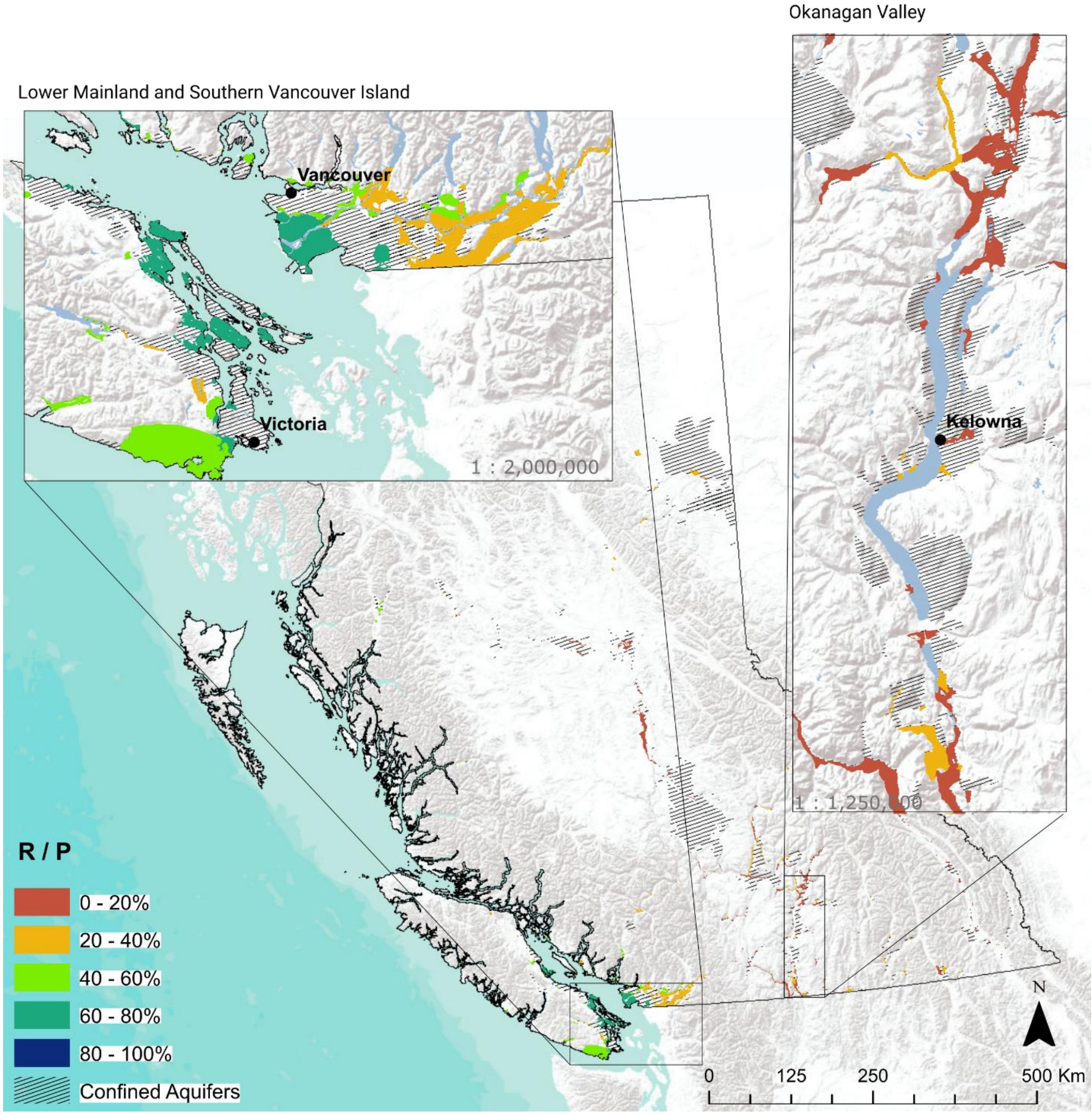

Figure 28: HELP modelled recharge (R_{HELP}) as a percent of precipitation distributed to mapped aquifers in B.C. (Recharge / Precipitation).

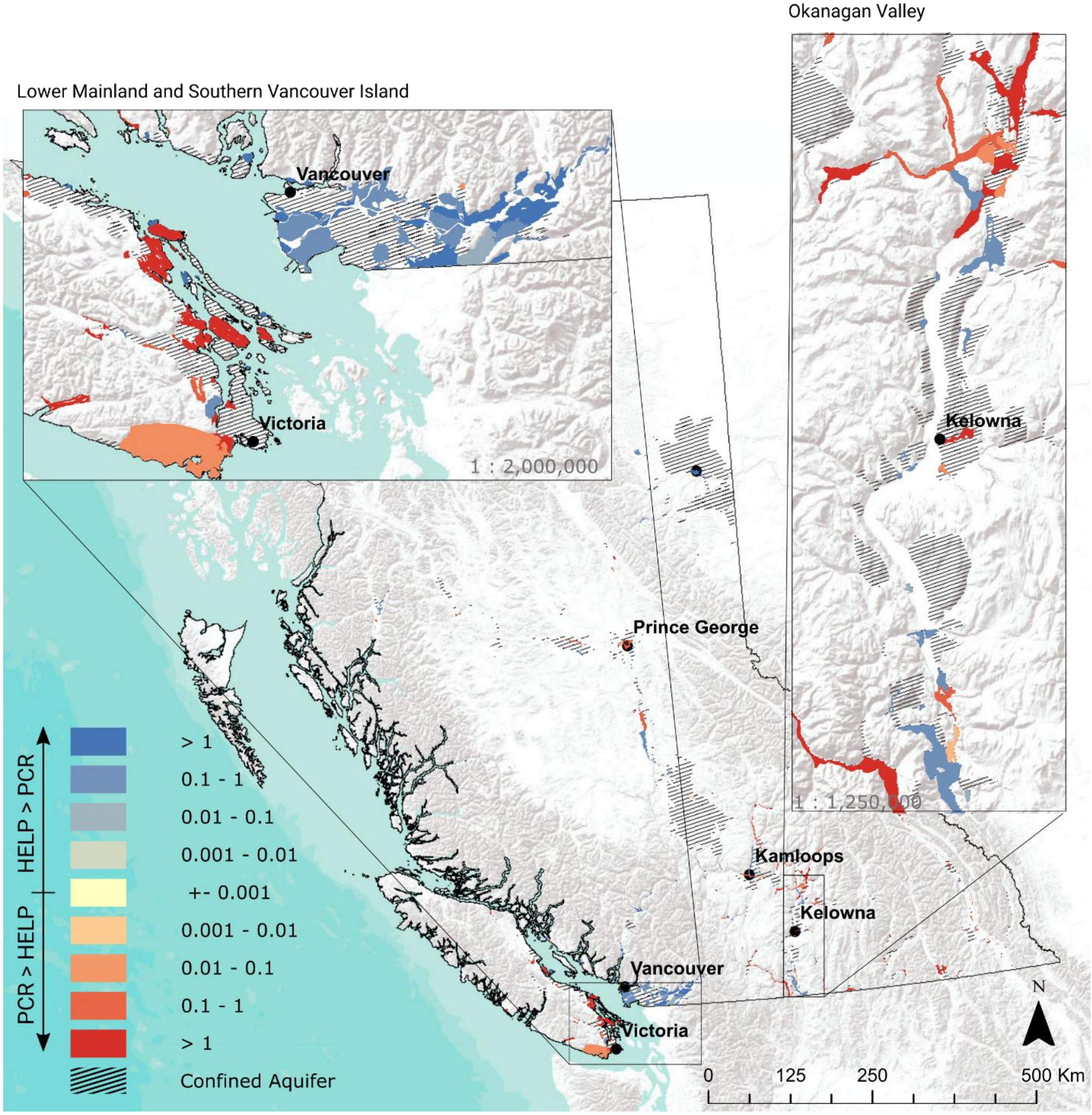

Figure 29: Modelled different of annual recharge (m / yr) of HELP and PCR-GLOBWB.

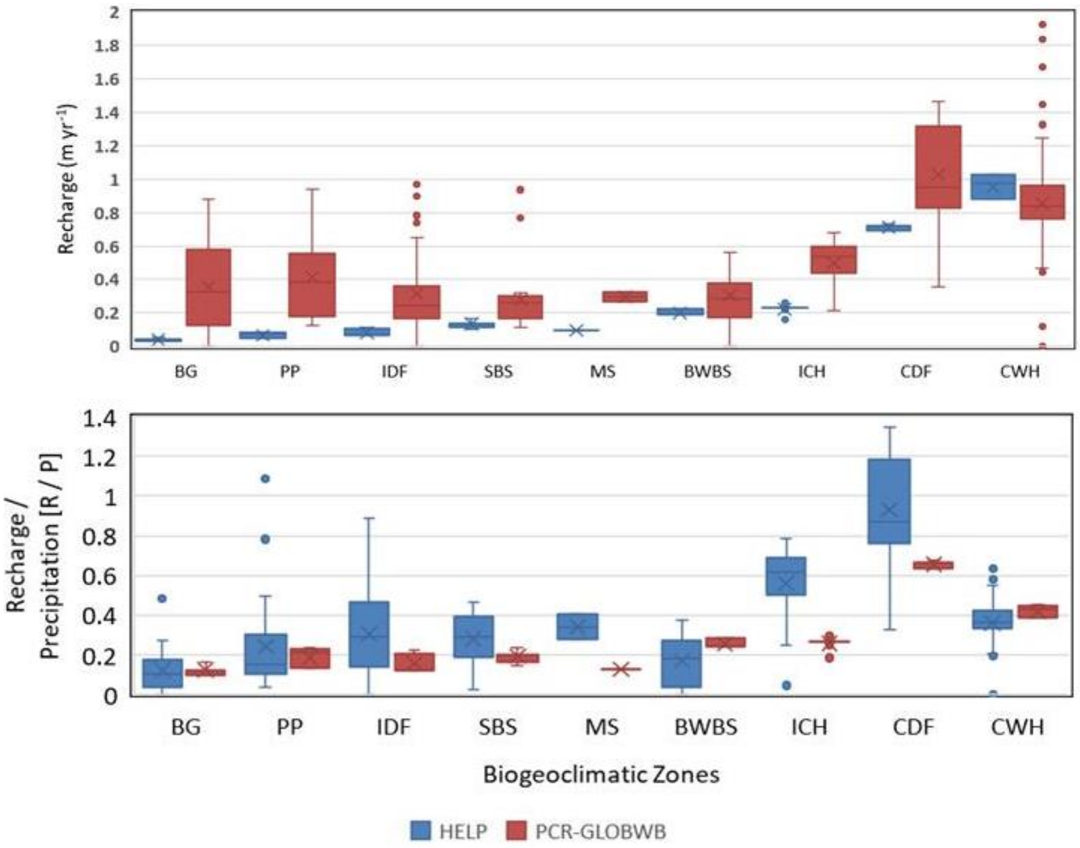

Figure 30: (above) Absolute values of derived recharge for HELP and PCR-GLOBWB. (below) Recharge represented as a percent of precipitation as per average BGCZ precipitations.

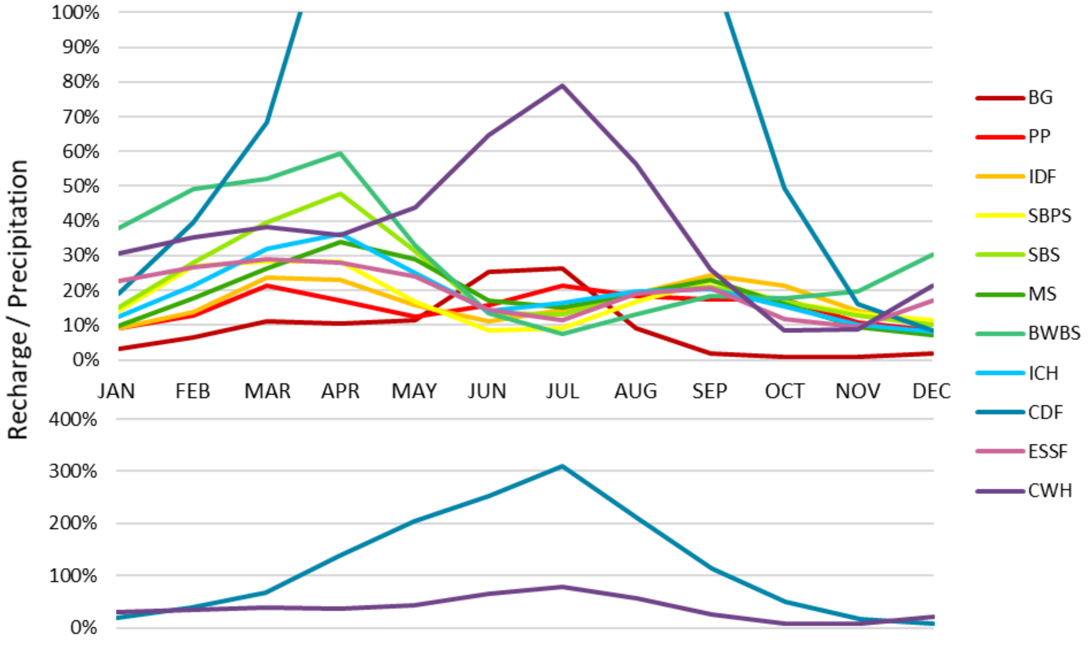

Figure 31: Monthly recharge for biogeoclimatic zones relative to precipitation for each biogeoclimatic zone (left) except CDF and CWH shown on right with a different y-axis.

4.4 Discussion

4.4.1 Comparison of Generalized Models to Previous Localized Recharge Models

We conducted comparisons to the previous localized recharge models of the Grand Forks aquifer (Scibek and Allen 2004) and the Abbotsford-Sumas aquifer (Scibek and Allen 2006b). This comparison is summarized here and detailed in Appendix C. The modelling purpose, as well as, the strategy for deriving input parameters is very different between these localized and generalized models so this should not be considered a calibration or validation, but rather a comparison of two different modelling strategies, using the same water balance model on the same aquifers. Table 26 and Table 27 show the differences in input parameters for the two aquifers. Note that Abbotsford-Sumas aquifer is at the boundary of Coastal Douglas Fir (CDF) and Coastal Western Hemlock (CWH) BGCZs, so it was modelled using weather input from both BGCZs. Results from the two different BGCZs of the Abbotsford-Sumas Aquifer in the generalized methodology bracket the range of absolute and relative recharge values modelled in the localized model (Table 28, Figure 32). Similarly, for the Grand Forks Aquifer, the generalized model is within the range of the previous localized model for both absolute and relative recharge (Table 29, Figure 33).

Table 26: Comparison of input values for Abbotsford-Sumas Aquifer

Input parameters	Localized Method	Generalized Method
Climate data	Abbotsford Airport climate normals	Biogeoclimatic Zone: CWH or CDF
Water table depth	*Mean:* 8.0 m (range of 0 to 78m)	8.95 m
Soil hydraulic conductivity	Weighted Average: 7.29cm/hr	0.684 cm/hr
Aquifer hydraulic conductivity	Mean: 371 cm /hr (range 0.3-437cm/hr)	Aquifer A1 - 45.3 cm hr^{-1}

Table 27: Comparison of input parameters for the Grand Forks Aquifer.

Input parameters	Localized Method	Generalized Method
Climate data	Grand Forks, B.C.	Biogeoclimatic Zone: PP
Water table depth	Mean: 11.4m (range of 1.5 to 46.8 m)	37 m
Soil hydraulic conductivity	Mean: 67cm/hr (4000 to 0 cm/hr)	10 cm hr^{-1}
Aquifer hydraulic conductivity	Inverse Distance Weighted (1300, 167, 5.83 and 0.06 cm/hr)	Aquifer A1 - 45.3 cm hr^{-1}

Table 28: Abbotsford-Sumas Aquifer results.

	Precipitation mm $year^{-1}$	Recharge mm $year^{-1}$	Recharge / precipitation -	Range mm $month^{-1}$
Generalized Method (CWH)	2277	912	40%	6 - 257
Generalized Method (CDF)	1088	728	67%	10.75 - 125
Localized Model	1570	650-1000	41-64%	0 - 120

Table 29: Grand Forks Aquifer results.

	Precipitation mm $year^{-1}$	Recharge mm $year^{-1}$	Recharge / precipitation -	Range mm $month^{-1}$
Generalized Method (CWH)	357	67	19%	0.65 - 7.92
Localized Model	534	30 - 120	5.6% - 22.5%	n/a

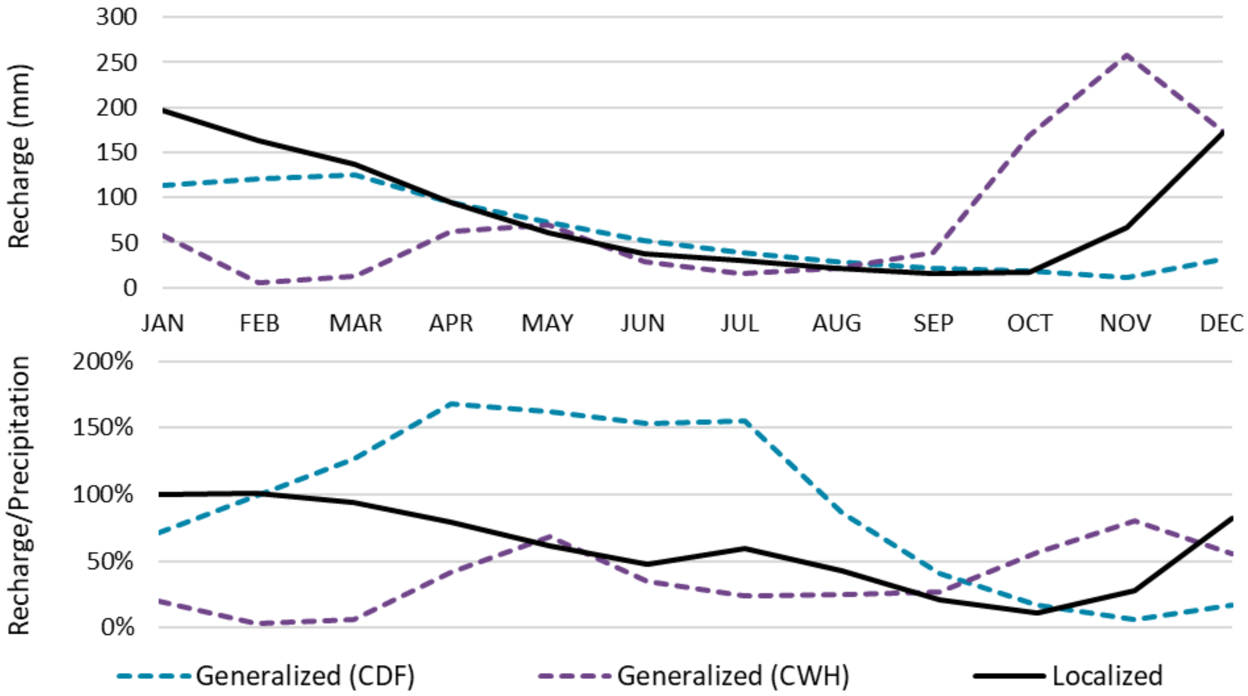

Figure 32: Abbotsford-Sumas comparison where the localized recharge was measured with HELP in a previous study by Scibek and Allen (2006b). As the aquifer falls closely to the BGCZs of Coastal Douglas-fir (CDF) and Coastal Western Hemlock (CWH), both are plotted here.

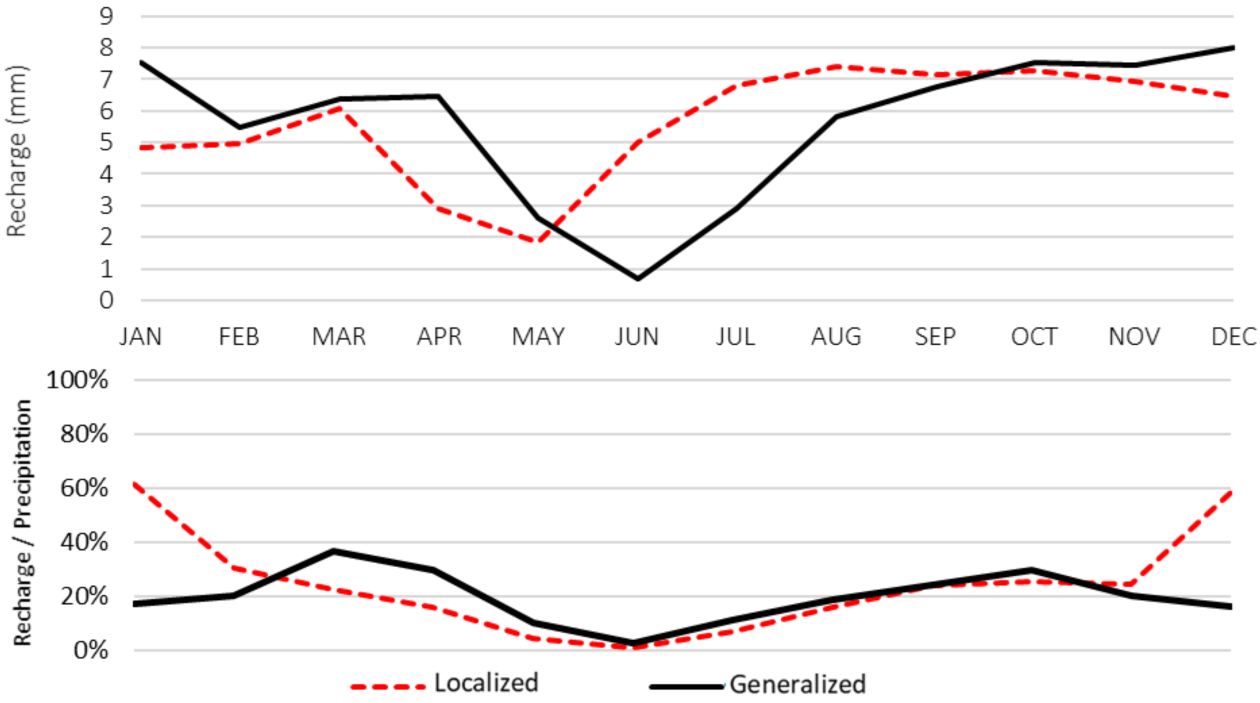

Figure 33: Grand Forks aquifer comparison where the localized recharge was measured with HELP in a previous study by Scibek and Allen (2006b).

4.4.2 Comparison of Generalized Models to PCR-GLOBWB

The modelled absolute and relative recharge for HELP lies within the distribution of PCR-GLOBWB (Figure 30).

HELP values are not as distributed as PCR-GLOBWB within biogeoclimatic zone likely due to the generalization of parameters when modelling. Evaporative depth, land cover, vegetation, soil thickness, and growing season were all kept constant for the HELP modelling and are parameters which vary per aquifer in PCR-GLOBWB possibly attributing to a greater distribution of modelled R_{PCR} values.

PCR-GLOBWB is a more complex model taking into account a variety of parameters, whereas HELP is a simple 1D vertical column. However, the scale of HELP includes a more controlled and aquifer scale estimate, as opposed to PCR-GLOBWB which measures and averages values over 10x10km scale. Therefore, if the aquifer in question is represented by these average conditions then the R value will be more precise.

The main uncertainty is calculated values of runoff and mountain block recharge. Therefore, aquifers where recharge is mainly from vertical infiltration, and is well represented by the surrounding 10x10km^2 area, R_{PCR} values are expected to be more accurate as they consider more hydrological processes, compared to HELP.

For aquifers in mountainous regions, recharge processes are more complex with the inclusion of mountain block groundwater flow recharging valley aquifers. PCR-GLOBWB impacts R in mountainous areas in two different ways: (1) increases R because precipitation is increased based on average elevation (and higher average elevation in that cell will mean higher modelled precipitation); and (2) decreases R as it takes into account runoff based on the percent of the cell areas which has a slope - but in mountainous areas that hillslope runoff is often recharged to the valley aquifer (mountain front recharge). In zones where local lateral recharge plays a significant role in aquifer recharge such as in valley aquifers, we would expect R_{PCR} values to be greater than R_{HELP} values.

In the HELP model, ignoring lateral flow is the biggest limitation, therefore R_{HELP} are expected to be underestimated in valley aquifers. Another major limitation in HELP, is the water table is at a fixed location throughout the simulation, therefore, recharge can be overestimated in areas where the water table fluctuates significantly annually. Other important model simplifications for vertical infiltration include: (1) ignoring preferential flow; (2) not considering the role of macroporosity; (3) ignoring focused recharge via leakage from ephemeral streams, wetlands, or lakes (Nasta et al. 2016).

5. GROUNDWATER CONTRIBUTIONS TO ENVIRONMENTAL FLOWS

5.1 Background & Theory

This section first contains some background on environmental flow needs (EFN) with a brief description of the definition for the purpose of this study, common methods, and the current B.C. framework. Groundwater's contribution to environmental flows (E) is a fraction of EFN which is sourced from groundwater, as opposed to surface water sources (such as runoff or interflow).

Environmental flow needs of a stream are defined in B.C. as 'the volume and timing of water flow required for proper functioning of the aquatic ecosystem'(Province of British Columbia 2016b). Scientific literature supports environmental flow regimes as essential to sustain freshwater and estuarine ecosystems and the human livelihood and well-being that depend on the ecosystems' (Zektser et al. 2005; Acreman et al. 2014; Harwood et al. 2014; Gleeson and Richter 2018).

Discharged groundwater into streams provides a consistent supply of water supporting dry periods in addition to helping to maintain water levels, temperature, oxygen content, and required chemistry (Wallis et al. 1981; Bottomley et al. 1984; Constantz 1998; Wood et al. 1999; Valett H. et al. 2003; Brown et al. 2007). It has long been understood that groundwater extraction reduces streamflow via the interception of groundwater that otherwise would have been discharged to the stream (Konikow and Kendy 2005; Barlow and Leake 2012; Famiglietti 2014 - Figure 34). Previous EFN studies have historically been focused on hydrologic alterations as a result to surface water alterations such as dams, impoundments, and stream dependent water diversions (Poff and Zimmerman 2010) even though groundwater abstractions have been long known to cause significant hydrologic alteration over prolonged temporal scales (Barlow and Leake 2012). In B.C., prior to the emergence of the WSA, there was no regulatory or legal authority for groundwater, and therefore, no need for assessing the impacts from groundwater abstraction on streams from a management perspective. Groundwater pumping eventually leads to a reduction in streamflow and the majority of the pumped groundwater is streamflow depletion - decreased groundwater discharge or induced infiltration from the river (Figure 34). As a critical and distinct driver impacting river ecological conditions and hydrology, groundwater's contribution to streamflow should be explicitly considered in environmental flow assessments (Gleeson and Richter 2018).

The current B.C. EFN policy mentions assessing groundwater in decisions. The policy is applied to the stream of interest using supply and demand information to characterize the environmental risk management level as 1, 2, or 3 (Province of British Columbia 2016b). Risk management measures are used to assess or mitigate potential effects of withdrawal from a stream, where a risk management level of 1 deems a stream to have sufficient natural water availability for the proposed withdrawal period and that cumulative withdrawals are below the specific threshold. A risk management level 3 is a stream or a period of flow where the aquatic environment may be flow-limited or the cumulative water withdrawals are greater that the specified threshold. There may be modifications to address regional hydrological and ecological sensitivities. Fish presence or absence should be demonstrated using existing standards conducted by qualified individuals or regional expertise, and all streams should be considered fish-bearing by default.

For the purpose of this study, based on the importance of considering groundwater's contribution of environmental flows, we use two methods to quantify the groundwater's contribution to EFN for spatially distributed aquifers in B.C. In an ideal situation, 'holistic' EFN studies are the most comprehensive and best suited to the overall consideration of the broad range of species and ecological relationships and processes. However, such holistic approaches are dependent on multidisciplinary sources, often requiring large amounts of data, are time consuming, and costly to collect and analyze data. Where holistic approaches are not available, hydrological approaches can provide relatively simple and inexpensive assessments. However, riverine ecosystems are inherently complex and assessments with generalization of natural flow variability should be considered as a screening level tool until future 'holistic' local studies are available.

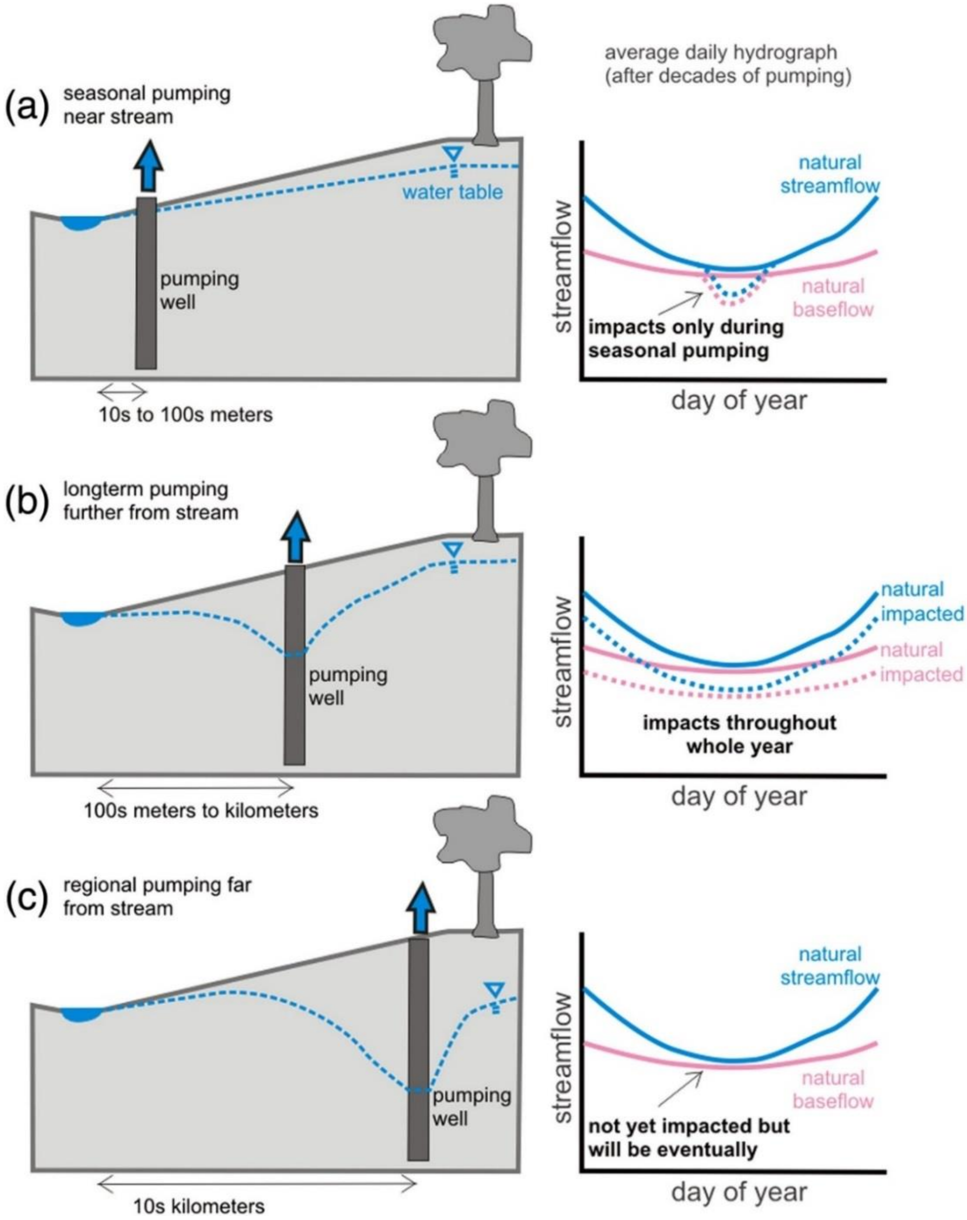

Figure 34: The impacts on streamflow are highly variable through time and space. Daily hydrographs at the end of decades of pumping to the right show natural streamflow and baseflow conditions and the resultant impacted streamflow and baseflow as dashed lines. (a) Seasonal pumping near a stream can potentially only impact part of the daily hydrograph. (b) Long-term pumping further from the stream could impact through the whole year. (c) Regional pumping far from the stream could potentially not significantly impact the stream for decades after the start of pumping. (Figure from Gleeson and Richter, 2017)

The two methods for the quantitative assessment of E will be useful until the province is able to fill the knowledge gap through local data and detailed aquifer studies. The first approach uses the groundwater presumptive standard (E_{PS}), which is a standard for managing groundwater pumping appropriate for maintaining environmental flows by explicitly including the potential impacts of groundwater pumping over long temporal scales. The second method introduces a novel approach for estimating the contribution of groundwater to environmental flows using the existing B.C. environmental flow needs framework and an understanding of low flow zone hydrology. Both methods are based on predevelopment conditions of baseflow and streamflow. As both these methods rely on modelled baseflow and streamflow respectively, uncertainties increase in mountainous terrain where the regional model may not fully represent local stream-aquifer dynamics. The main purpose of this section is to provide quantitative assessment of E for the purpose of measuring aquifer stress for all unconfined aquifers in B.C. (404 aquifers). E is a difficult parameter to measure in the field, and is time and data intensive. Therefore, we used modelled data which allows for quantification of E for aquifers in data scarce regions. For this purpose, two methods are applied based on different datasets, the E_{PS} is advantageous because it is more aligned with groundwater stress management and is a peer-reviewed approach to evaluating E, however comparing estimates of baseflow to observations is inherently difficult, therefore, limitations exists in using modelled baseflow values. In contrast, E_{LF} approaches quantification of E using streamflow data, where the extraction of groundwater's contribution to flow is more difficult and based on many hydrologic assumptions. However, advantages include being able to apply a more B.C. specific approach inspired by the established EFN policy. Additionally, using streamflow data is often more abundant and measureable compared to baseflow data. Both methods quantify annual fluxes of E over long term simulations which derive a steady state value for the purpose of aquifer stress, therefore, inherently masking seasonal fluctuations where E may be much higher.

5.2 Groundwater Contribution to Environmental Flows from the Groundwater Presumptive Standard (GPS)

The groundwater presumptive standard is based on the Sustainability Boundary Approach of Richter (2010) which involves restricting hydrologic alterations to within a percentage-based range of natural or historical flow variability (Figure 35). The groundwater presumptive standard is a standard for managing groundwater pumping appropriate for maintaining environmental flows by explicitly including the potential impacts of groundwater pumping over long temporal scales. The groundwater presumptive standard suggests that high levels of ecological protection will be provided if groundwater pumping decreases monthly natural baseflow by less than 10% through time.

$$E_{PS} = 0.9 \cdot Q_{bf} \qquad \text{(Eq. 19)}$$

where E_{PS} is groundwater's contribution to environmental flows [L/T], and Q_{bf} is baseflow [L/T]. Baseflow is commonly defined as "the portion of [stream] flow that comes from groundwater or other delayed sources" (Hall 1968; Tallaksen 1995) and can originate from groundwater, lakes, reservoirs, snowpack, or glaciers. For the purpose of this study, we will focus on groundwater-derived baseflow since the focus of this study is on aquifer stress. This groundwater presumptive standard of 10% should be considered nested within and part of current EFN frameworks for streamflow rather than additional 10%. This presumptive standard is intended to provide estimation of E where detailed scientific assessment of environmental flow needs cannot be undertaken.

5.2.1 Data

Baseflow separation is usually conducted on gauged basins and/or regions with detailed field data which does not provide enough spatial coverage of the aquifers in B.C., so these methods are not applied herein. Field methods include temperature, artificial and natural tracer concentrations, and flow in seepage meters installed in stream beds, however, these often provide site specific baseflow, and it is difficult to apply these techniques over an entire catchment or aquifer area (Smakhtin 2001b; Partington et al. 2012). Baseflow separation techniques are often event based from streamflow hydrographs and formulaic specifications for baseflow peak timing is not necessarily representative of fundamental basin characteristics and remains inherently subjective. The alternative approach to estimating baseflow is to utilize stochastic simulation data (Smakhtin 2001b; Schwartz 2007).

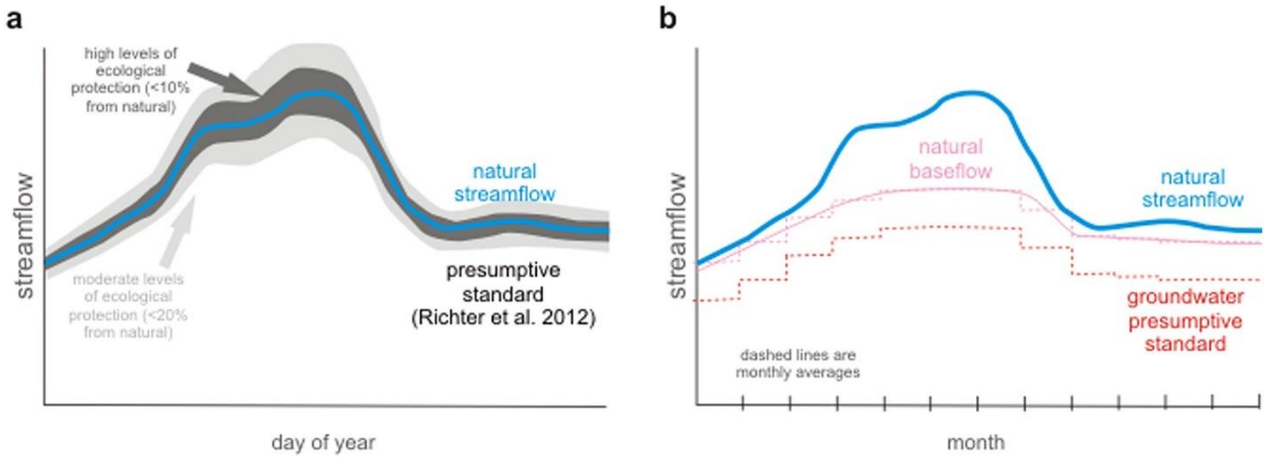

Figure 35: (a)The presumptive standard for protecting streamflow (adapted from Richter et al., 2012) and (b) the groundwater presumptive standard for protecting baseflow from the impact of groundwater pumping. (Figures (a) and (b) from Gleeson and Richter 2017).

5.2.2 Methods

Spatially distributed estimates of baseflow were derived using a MODFLOW groundwater model (De Graaf et al. 2015) which is coupled with PCR-GLOBWB. Q_{bf} is the sum of two model outputs:

$$Q_{bf} = Q_{drn} + Q_{riv} \qquad \text{(Eq. 20)}$$

where

Q_{bf} is the flux of flow from aquifer into the stream ($L^3\ T^{-1}$).
Q_{riv} is the flow from the aquifer to large (width > 10 m) ($L^3\ T^{-1}$).
Q_{drn} is the flow from the aquifer to small rivers (width < 10 m) ($L^3\ T^{-1}$).

Where Q_{riv} or Q_{drn} had positive values, indicating a positive flux from the stream to the aquifer, these values were set to zero, and E_{PS} is consequently equal to 0. Due to the resolution of the model, the main stream is insufficient to represent all locations within cell where groundwater levels intersect the terrain and additional drainage is needed to represent local sages, springs, and streams higher up in mountainous areas (De Graaf et al. 2015). Therefore, the estimation of Q_{bf} can be expected to be conservative in mountains areas which represent a large portion of the province, and locations where large groundwater gradients exist within a small spatial scale (springs).

As Q_{bf} is reported as m^3d^{-1}, volumes were converted to annual fluxes ($m\ yr^{-1}$) and area averaged for the spatial coverage of mapped aquifers.

$$Q_{bf,i} = Q_{bf} \cdot A_i \qquad \text{(Eq. 21)}$$

where

$Q_{bf,i} =$ represents the baseflow discharge ($m^3\ yr^{-1}$).
A_i is aquifer area (m^2) for aquifer i.

The annual flux of aquifer (i) groundwater contribution to EFNs is then derived as follows:

$$E_{PS} = 0.9 \cdot Q_{bf,i} \qquad \text{(Eq. 22)}$$

where E_{PS} (m^3yr^{-1}) represents the annual flux of groundwater to streamflow in order to maintain a high level of ecological protection based on the groundwater presumptive standard.

5.3 Groundwater Contribution to Environmental Flows from Streamflow (ELF)

The second method introduces a novel approach for estimating E using the existing B.C. EFN framework and an understanding of low flow zone hydrology. This method derives E based on modelled streamflow hydrographs, which provides consistent data coverage for most aquifers in B.C., as well as provides a comparison to gauged stations to better evaluate how well they represent conditions in B.C.

Low flows can have many definitions to different interest groups, the International glossary of hydrology defines low flows as "flow of water in a stream during prolonged dry [but not drought] weather" (WMO 2012). The majority of natural gains to streamflow during low-flow periods are derived from releases from groundwater storage (Smakhtin 2001a; Frisbee et al. 2011), which allows low flow statistics and metrics to be used as a surrogate for estimating groundwater's contribution to environmental flows (Gleeson and Richter 2018).

This methodology approaches deriving E, an annual flux, with the underlying assumption that groundwater supports seasonal low flows. The approach utilizes streamflow data to extract a representative annual contribution of groundwater to streamflow over an aquifer area from long-term monthly hydrographs derived from gridded models.

$$E_{LF} = k_{EFN} \cdot Q_{GW} \cdot f_{local} \qquad \text{(Eq. 23)}$$

where

E_{LF}	is groundwater's contribution to environmental flows ($m^3\ yr^{-1}$)
k_{EFN}	is the coefficient representing the proportion of annual streamflow reserved for EFN (unitless)
Q_{GW}	is mean annual groundwater supported streamflow
f_{local}	is the proportion of streamflow originating from the area of interest.

5.3.1 *Data*

Spatially distributed mean monthly streamflow was derived from the streamflow model from PCR-GLOBWB. Modelled streamflow ($m^3\ yr^{-1}$) is reported on a 100 km^2 resolution grid and is the combined modelled output of baseflow, direct runoff, and interflow, which are routed as streamflow based on topology within the model (see Appendix D for streamflow comparison between observed streamflow stations and modelled streamflow).

5.3.2 *Methods*

To derive Q_{GW}, the mean annual groundwater supported streamflow, mean monthly streamflow data is classified into low, moderate, and high sensitivity months based on the B.C. EFN policy assuming all streams are fish bearing. The classification of high sensitivity streams (Table 30) are assumed to represent low flow conditions and supported primarily by groundwater.

Table 30: Classification of flow sensitivities based on B.C.'s EFN policy using mean monthly flows and mean annual discharge values.

Hydrologic season	B.C. stream classification	Determination method	k_{EFN}
Low flow	High sensitivity	< 10 % MAD	95%
Intermediate flow	Moderate sensitivity	10 -20 MAD	90%
High flow	Low sensitivity	≥ 20% MAD	80%

The highest mean monthly flow (MMF) within the low flow months was used to provide a conservative estimate for groundwater supported streamflow (Q_{GW}) on an annual basis, as groundwater discharge to streams would increase during high flow seasons.

$$Q_{GW} = 12 \cdot Q_{LF} \quad \text{(Eq. 24)}$$

where Q_{GW} represents groundwater's annual contribution to streamflow (m^3 yr^{-1}), and Q_{LF} is the mean monthly flow (m^3) for the highest low flow month.

As modelled streamflow is represented by a cell area, streamflow in composed of two main parameters, $Q_{LF,upstream}$, the upstream sourced flow, and Q_{LF}, the flow sourced from within the local cell area. The local additions equate to the sum of discharges into the stream from the local cell area, such as baseflow, runoff, interflow. The local additions (f_{local}, unitless) to streamflow are derived as follows:

$$f_{local} = \left(1 - \frac{Q_{LF,upstream}}{Q_{LF}}\right) \quad \text{(Eq. 25)}$$

The proportion of streamflow reserved for EFN, k_{EFN}, is motivated by the risk management categories in the B.C. EFN policy and summarized in Table 25. Risk management measures are used to guide water managers in water permit allowances and assess and mitigate potential effects of surface water or groundwater withdrawal from a stream. For the purpose of this study, EFN allocations will be based on maintaining streams in the risk management level 1, which is defined as a stream with "sufficient natural water availability".

E_{LF} (m^3 yr^{-1}), the required annual flux of groundwater to EFN streamflow based on the current B.C. EFN policy can then be derived by:

$$E_{LF} = k_{EFN} \cdot Q_{GW}\left(1 - \frac{Q_{LF,\ upstream}}{Q_{LF}}\right) \quad \text{(Eq. 26)}$$

As E_{LF} is reported as $m^3 yr^{-1}$, volumes were converted to annual fluxes (m yr^{-1}) and area averaged for the spatial coverage of mapped aquifers.

$$E_{LF,i} = E_{LF} \cdot A_i \quad \text{(Eq. 27)}$$

where $E_{LF,i}$ represents the required groundwater discharge to EFN for a given aquifer i ($m^3 yr^{-1}$), and A_i is aquifer area (m^2) for aquifer i.

5.4 Results

Annual flux values of E_{PS} and E_{LF} have variable coverage in coastal regions. E_{PS} was derived for 367 unconfined aquifers with flux values ranging from 0 to 1.07 m yr^{-1} with an average value of 0.234 m yr^{-1} for mapped aquifers in B.C. (Figure 36). 373 aquifers have calculated E_{LF} (Figure 37). Derived E_{LF} flux values for aquifers range from 0 to 36.1 m yr^{-1} with an average value of 7.704 m yr^{-1} (Table 31).

Table 31: R Results for derived values of E using the groundwater presumptive standard and the low flow zone approach.

Method	Mean	Median	Min	Max	No. Aquifers
		m yr^{-1}			n
E_{PS}	0.234	0.148	0	1.19	367
E_{LF}	7.70	0.252	0	197	372

Derived values of E_{PS} have little variation, and are more regionally consistent (Figure 36). Larger distribution of values is expected for E_{LF} as values are based on streamflow under the assumption that flow is supported by groundwater supply. Therefore, in regions where flows have significant contributions from surface water sources (such as runoff or snowmelt), this method will significantly overestimate E (Figure 37). When the methods are compared, E_{LF} is consistently greater than E_{PS} in mountainous terrain, possibly attributing to the greater influx from surface water sources in these regions (Figure 38).

In general, E_{PS} and E_{LF} have larger contributions from groundwater to environmental flows in the Lower Mainland and southern Vancouver Island compared to the Interior. In general, results from the Interior of the province suggests the E_{LF} > E_{PS} as opposed to the coastal regions where E_{PS} > E_{LF} (Figure 38).

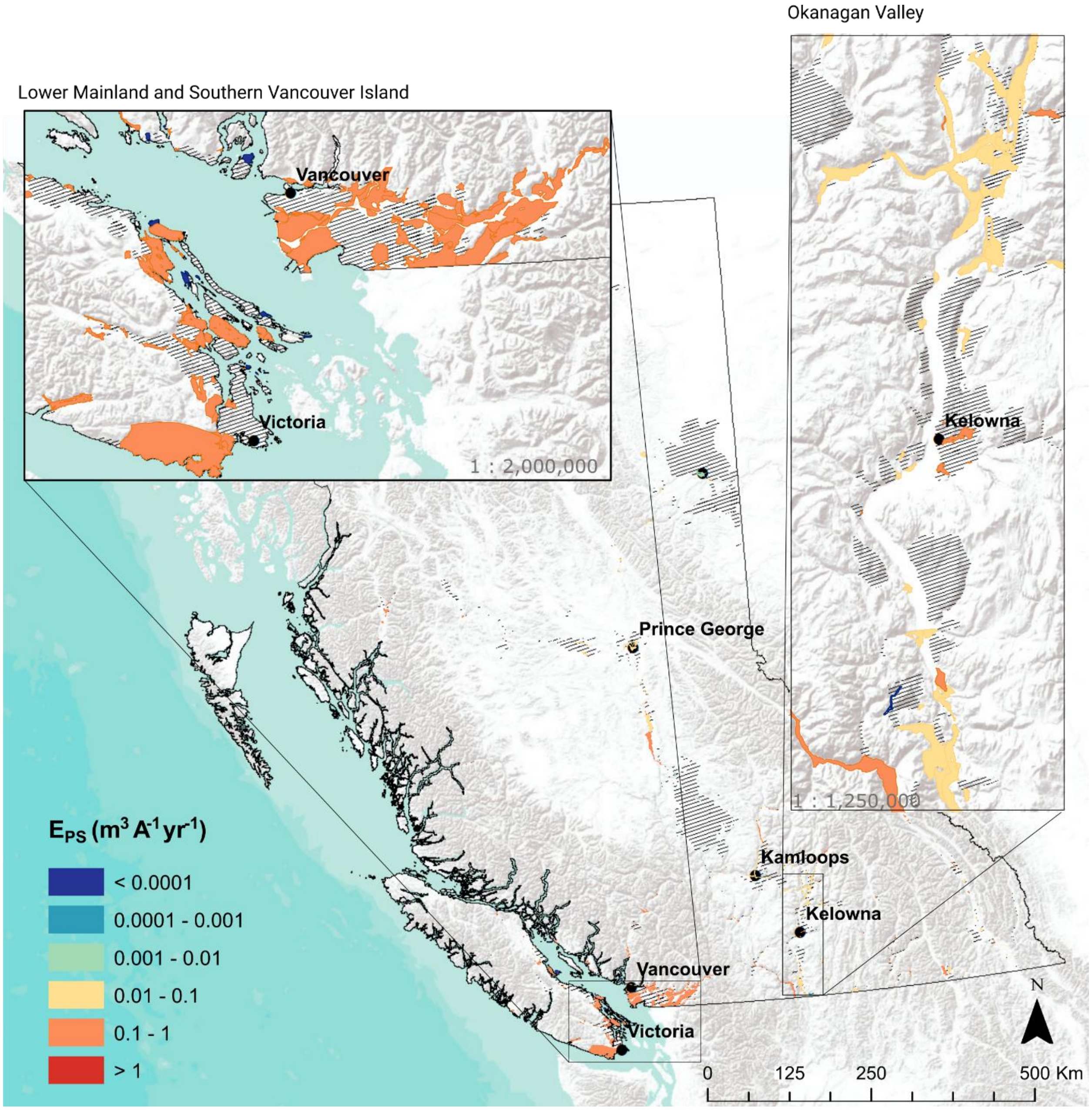

Figure 36: Resultant fluxes of groundwater's contribution to environmental flows based on the groundwater presumptive standard.

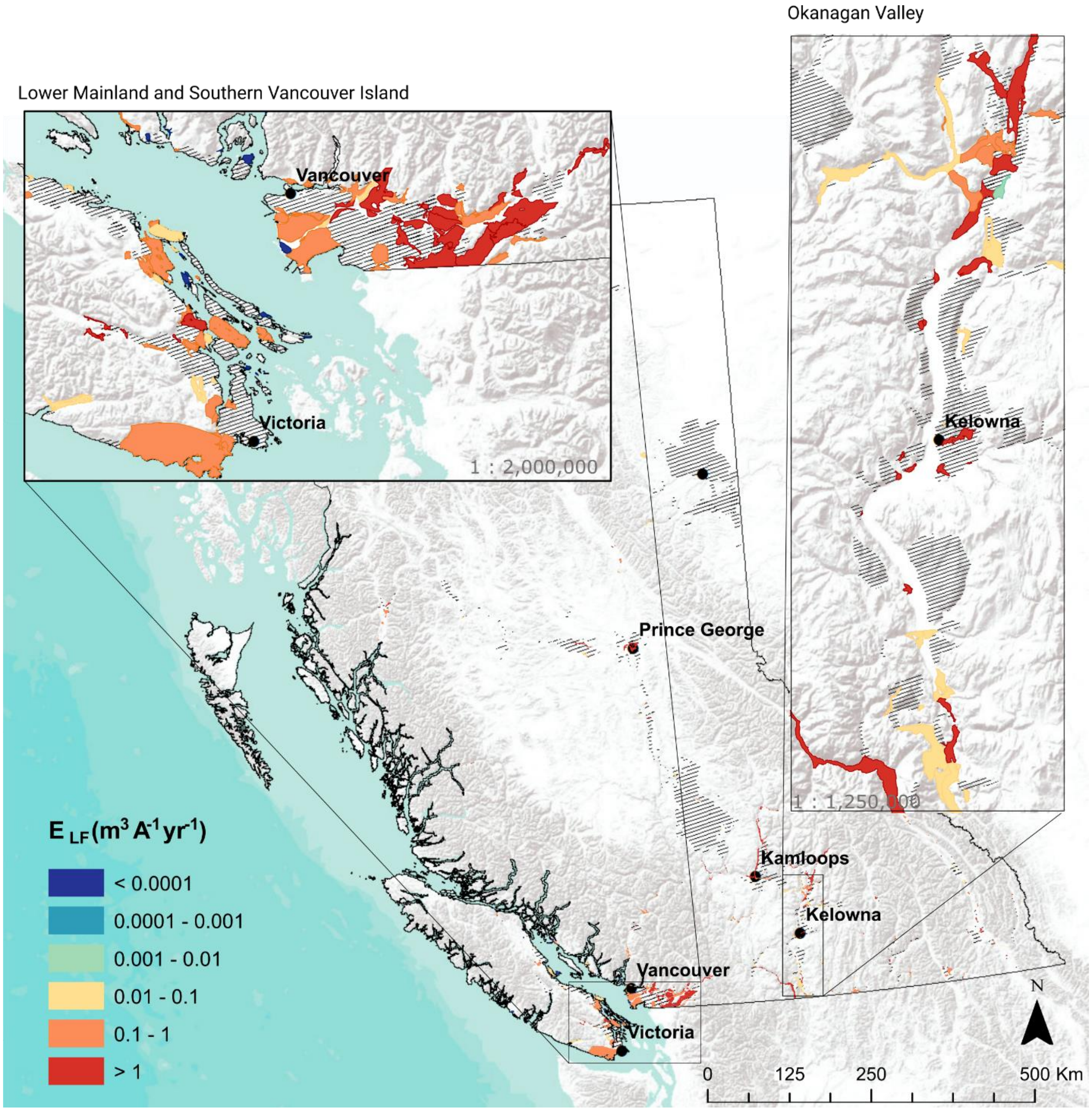

Figure 37: Resultant fluxes of groundwater's contribution to environmental flows based on the low flow zones approach.

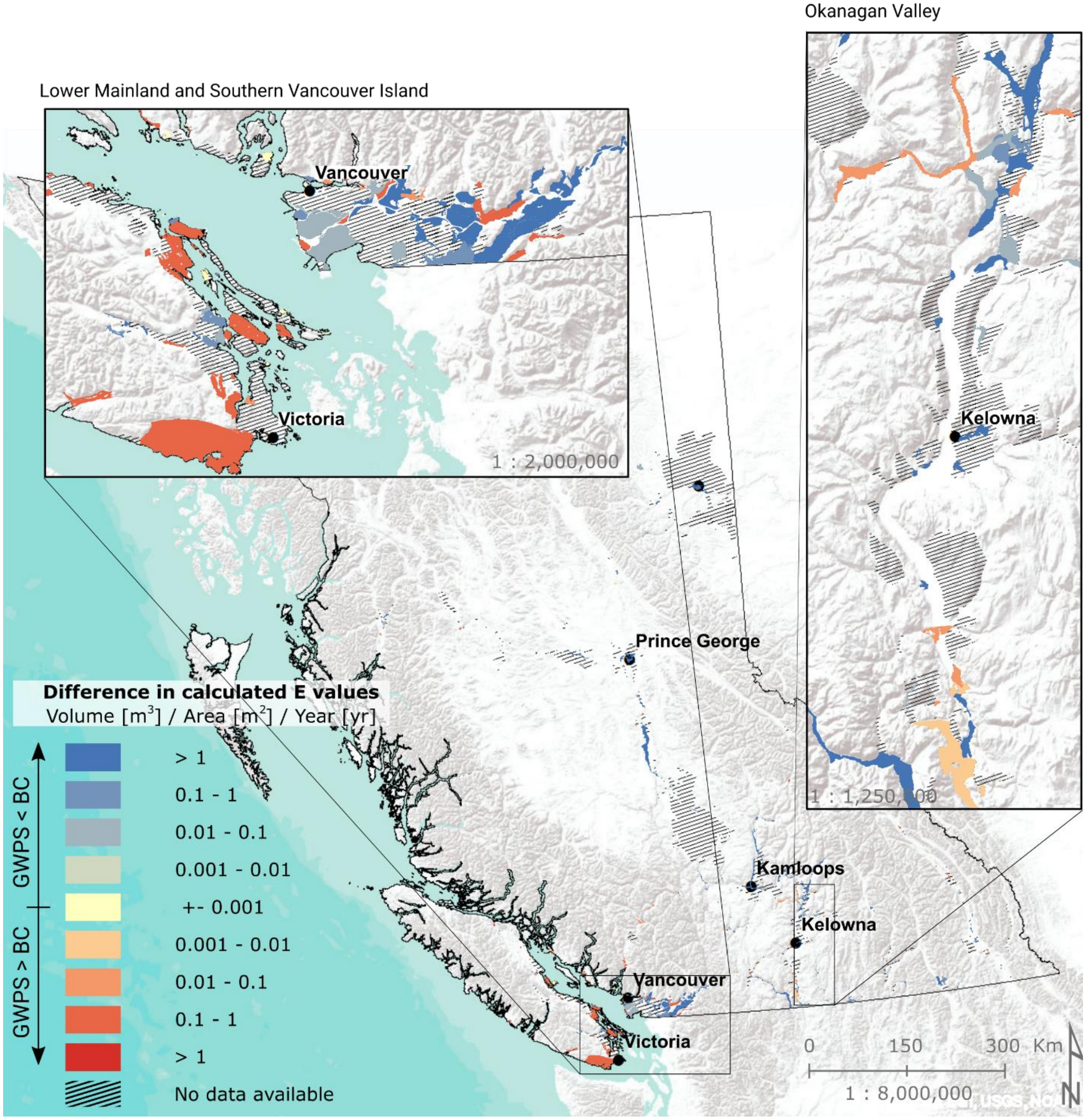

Figure 38: Resultant fluxes from the difference in groundwater's contribution to environmental flows approaches.

In general, aquifer E_{PS} and $E_{LF.}$ values increase in BGCZs of increased precipitation (Figure 39a). E values increase with zones of increased precipitation for more arid (BG, PP, IDF) and humid (ICH, CDF, CWH) zones, which agrees with expected values.

Low flow zones were characterized by Coulson and Obedkoff (1998) based on hydrologic zones and annual average 7-day low flows. Low flow zones are organized from zones high drainage/discharge area (i.e. Queen Charlottes) to zones of lower discharge/drainage area (i.e. Northeast Plains). Observed derived E_{PS} values decrease in zones of lower discharge/drainage area (Figure 39b). Georgia basin has higher than trend E_{PS} values, however, lies within a precipitation zone similar to the coastal regions of Queen Charlotte, Vancouver Island, and Coastal Mountains which could explain the higher than average trend E_{PS} values. E_{LF} values also decrease in zones of lower discharge/drainage area, however have a large variation in values in the Coast Mountains.

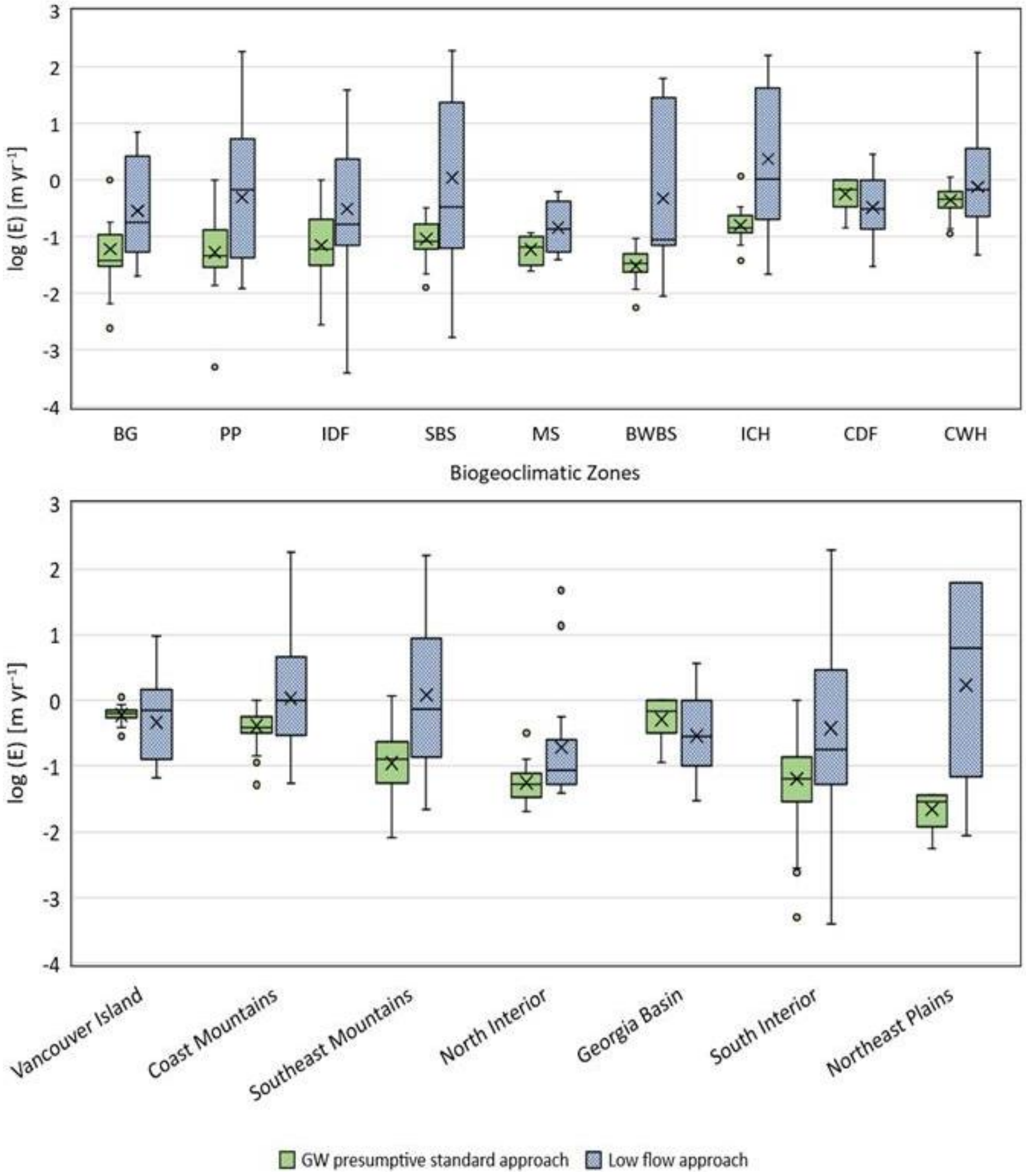

Figure 39: (above) Derived E values by BGCZ. (below) Derived E values by low flow zones.

Compared to E_{PS}, E_{LF} have a large distribution of E values which can be seen when absolute values are compared**.** Low flows zones associated with high discharge to drainage area in arid regions have greater E_{LF} values than E_{PS} values (Figure 40).

Values of E/R are expended to be <1, as natural long term discharge should be equal to recharge (Figure 41). In zones of higher precipitation, values of E/R decrease, likely related to regions of high recharge and low discharge to streams however with significant lateral down gradient flow. Derived E_{PS} values compared to R are consistently <1 for almost all biogeoclimatic zones.

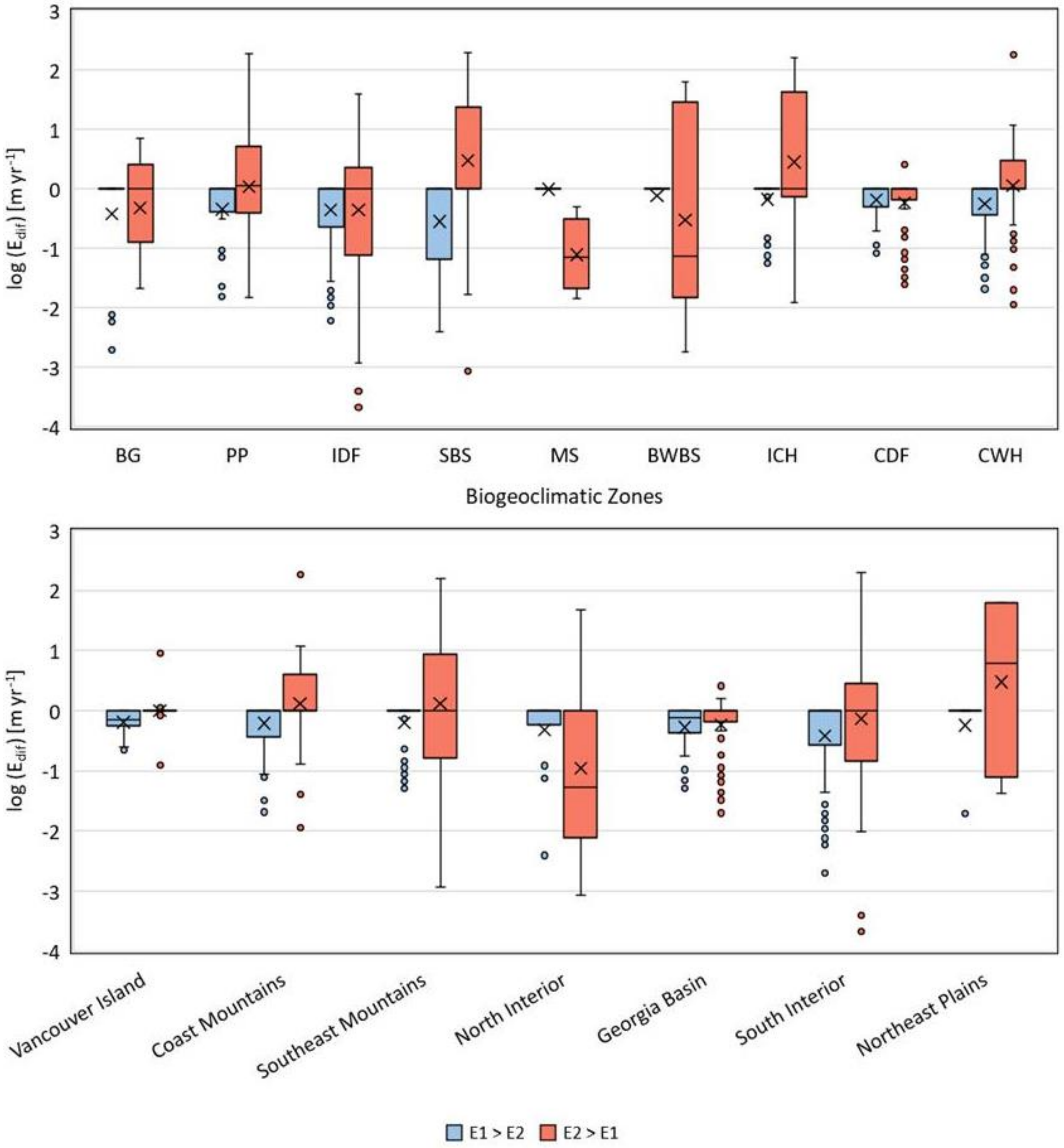

Figure 40: (above) Derived E_{dif} values by low flow zones. (below) Derived E_{dif} values by BGCZ.

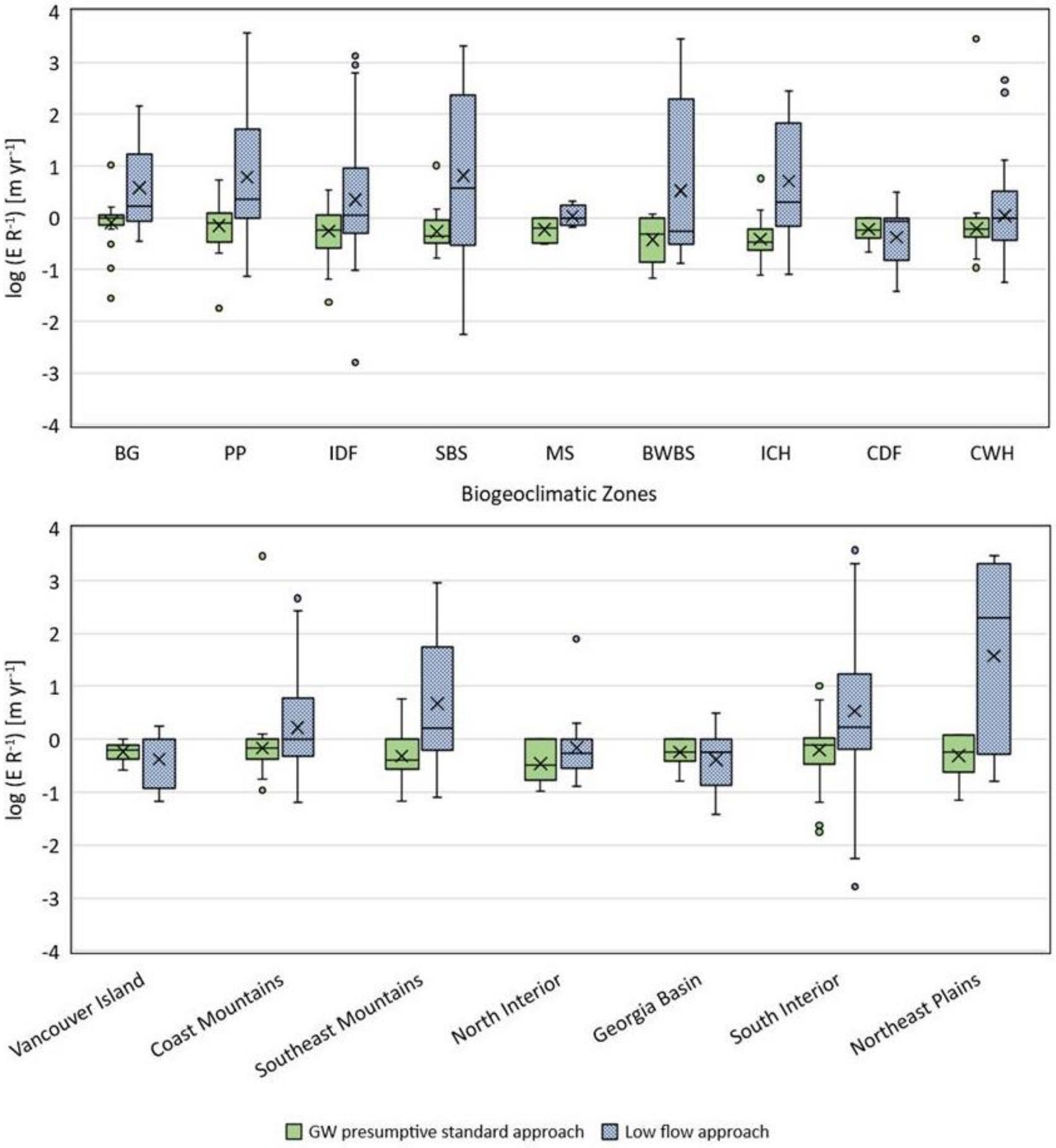

Figure 41: (above) Derived E/R values by BGCZ. (below) Derived E/R values by low flow zones.

5.5 Discussion

The derived values of E from the groundwater presumptive standard and low flow approaches both use PCR-GLOBWB model data which is at large resolutions (pixels ~100 km^2). Although fluxes are averaged over aquifer area, the groundwater's contribution to environmental flows may fluctuate greatly on a local scale based on stream and aquifer properties.

Both methods provide estimates for quantifying aquifer stress, where the groundwater presumptive standard aligns with explicitly considering groundwater fluxes in determining groundwater stress, whereas, the low flow zone approach, uses surface water streamflows to derived groundwater fluxes, and therefore is not groundwater specific.

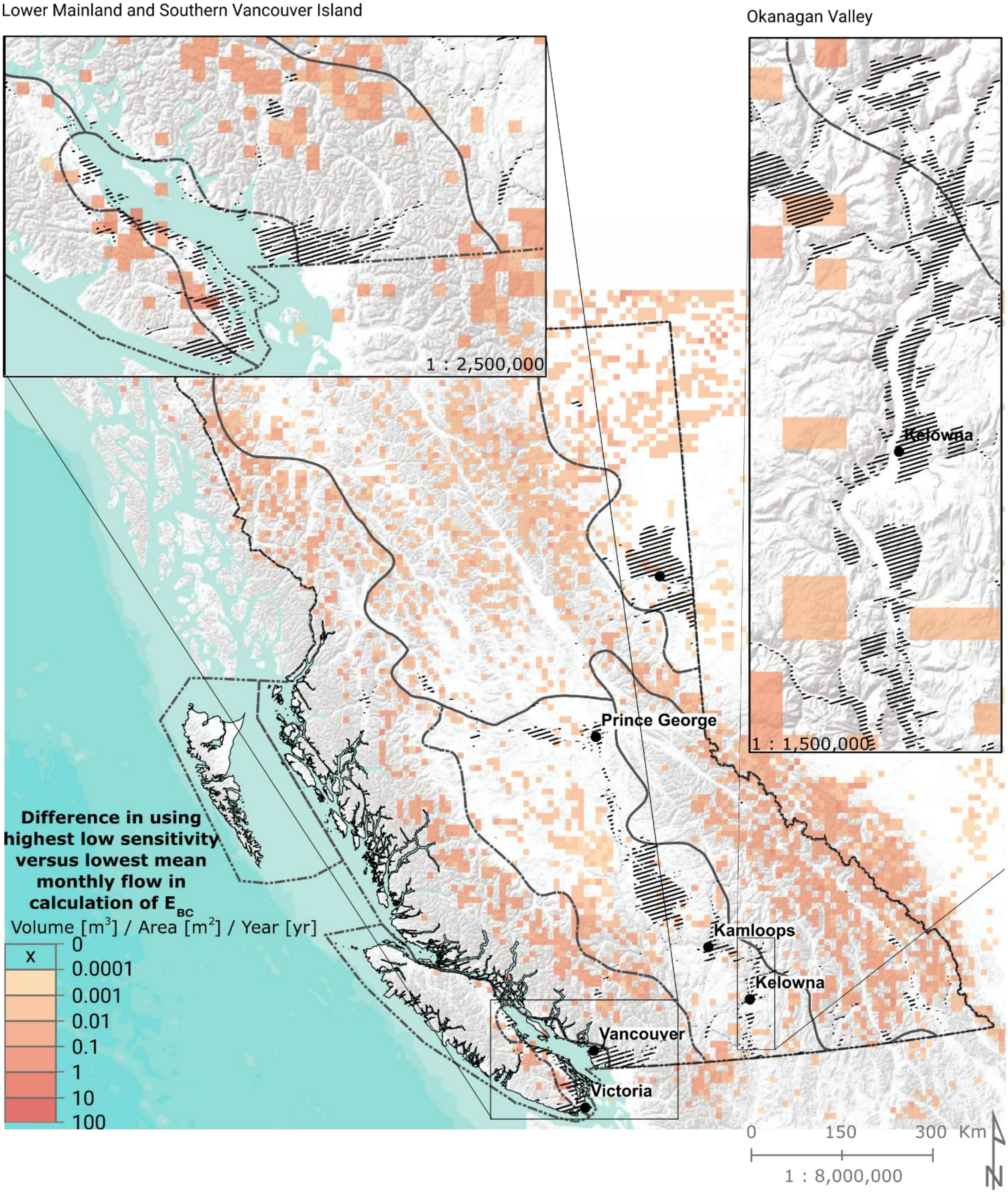

Figure 42: Difference in using the derived E_{LF} from using the lowest monthly flow and the highest low flow monthly flow in the E_{LF} approach.

Field observations of baseflow are not available, and therefore, there is limitations to the groundwater presumptive method, as we have no measured values with which to compare to modelled values. Streamflow comparisons (Appendix F) show that when streamflow gages are compared to modelled streamflow, PCR-GLOBWB is best representing streamflow from larger drainage areas.

Valley aquifers, such as many found in the Interior, have the largest uncertainty, as derived values are based on cell averages. If a cell is dominated by headwater streams, and the aquifer is located in a valley, E_{PS} will be underestimated. However, for aquifers in the Lower Mainland where the terrain is more homogeneous, estimates of E_{PS} are representative of a smaller distribution of fluxes in these regions.

In the low flow approach, the method assumes the cell streamflow characteristics are representative of the cell area. However, the modelled streamflow represents all streamflow within the cell, therefore, if aquifers underlay smaller streams not represented by the modelled streamflow, derived E_{LF} values are likely overestimated. The low flow classification is dependant on streamflow characteristics of the model. In some regions, only one month is in low flow conditions, and therefore, aquifers in these regions likely have underestimated E_{LF} values as the lowest mean monthly flux is used to estimate annual flux (Figure 42). Derived E_{LF} is greatly dependant on the assumption that groundwater is the main contributor in supporting low flows. Regions where low flows are supported by surface water inputs, such as meltwater, can expect to have overestimated values of E_{LF}.

The methods presented here should not be taken over detailed local studies. The complexities of understanding actual environmental flow needs such as the role of temperature, chemistry and stream morphology for supporting an ecosystem is variable across the province. In addition, the seasonal fluctuations of E are not represented by these values, as they are steady-state estimates based on long term annually averaged data.

6. GROUNDWATER FOOTPRINT

6.1 Results

The groundwater footprint methodology is applied to 404 mapped aquifers in B.C. (n = 1130). Although W was derived for most (n = 1118) aquifers, the other components of R and E are derived only for unconfined aquifers (n = 404).

The groundwater footprint was calculated for four combinations input parameters (Table 32). Each combination of input parameters has inherent uncertainties, so aquifers were categorized using a simple and transparent stress index that also clarifies the uncertainty of results. If all calculations of the GF/A indicates GF/A > 1 where the method is applicable, the aquifer is considered “stressed (high certainty)”. If GF/A > 1 based on at least one set of data, the aquifer is considered “stressed (less certainty)”. If all calculations indicate GF/A < 1, the aquifer is considered “less stressed”. The GF calculation is based on regional data and the data is limited by uncertainties, and therefore, an aquifer with a GF/A = 2 is not considered more stressed than a GF/A = 10 (Figure 43).

Table 32: Groundwater footprint normalized by aquifer area (GF/A) for each method.

	Mean	Median	Min	Max
GF_1/A	1.8	0.076	0	98
GF_2/A	1.3	0.052	0	60
GF_3/A	0.83	0.033	0	47
GF_4/A	0.91	0.033	0	23

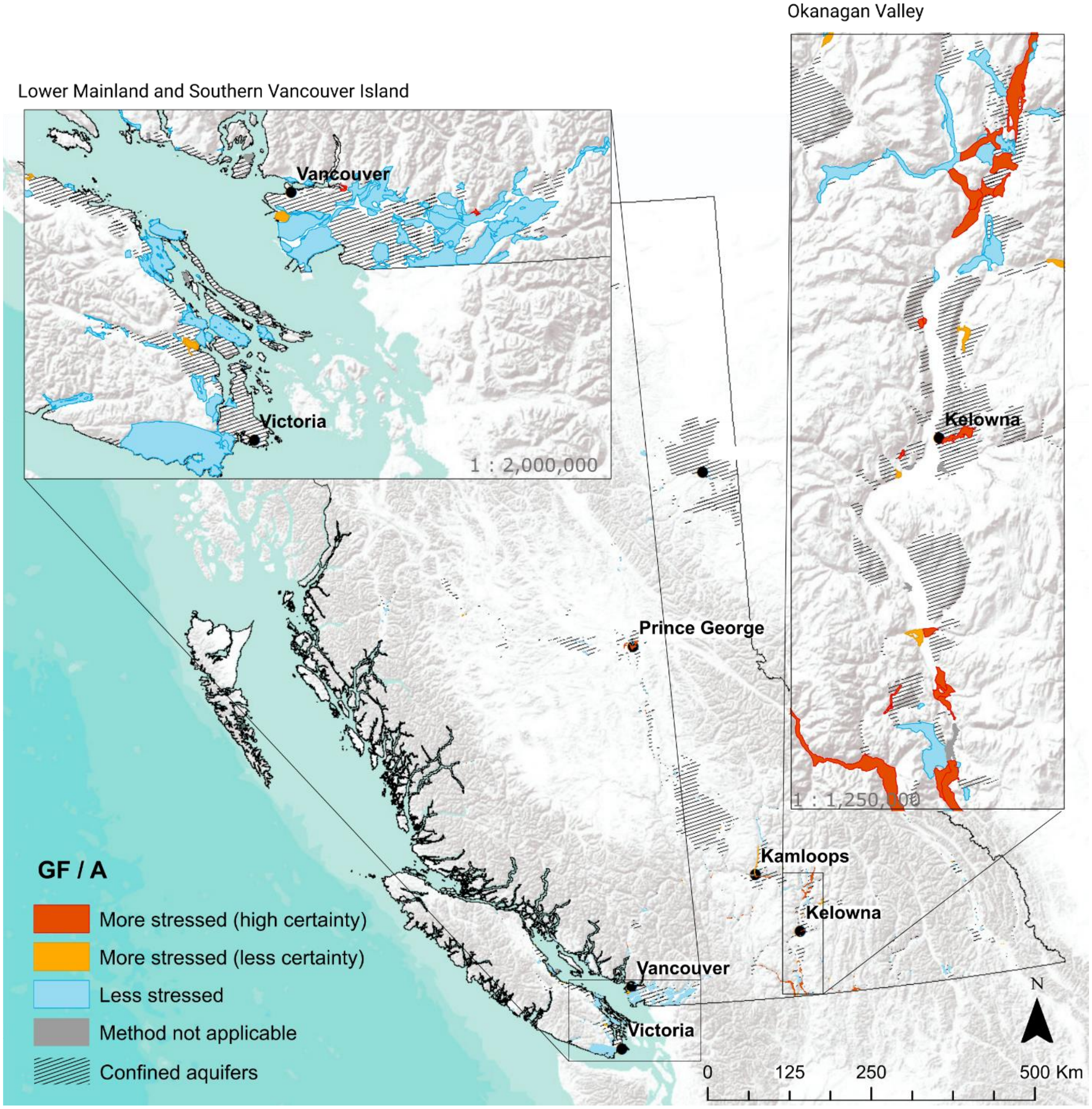

Figure 43: Spatial distribution of aquifers with derived GF values that are classified with the stress index.

Based on this stress index for unconfined aquifers (n = 404), 43 aquifers are stressed with high certainty, 32 aquifers are stressed with less certainty, 283 aquifers are less stressed, and 46 aquifers were not included due to missing parameters or issues where modelled recharge was less than the groundwater contribution to environmental flows. Biogeoclimatic zones with the greatest number of stressed aquifers (high certainty) are Bunchgrass (n=12), Ponderosa Pine (n=10), and Interior Douglas-Fir (n=8), which are located mainly in the Interior and have the lowest annual precipitation of the biogeoclimatic zones included in this study (Figure 44). Based on the stress index, aquifers in the Lower Mainland and Vancouver Island appear less stressed than aquifers in the Interior. Of the total percent of unconfined aquifers in each biogeoclimatic zone, there is also a weak inverse trend whereby as precipitation increases there appears to be less stress (Figure 46).

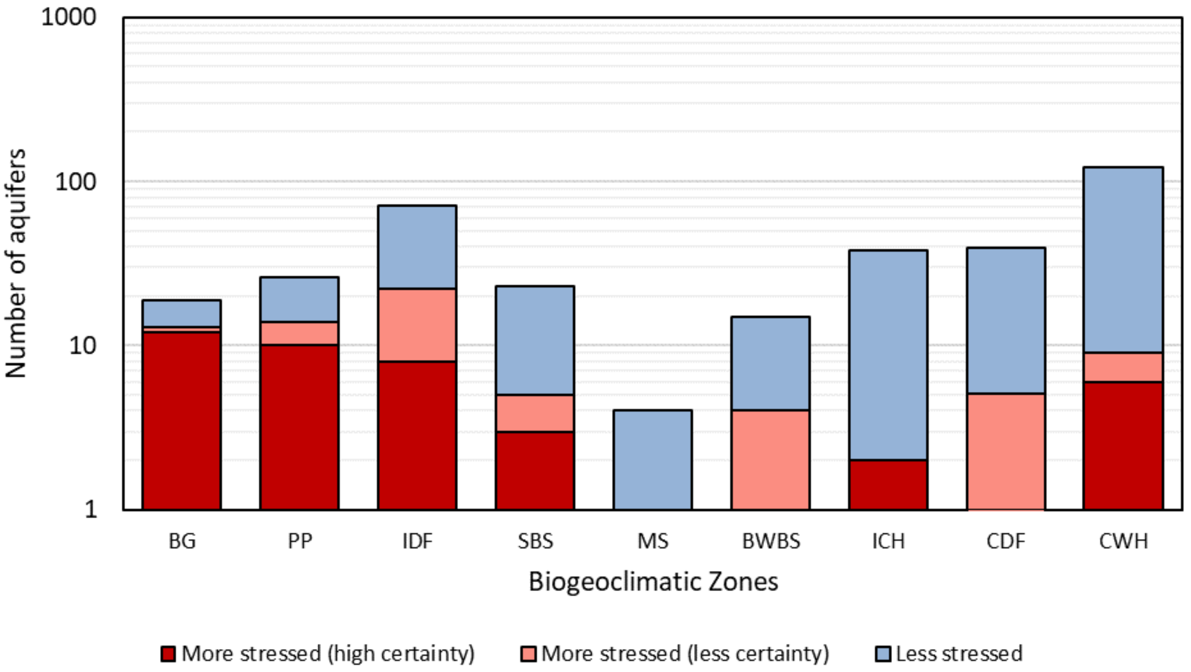

Figure 44: Number of aquifers per biogeoclimatic zone that are classified in the stress index.

6.2 Discussion

Deriving GF for aquifers in B.C. inherently contains uncertainty since each component has significant uncertainty; for overviews of the limitations and uncertainties for each component see their respective sections.

When the groundwater footprint equation is normalized by aquifer area it is simply the ratio of volumetric withdrawal to availability. Availability is the term which does not change in the four calculations of GF for each aquifer; therefore, the significant uncertainty in withdrawal is not included in the categorization of aquifers as 'high certainty' and 'low certainty' described above. The groundwater footprint is overestimated in regions where derivations of R are possibly underestimated, such as aquifers with significant recharge from lateral flow, or where E is overestimated, for example where aquifers are misrepresented by modelled streamflow or baseflow.

Figure 43 illustrates the results of the groundwater stress index. There are a greater number of stressed aquifers in the Okanagan Valley compared to Lower Mainland and Vancouver Island. There is a general decreasing trend in groundwater stress in biogeoclimatic zones with increasing precipitation regardless of the combination of input data used (Figure 44).

Figure 45 illustrates the groundwater footprint compared to parameters used within the study to explore what parameters might be controlling aquifer stress. No correlation is apparent between GF/A and aquifer area, soil saturated hydraulic conductivity, and water table depth. Aquifer type and biogeoclimatic zone seem to have apparent trends. Unconsolidated aquifers (1-4a) appear to generally be more stressed than bedrock aquifers (5a, 6b). Biogeoclimatic zones in regions of lower precipitation also appear to increase stress.

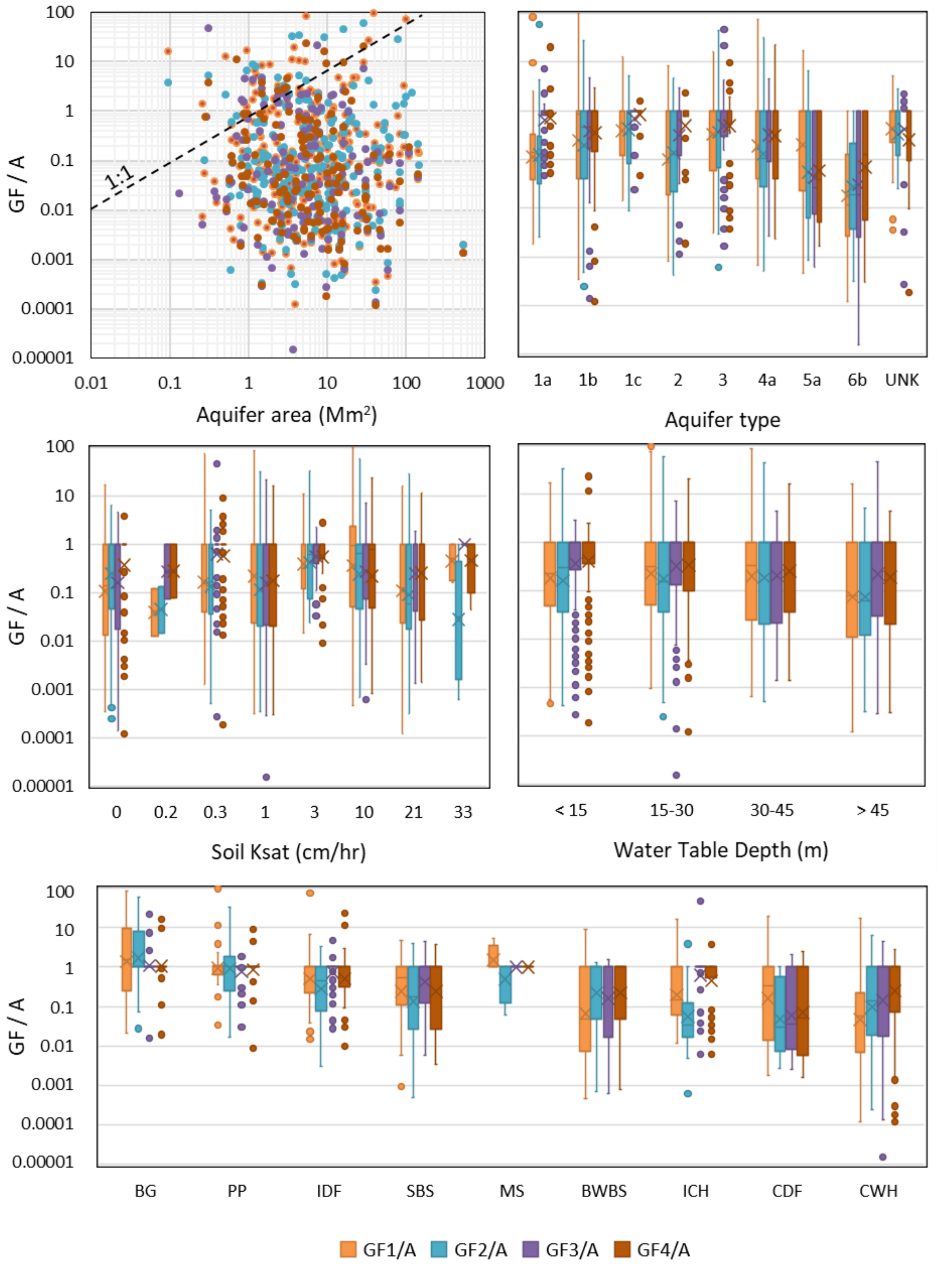

Figure 45: Results of the groundwater footprint normalized by aquifer area (GF / A) by aquifer area in Mm^3 (top, left), aquifer type (top, right), average soil K$_{sat}$ from Soil Landscapes of Canada Working Group (2010) (middle, left), average water table depth from Fan et al. (2013) (middle, right), and by biogeoclimatic zones (bottom).

To parse out how aquifer type and biogeoclimatic zones, may be controlling aquifer stress, Figure 46 compares the annual fluxes of use and availability per biogeoclimatic zones and aquifer type. Here we see that W is fairly constant for aquifer types 1-5a, and is approximately an order of magnitude lower for 6b. The higher W flux for unconsolidated aquifers is likely explained by the preference of drilling wells in unconsolidated aquifers as they generally provide a higher yield compared to bedrock aquifers. Additionally, bedrock aquifers have on average an order of magnitude higher availability fluxes (R – E) compared to unconsolidated aquifers. The increasing trend in GF/A in regions of decreasing precipitation is illustrated in Figure 46 (bottom), where the annual availability fluxes are generally less than in regions of greater precipitations. This trend is likely controlled by the recharge flux which has been seen to decrease in regions of decreasing precipitation.

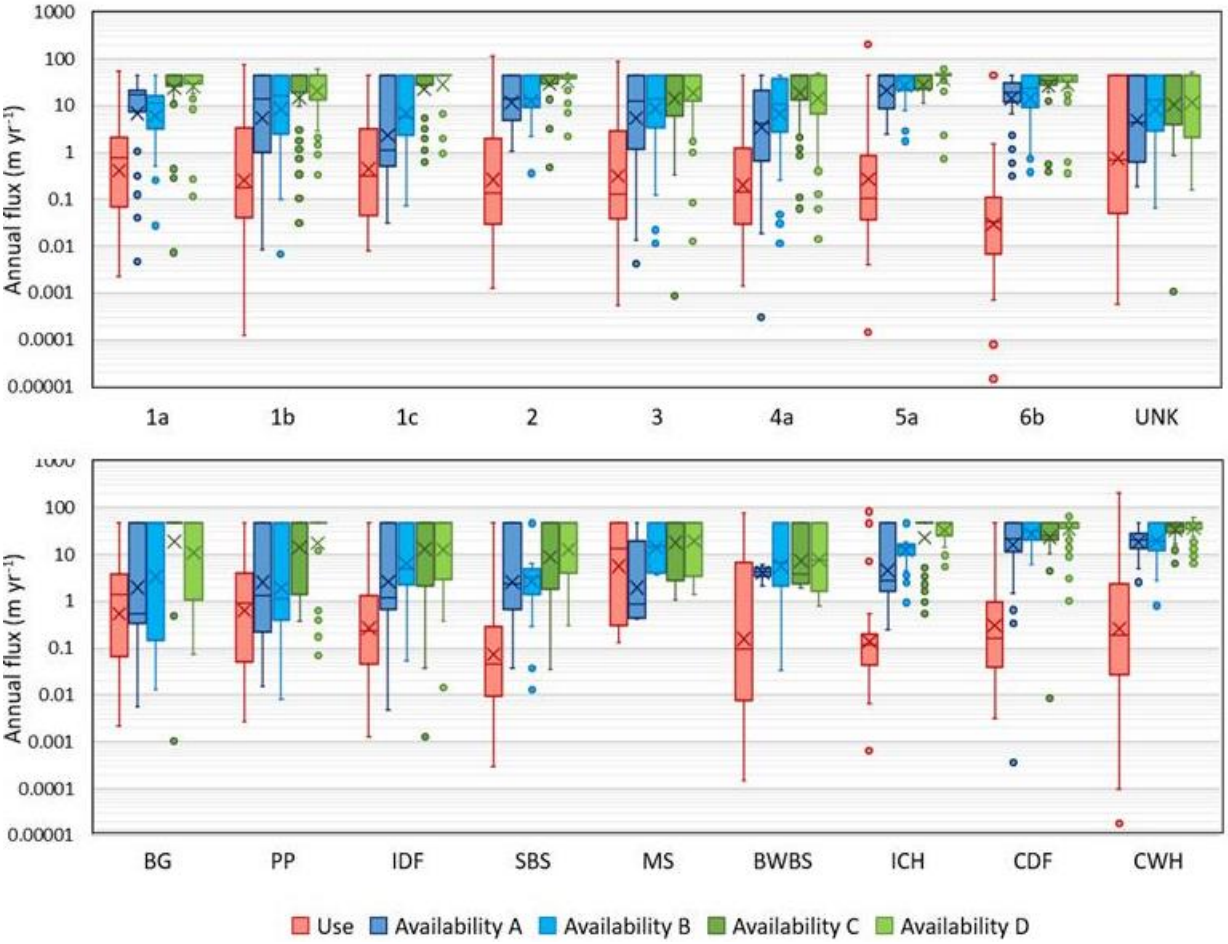

Figure 46: Compared use and availability fluxes per aquifer type (top) and biogeoclimatic zone (bottom). Availability A: R_{HELP}-E_{PS}; Availability B: R_{PCR}-E_{PS}; Availability C: R_{HELP}-E_{LF}; Availability D: R_{PCR}-E_{LF}.

7. RECOMMENDATIONS & FUTURE WORK

7.1 Withdrawal

With the establishment of the WSA, all groundwater wells require a license, with the exception of domestic wells. Domestic users are encouraged to register their well in order to account for withdrawn groundwater volumes and establish a priority date for protection of water rights under FITFIR (First in time, first in right). Through data collected in the licensing process, this report could be improved significantly: licensed amounts of groundwater could be used to corroborate annual groundwater withdrawal, well location and status could be used to verify well information, and licenses issued could be used to verify groundwater users. However, measuring and reporting would be necessary to verify actual diversion and use. The Province is currently developing policy to address the need for measuring and reporting of actual water diversion and use, and we recommend implementing this policy so that estimates of groundwater withdrawal can be improved in the future.

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

- Compare annual groundwater volumes to results from local or regional studies which could help determine the accuracy of our estimates in different regions.
- Create and provide public access to data on provincial groundwater sources and volumes of use. The largest uncertainty of this groundwater use analysis was due to a lack of available data.
- eLicensing, Province of B.C. aquifer mapping and the WELLS database should be easily accessible and linked for transparency in assessment of groundwater resources. Often small discrepancies exist between datasets, leading to additional uncertainties in reported data.
- Water meters should be encouraged for all well users to improve estimates of water use.
- The results of this study could improve the classification of “Level of Development” for Province of B.C. mapped aquifers and assist with the preliminary development and scoping of water budgets.
- Water supply systems can be complex, based on the operating purveyor, and finding data on location, volumes, and population supported by extraction points is difficult. Information often exists on municipality websites; however, a provincial database should be available to document mean monthly volumetric extractions, source of water, extracting aquifer/stream, number of people supported, and approximate leakage within that system, which would aid in groundwater management and community awareness of water sources.

7.2 Recharge

Recharge is a difficult parameter to quantify and often relies on a combination of regional models or local field studies, which all inherently contain uncertainty. Water levels can be used to quantify recharge for unconfined aquifers using the water table fluctuation method and provide local- to aquifer-scale annual estimates. We conducted a preliminary analysis (not included in this report) screening wells as potential candidates for applying the water table fluctuation method. Unfortunately, only 13 observational wells were eligible from the 219 wells in the Provincial Observation Well Network. Observation wells in unconfined aquifers are required to have daily water level measurements in addition to (1) be within 33% of the distance to the watershed divide compared to stream (constant head discharge) [73% of observational wells did not meet this requirement], and (2) be at a distance where pumping has little influence on the water table [70% of observational wells were located within 100 metres of pumping wells]. We recommend improving the observational well network specifically by targeting wells that could be used in recharge calculations, in order to better quantify recharge for unconfined aquifers in the province.

7.3 Groundwater's Contribution to Environmental Flows

Groundwater use impacts on environmental flow needs (EFN) are considered in the current EFN policy, but the policy does not provide guidance for decisions of groundwater extractions. A few considerations are that 1) groundwater is often critical to environmental flows and can have a thermally or chemically distinct and non-substitutable contribution to EFN; 2) groundwater pumping has different hydrologic impact (always depleting) than surface water controls and 3) groundwater impacts on environmental flows occur often on different timescales (over months to centuries) than surface water withdrawals impacts. Groundwater and surface water is a single, connected resources as recognised by the WSA so we support the continued leadership of the province in protecting environmental flows by recommending a new environmental flow regulation, incorporating many of the elements of the existing EFN policy, but more fully and holistically incorporating the importance of groundwater. To more fully and holistically incorporate the role and importance of groundwater, this environmental flow regulation should (1) explicitly include the assessment of the flux of groundwater's contribution to EFN, (2) recognize the sometimes non-substitutable contribution of groundwater to EFN, (3) incorporate the potential long term (decades or centuries) impact of groundwater pumping. In this way, conjunctive management of streams and aquifers would include groundwater discharge as an integral component of streamflow regimes and aid in meeting community and stakeholder objectives for environmental flow needs.

Additionally, we recommend further testing and development of the two methods developed herein for assessing the groundwater contribution to environmental flows; in the future, these methods could be useful in operational water management in the province.

Due to the spatial distribution and diverse hydrological regimes of aquifers in B.C., use of observational data (such as stream gauge stations or field data sites) for the purpose of deriving the groundwater contribution to environmental flows is not possible for many streams and aquifers. In order to capture long term climatic and hydrologic variability, streamflow stations should include at least 50 years of continuous discharge data. In addition, many hydrological assessments rely on regionalization techniques to transfer data from gauged catchments to developed or ungauged catchments; however, similar catchments are difficult to find and often do not fully represent the complex flow regime. Although B.C. has an extensive network of stream gauge stations (operated by various government, community, and industry organizations) most stations are located within developed regions and do not meet the temporal data requirements. We recommend the continued support and expansion of the stream gauging network, especially in regions where assessing the groundwater contribution to environmental flows is important.

7.4 Groundwater Footprint

The first province-wide calculations of groundwater stress using the groundwater footprint are estimates. In order to increase the accuracy of the groundwater footprint, parameters within the equation need to be locally refined. For example, with groundwater licensing, allocation volumes can be used as a proxy for groundwater use in the future. Recharge and groundwater's contribution to environmental flows are more challenging to derive and often require field work and detailed local conceptualization for each aquifer. We recommend the results of the groundwater stress be used to provide direction to screen priority aquifers for these detailed studies as well as potentially flag currently high stress aquifers for more immediate action.

In addition to providing a more accurate stress index, with more detailed and readily available data the groundwater footprint could be expanded to reflect seasonal or monthly aquifer stress, as in many regions in B.C., the annual groundwater footprint may be underestimated for aquifers that experience a greater seasonal stress.

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APPENDIX A: GROUNDWATER USE METHODOLOGY FLOW CHARTS

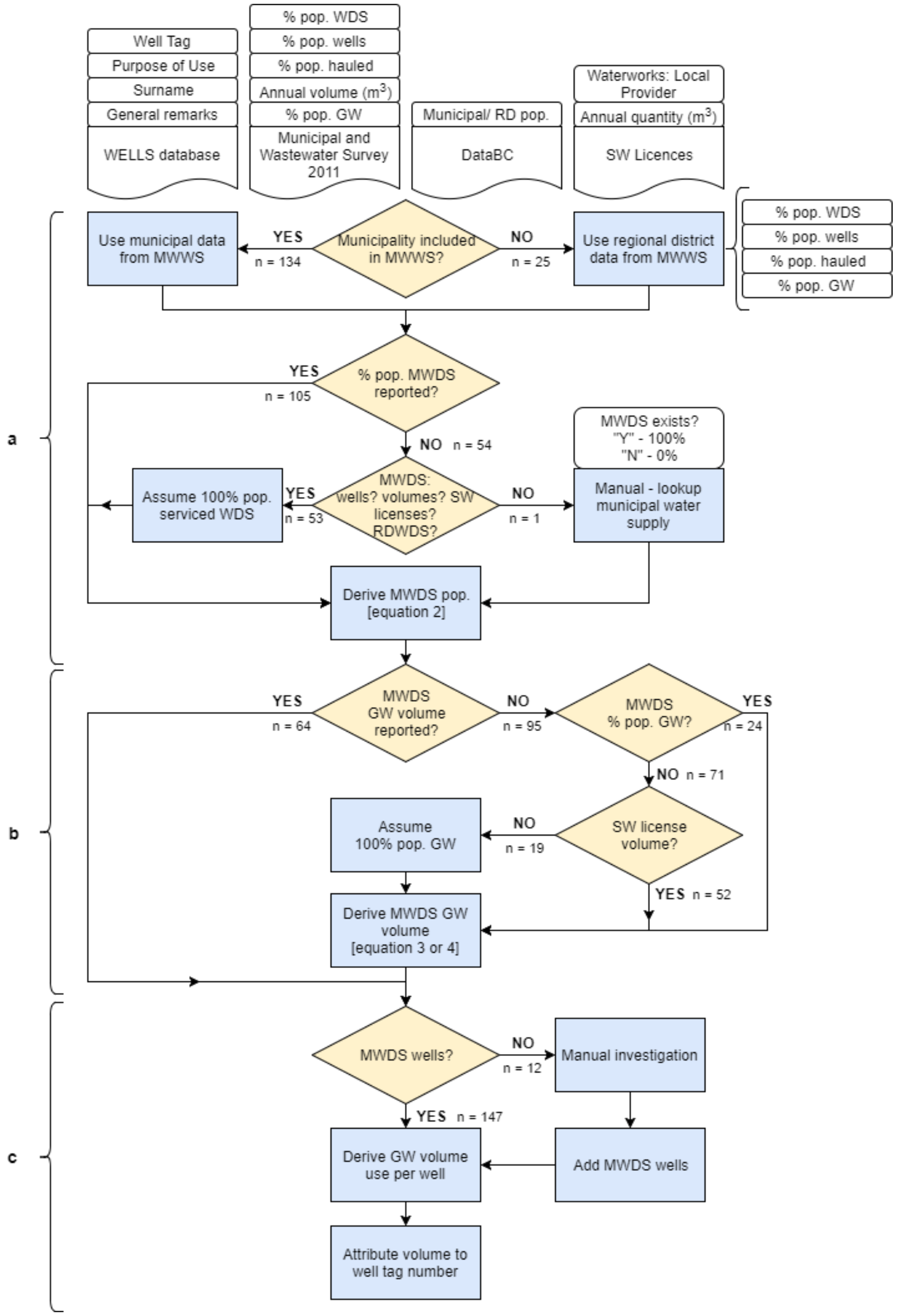


Figure A1: Flowchart for deriving MWDS groundwater volumes. The white boxes at the top correspond to data variable of interest grouped by WELLS database, MWWS, DataBC, and surface water licenses. Steps a-c represent: determination of MWDS population, deriving groundwater volume, and attribution to wells, respectively.

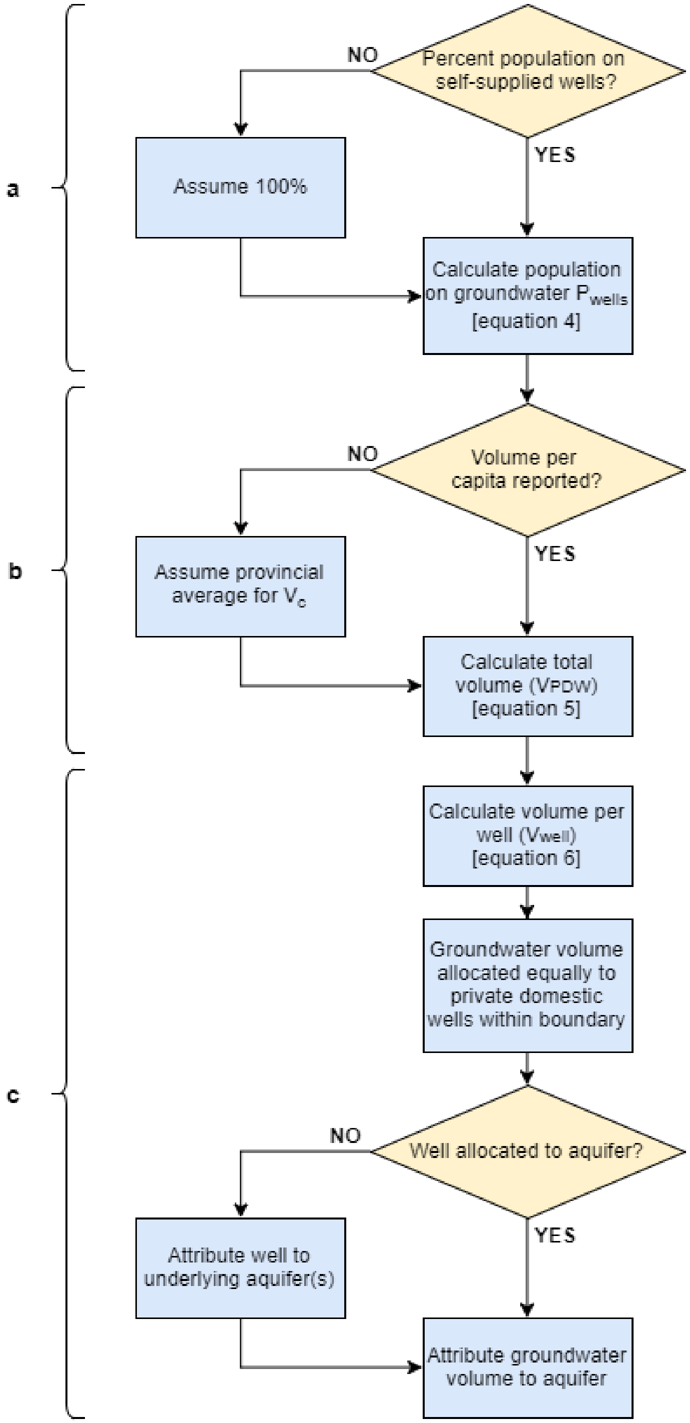


Figure A2: Flowchart for deriving private domestic well user groundwater volumes. Steps a-c represent: determination of population supported by PDWs, deriving groundwater volume, and attribution to wells, respectively.

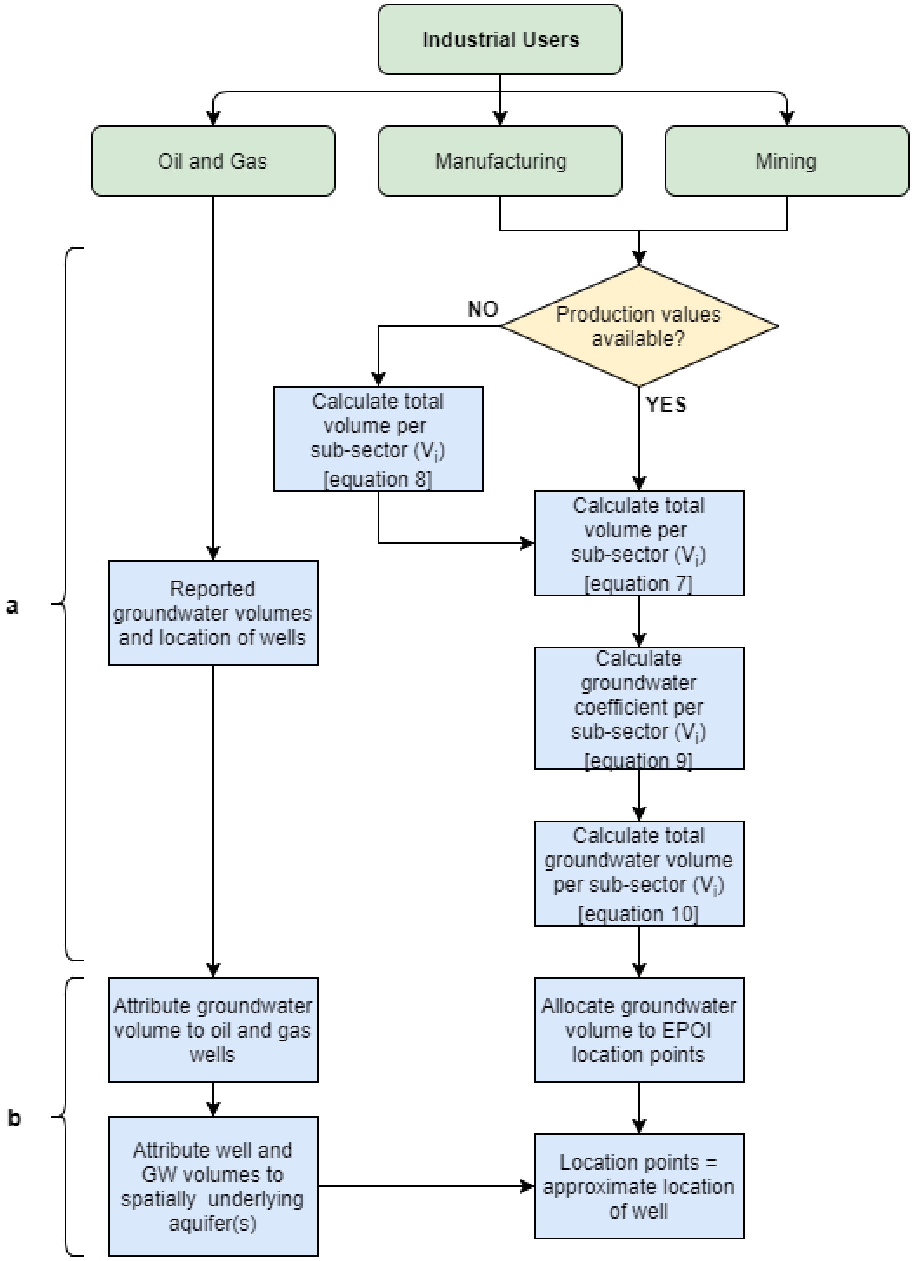


Figure A3: Flowchart for deriving industrial sector groundwater volumes. Steps a-b represent: deriving groundwater volume and attribution to wells, respectively.

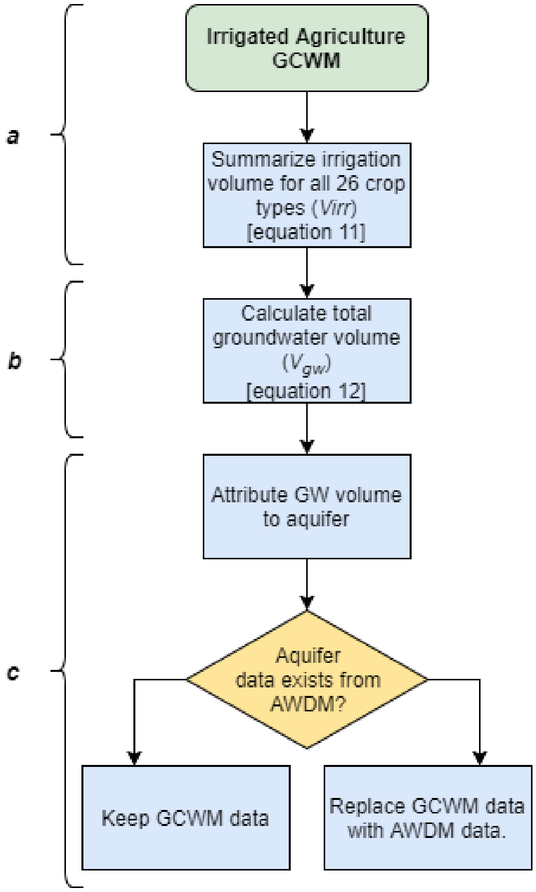


Figure A4: Flowchart for deriving self-supplied irrigated agriculture. Steps a-c represent: deriving total irrigated volume, deriving groundwater volume and attribution to wells, respectively.

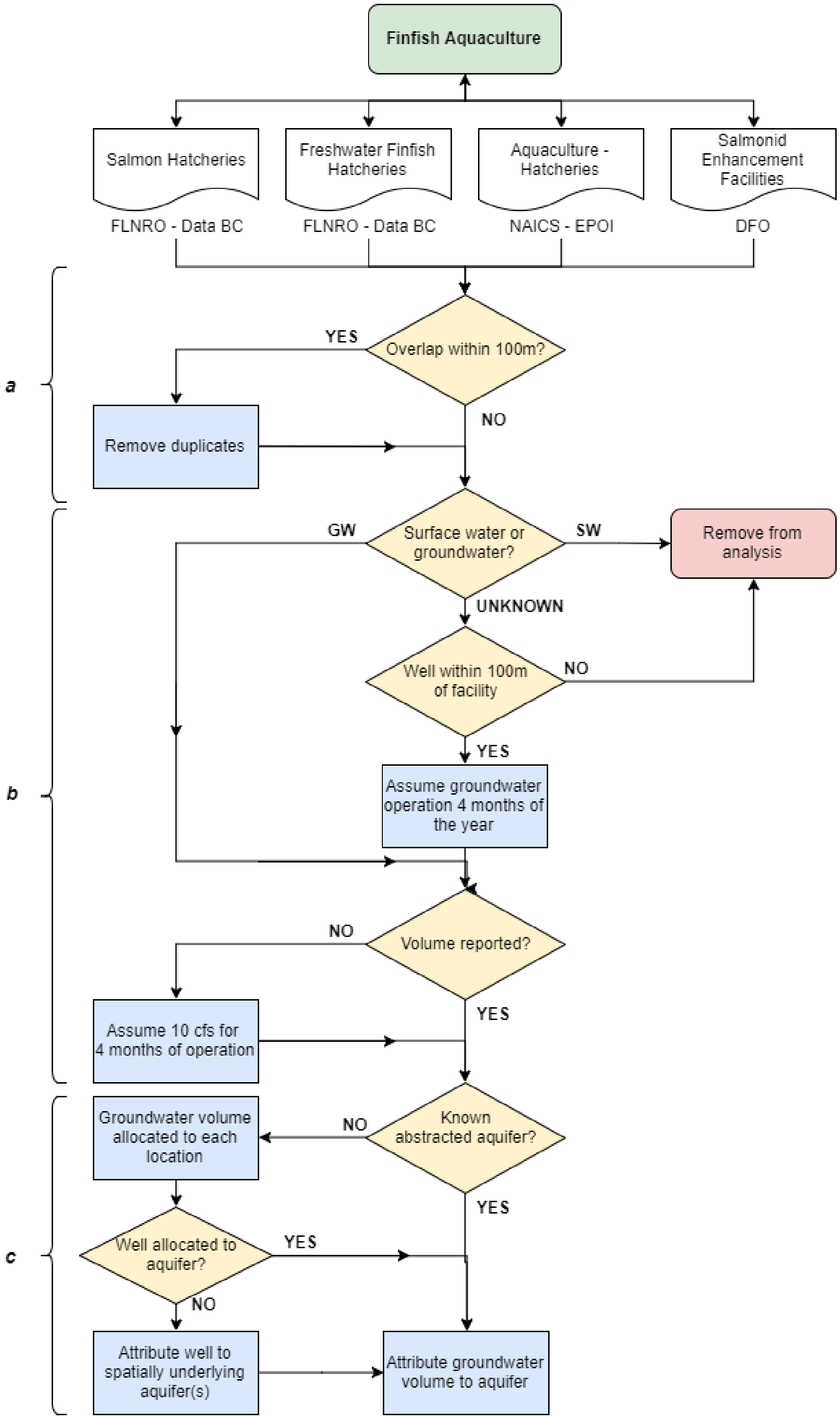


Figure A5: Flow chart for deriving annual groundwater per aquifer for self-supplied finfish aquaculture users.

APPENDIX B: GROUNDWATER USE PER MUNICIPALITY

Table B1: Annual municipal water distribution systems (MWDS) and private domestic & commercial (PDW) volumes. SW: surface water; GW: groundwater; pop.: population; MWDS; water distribution system. GVWD: Greater Vancouver Water District; CRD: Capital Regional District; CVWD: Comox Valley Water District; RDN: Regional District of Nanimo; RDNO: Regional District of North Okanagan

Municipality	Pop. (x 1000)	% Pop.		SW licence (Mm^3/yr)	Num. Wells		GW (Mm^3 yr^{-1})		Regional MWDS	
		MWDS	PDW		MWDS	PDW	MWDS	PDW	Multi-WDS	% GW
100 Mile House	1.9	100	-	0.05	1	-	0.29	-	-	-
Abbotsford	135.0	82	18	0.98	26	3070	1.46	3.16	-	-
Alert Bay	0.5	100	-	0.35	-	-	-	-	-	-
Anmore	2.1	100	-	0.15	-	-	-	-	GVWD	-
Armstrong	4.8	100	-	0.18	2	-	0.05	-	-	-
Ashcroft	1.7	100	-	0.41	-	-	-	-	-	-
Barriere	1.8	100	-	6.65	1	-	0.08	-	-	-
Belcarra	0.7	-	100	-	-	152	-	0.09	GVWD	-
Bowen Island	3.4	100	-	0.00	12	-	0.62	-	-	-
Burnaby	223.1	100	-	-	-	-	-	-	GVWD	-
Burns Lake	2.1	100	-	9.96	-	-	-	-	-	-
Cache Creek	1.1	100	-	1.00	-	-	-	-	-	-
Campbell River	31.2	99	1	6.79	-	131	-	0.04	-	-
Canal Flats	0.8	85	15	3.84	-	62	-	0.01	-	-
Castlegar	7.9	100	-	26.33	-	-	-	-	-	-
Central Saanich	16.1	100	-	-	-	-	-	-	CRD	-
Chase	2.5	100	-	0.16	2	-	0.28	-	-	-
Chetwynd	2.7	98	1.8	3.32	-	82	-	0.01	-	-
Chilliwack	76.6	92	8	10.80	10	1039	10.66	0.80	-	-
Clearwater	2.4	100	-	2.20	1	-	0.11	-	-	-
Clinton	0.6	85	15	0.83	-	26	-	0.01	-	-
Coldstream	10.4	86	14	-	1	111	0.77	0.19	RDNO	-
Colwood	16.1	100	-	-	-	-	-	-	CRD	-
Comox	13.6	100	-	-	-	-	-	-	CVWD	-
Coquitlam	125.0	99	1	7.96	-	69	-	0.16	GVWD	-
Courtenay	23.9	100	-	-	-	-	-	-	CVWD	-
Cranbrook	19.5	100	0.5	0.02	-	238	-	0.01	-	-
Creston	5.3	100	-	5.32	1	-	0.08	-	-	-
Cumberland	3.2	99	1	0.57	-	15	-	0.00	-	-
Dawson	11.2	100	-	121.04	-	-	-	-	-	-
Delta	100.9	100	-	-	1	-	1.35	-	GVWD	-
Duncan	5.0	100	-	36.11	-	-	-	-	-	-
Elkford	2.5	100	-	2.39	8	-	1.43	-	-	-
Enderby	2.9	100	-	0.23	1	-	0.22	-	-	-
Esquimalt	17.1	100	-	-	-	-	-	-	CRD	-
Fernie	4.4	100	-	5.64	-	-	-	-	-	-
Fort St James	1.5	100	-	-	-	-	-	-	-	-
Fort St John	18.6	100	-	31.97	7	-	3.25	-	-	-
Fraser Lake	1.1	100	-	5.42	-	-	-	-	-	-
Fruitvale	2.0	98	2	-	1	8	0.11	0.01	-	-
Gibsons	4.5	100	-	5.22	6	-	0.75	-	-	-
Gold River	1.4	100	-	-	5	-	0.24	-	-	-
Golden	3.8	99	1	-	8	53	1.26	0.00	-	-
Grand Forks	4.2	97	3	26.22	14	69	1.97	0.02	-	-
Granisle	0.3	100	-	0.96	-	-	-	-	-	-
Greenwood	0.7	100	-	3.98	-	-	-	-	-	-
Harrison Hot Springs	1.5	65	35	0.81	-	40	-	0.07	-	-
Hazelton	0.3	100	-	0.10	-	-	-	-	-	-
Highlands	2.1	100	-	-	-	-	-	-	-	-
Hope	6.1	95	4	0.29	8	210	0.76	0.03	-	-
Houston	3.0	70	25	0.00	7	135	0.38	0.10	-	-
Hudson Hope	1.0	70	20	-	3	75	0.01	0.03	-	-
Invermere	3.3	95	5	4.65	-	80	-	0.02	-	-

Municipality	Pop. (x 1000)	% Pop.		SW licence (Mm^3/yr)	Num. Wells		GW (Mm^3 yr^{-1})		Regional MWDS	
		MWDS	PDW		MWDS	PDW	MWDS	PDW	Multi-WDS	% GW
Kamloops	87.2	100	-	1.00	4	-	0.35	-	-	-
Kaslo	1.1	100	-	1.24	-	-	-	-	-	-
Kelowna	119.6	99	1	112.66	-	981	-	0.16	-	-
Kent	5.7	25	75	-	6	336	0.22	0.55	-	-
Keremeos	1.4	100	-	-	1	-	0.25	-	-	-
Kimberley	6.7	100	-	89.96	-	-	-	-	-	-
Kitimat	8.9	100	0.1	5.86	-	50	-	0.00	-	-
Ladysmith	7.9	100	-	1.34	-	-	-	-	-	-
Lake Country	11.5	100	-	6.90	-	-	-	-	-	-
Lake Cowichan	3.1	100	-	12.48	-	-	-	-	-	-
Langford	27.4	100	-	-	-	-	-	-	CRD	-
Langley - City	25.4	100	-	-	-	-	-	-	GVWD	-
Langley - District	103.8	100	-	-	-	-	-	-	GVWD	-
Lantzville	3.7	100	-	-	6	-	0.66	-	RDN	100
Lillooet	2.3	70	20	26.75	-	155	-	0.06	-	-
Lions Bay	1.4	100	-	4.98	-	-	-	-	-	-
Logan Lake	2.1	100	-	-	-	-	-	-	-	-
Lumby	1.7	100	-	0.86	-	-	-	-	-	-
Lytton	0.2	100	-	1.66	-	-	-	-	-	-
Mackenzie	3.7	100	-	0.37	2	-	0.74	-	-	-
Maple Ridge	75.4	80	20	-	-	1192	-	1.96	GVWD	-
Masset	0.9	100	-	-	2	-	0.16	-	-	-
McBride	0.6	100	-	1.16	-	-	-	-	-	-
Merritt	7.4	100	-	38.41	13	-	3.08	-	-	-
Metchosin	4.9	100	-	-	-	-	-	-	CRD	-
Midway	0.7	100	-	1.04	-	-	-	-	-	-
Mission	37.2	80	20	9.64	-	1395	-	0.97	-	-
Montrose	1.0	100	-	-	21	-	0.19	-	-	-
Nakusp	1.6	95	5	4.31	1	25	0.12	0.01	-	-
Nanaimo	83.2	73	26.3	3.22	-	404	-	2.84	RDN	-
Nelson	10.2	100	-	80.64	-	-	-	-	-	-
New Denver	0.5	100	-	4.49	-	-	-	-	-	-
New Hazelton	0.6	100	-	0.10	-	-	-	-	-	-
New Westminster	64.9	100	-	-	-	-	-	-	GVWD	-
North Cowichan	29.0	80	20	0.40	19	1623	3.77	0.75	-	-
North Saanich	11.0	100	-	-	-	-	-	-	CRD	-
North Vancouver - City	48.0	100	-	0.07	-	-	-	-	GVWD	-
North Vancouver - District	85.3	100	0.1	4.21	-	35	-	0.01	GVWD	-
NRRM	5.8	-	95	-	-	201	-	0.71	-	-
Oak Bay	18.0	100	-	-	-	-	-	-	CRD	-
Oliver	5.0	100	0.5	0.18	15	130	3.91	0.00	-	-
Osoyoos	5.0	100	-	0.24	14	-	0.66	-	-	-
Parksville	12.0	100	-	0.07	25	-	2.16	-	RDN	100
Peachland	5.3	95	5	6.26	-	35	-	0.03	-	-
Pemberton	2.5	100	-	0.00	5	-	0.44	-	-	-
Penticton	33.3	99	1	4.74	-	128	-	0.04	-	-
Pitt Meadows	17.9	100	-	-	-	-	-	-	GVWD	-
Port Alberni	17.7	100	-	65.78	-	-	-	-	-	-
Port Alice	0.8	100	-	-	1	-	0.15	-	-	-
Port Clements	0.4	100	-	-	2	-	0.07	-	-	-
Port Coquitlam	56.3	100	-	-	-	-	-	-	GVWD	-
Port Edward	0.6	100	-	11.62	-	-	-	-	-	-
Port Hardy	4.1	100	-	17.53	-	-	-	-	-	-
Port McNeill	2.6	100	-	-	4	-	0.46	-	-	-
Port Moody	32.8	100	-	-	-	-	-	-	GVWD	-
Pouce Coupe	0.7	100	-	0.12	-	-	-	-	-	-
Powell River	13.1	3	6	21.06	-	6	-	0.10	-	-
Prince George	73.1	85	15	47.46	25	1026	17.78	1.43	-	-
Prince Rupert	12.7	100	-	96.94	-	-	-	-	-	-
Princeton	2.6	100	-	0.17	17	-	0.29	-	-	-

Municipality	Pop. (x 1000)	% Pop.		SW licence (Mm^3/yr)	Num. Wells		GW (Mm^3 yr^{-1})		Regional MWDS	
		MWDS	PDW		MWDS	PDW	MWDS	PDW	Multi-WDS	% GW
Qualicum Beach	8.8	100	-	-	17	-	1.58	-	RDN	100
Queen Charlotte	1.0	85	15	0.19	3	80	0.13	0.02	-	-
Quesnel	9.8	98	2	133.20	-	283	-	0.03	-	-
Radium Hot Springs	0.9	100	-	1.25	-	-	-	-	-	-
Revelstoke	7.1	100	-	4.53	-	-	-	-	-	-
Richmond	192.6	100	-	-	-	-	-	-	GVWD	-
Rossland	3.5	99	1	28.71	-	13	-	0.00	-	-
Saanich	112.3	100	-	2.33	-	-	-	-	CRD	-
Salmo	1.1	99	1	2.50	2	13	0.30	0.00	-	-
Salmon Arm	17.3	100	-	2.50	3	-	0.62	-	-	-
Sayward	0.3	86	14.3	4.98	-	2	-	0.01	-	-
Sechelt	8.9	100	-	-	-	-	-	-	-	-
Sicamous	2.7	100	-	0.00	1	-	0.48	-	-	-
Sidney	11.4	100	-	-	-	-	-	-	CRD	-
Silverton	0.2	40	59.9	0.84	-	1	-	0.02	-	-
Slocan	0.3	100	-	0.00	-	-	-	-	-	-
Smithers	5.4	90	10	6.97	10	55	0.87	0.07	-	-
Sooke	11.0	100	-	-	-	-	-	-	CRD	-
Spallumcheen	5.1	100	-	0.01	-	-	-	-	RDNO	-
Sparwood	3.8	84	16	0.63	-	92	-	0.08	-	-
Squamish	16.6	100	0.25	8.46	4	139	3.61	0.01	-	-
Stewart	0.5	100	-	-	5	-	0.09	-	-	-
Summerland	11.5	100	-	3.12	4	-	0.10	-	-	-
Surrey	453.3	98	2	-	-	2837	-	1.18	GVWD	-
Tahsis	0.3	86	14.3	0.50	-	-	-	0.01	-	-
Taylor	1.4	100	-	42.98	-	-	-	-	-	-
Telkwa	1.3	100	-	13.70	-	-	-	-	-	-
Terrace	11.5	95	5	14.51	-	33	-	0.07	-	-
Tofino	1.9	100	-	2.21	-	-	-	-	-	-
Trail	7.6	100	-	20.74	-	-	-	-	-	-
Tumbler Ridge	2.7	100	-	0.02	7	-	0.46	-	-	-
Ucluelet	1.6	100	-	1.95	-	-	-	-	-	-
Valemont	1.0	99	1	-	-	6	-	0.00	-	-
Vancouver	610.4	100	-	-	-	-	-	-	GVWD	-
Vanderhoof	4.4	80	20	1.18	1	297	0.95	0.11	-	-
Vernon	38.7	97	3	17.01	-	451	-	0.15	RDNO	-
Victoria	81.8	100	-	-	-	-	-	-	CRD	-
View Royal	9.4	100	-	-	-	-	-	-	CRD	-
Warfield	1.8	100	-	1.63	-	-	-	-	-	-
Wells	0.2	100	-	0.00	1	-	0.04	-	-	-
West Kelowna	26.6	90	10	1.36	-	301	-	0.35	-	-
West Vancouver	42.6	98	2	1.66	-	13	-	0.11	GVWD	-
Whistler	10.2	100	-	7.08	-	-	-	-	-	-
White Rock	19.1	100	-	-	8	-	3.44	-	-	-
Williams Lake	11.1	99	1	0.88	3	329	4.02	0.01	-	-
Zeballos	0.1	86	14.3	1.25	-	3	-	0.00	-	-

APPENDIX C: HELP LOCAL COMPARISON - INPUT DATA AND METHODOLOGY

Localized recharge models of the Abbotsford-Sumas aquifer and the Grand Forks aquifer (Scibek and Allen 2004) were directly compared to the generalized recharge models. Here we detail the input data and methodology for both methods. Percolation (recharge) through a HELP vertical profile consisting of a soil zone overlying an aquifer is modelled using input climate data.

C.1 Abbotsford-Sumas Aquifer

The Abbotsford-Sumas aquifer was run for both the localized method and generalized method. The greatest distinction between the two methods is that the localized method was done through the processing of 64 different profiles across the aquifer, whereas generalized method used one profile to represent the entire aquifer.

a. Climate Data Comparison

Climate data for the generalized method were based on representative climate for BGCZs whereas the localized method imported climate normals from Environment Canada for the specific climate station (In this case Abbotsford International Airport).

Abbotsford-Sumas aquifer is near the boundary of the Coastal Douglas Fir (CDF) and Coastal Western Hemlock (CWH) BGCZ; therefore, climate normals for a representative station in each zone are compared to the BGCZ data (Figure C1). The representative stations within HELP for each included Victoria B.C. (49°34’ N and 122°19’ W) in CDF, and Haney B.C. (49°27’ N and 122°96’ W) in CWH.

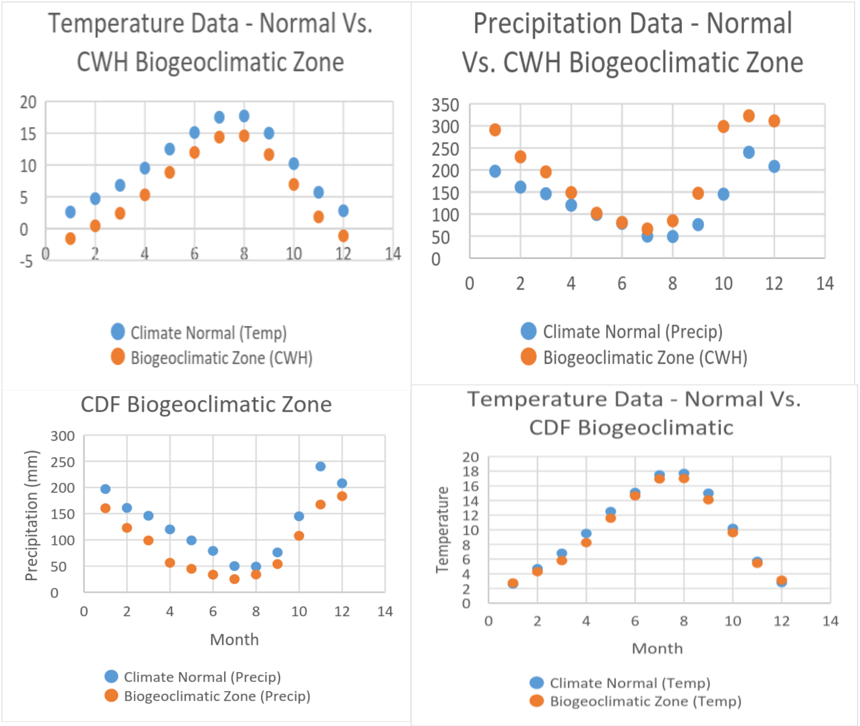


Figure C1: Climate comparison between CDF and CWH and climate normals for Abbotsford International Airport.

b. Aquifer Properties

Saturated hydraulic conductivity values of the aquifer material for the generalized method were extracted from Soil Landscapes of Canada (SLC) version 3.2 in cm/hr. The Abbotsford-Sumas aquifer is classified by the Province of B.C. as a Type 4A aquifer, which is a type A1 in the generalized coding system used in this study. This K_{sat} value coincides with the Coarse Sand material in HELP. Additional material properties are required by HELP, which include total porosity, field capacity, wilting point and subsurface inflow. The values used in the generalized model were based on Coarse Sand (Table 1C).

Table C1: Coarse Sand material properties in HELP used for the generalized method.

Property	Value	Units
Total Porosity	0.417	vol/vol
Field Capacity	0.045	vol/vol
Wilting Point	0.018	vol/vol
Sat. Hyd. Conductivity	45.3	cm/hr
Subsurface inflow	0	mm/year

In contrast, the localized method used a range of K_{sat} values with a mean of 371 cm /hr and a range of range 0.3- 437 cm/hr.

c. Soil Properties

The generalized method used one value of K_{sat} for the soil zone, which was classified as S6, Silty Loam, with a K_{sat} value of 0.684 cm/hr. The additional material properties were the default values in HELP for Silty Loam (Table C2).

Table 2C. Silty Loam material properties in HELP used for the generalized method.

Property	Value	Units
Total Porosity	0.501	vol/vol
Field Capacity	0.284	vol/vol
Wilting Point	0.135	vol/vol
Sat. Hyd. Conductivity	0.684	cm/hr
Subsurface inflow	0	mm/year

The localized method K_{sat} of the soil overlying the aquifer was classified according to the soil drainage properties in the B.C. Soils database. Each class was assigned a K_{sat} value representative of the material type (e.g. low = silty loam; moderate = sandy loam; high = loamy sand; very high = sandy gravel). There was a wide variation of different soils used, with a weighted average of 7.29 cm/hr.

Scibek and Allen (2006b) calculated the median thickness of soil over the Abbotsford-Sumas aquifer as 0.92, and the median 0.60 m if few large overburden depths are excluded (>12 m). For both the localized and generalized methods, a uniform soil thickness of 1.0 was used.

d. Water Table Depth

Water table depth for the profiles in the localized method were variable and based on historic static water elevations in several thousand wells across the Abbotsford-Sumas model. Out of these samples, the median water table depth was 5 m, with a mean 8.0 m, standard deviation 9.3 m and range from 0 to 78 m.

For the generalized method, the mean and standard deviation of water table depth were derived for each B.C. aquifer from the 1-km resolution model from Fan et al. (2013). This value was 8.95 m for the Abbotsford-Sumas aquifer.

C.2 Grand Forks Aquifer

To increase confidence in methodology, a comparison was also done for the Grand Forks aquifer.

a. Climate Data Comparison

The localized method used climate normals for the Grand Forks climate station (49°01'34.2" N and 118°27'56.4" W) from Environment Canada. The generalized method used climate data representative of BGCZ Ponderosa Pine (PP). The climate date comparisons are shown in Figure C2.

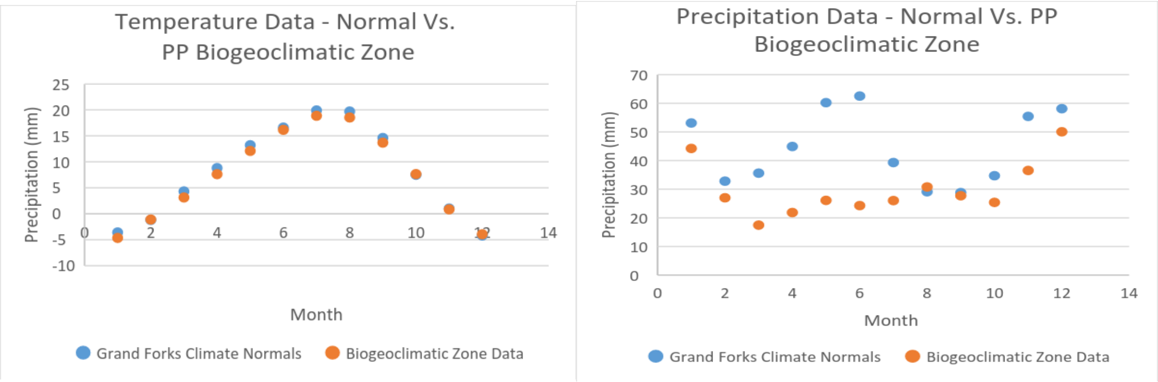


Figure 2C: Climate comparison between PP and the climate normals for Grand Forks.

b. Aquifer Properties

For the localized method, the aquifer properties were categorized according to the K_{sat} of the vadose zone. These values were determined from K_z values in 285 wells, and ranged from 1000 to $1x10^{-6}$ m/d, with a median of 13 m/d and quartile values of 100 and 0.14 m/d. Mid values were selected for each quartile, resulting in representative values of aquifer materials including types: 315, 40, 1.4, 0.015 (m/d).

The Grand Forks aquifer is classified by the Province of British Columbia as a Type 4A aquifer, which is a type A1 in the generalized coding system used in this study. Both methods used the HELP default values of Coarse Sand for the other material properties (Table 3C).

Table 3C. Coarse Sand material properties in HELP used for the generalized method.

Property	Value	Units
Total Porosity	0.417	vol/vol
Field Capacity	0.045	vol/vol
Wilting Point	0.018	vol/vol
Sat.Hyd. Conductivity	45.3	cm/hr
Subsurface inflow	0	mm/year

a. Soil Properties

The localized method classified K_{sat} of the soil overlying the aquifer according to the soil drainage properties in the B.C. Soils database. Each class was assigned a K_{sat} value representative of the material type (e.g. low = silty loam; moderate = sandy loam; high = loamy sand; very high = sandy gravel) (Figure C3).

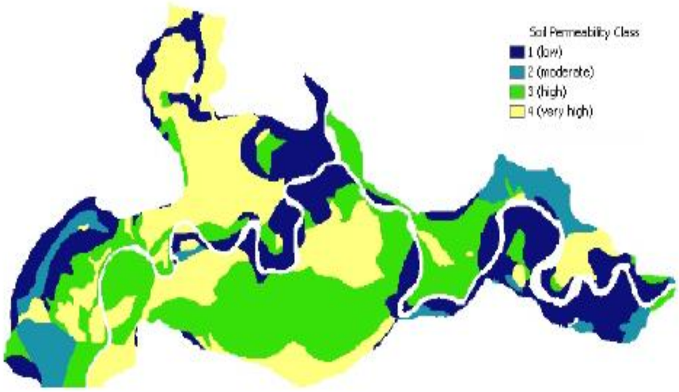


Figure C.3: Relative soil permeability map derived from soil drainage map. Used with permission from Scibek and Allen (2004).

For the generalized model, a single representative K_{sat} value of 10 cm/hr was used for the soil, which corresponds to the coding S3. Within HELP, this corresponds to the properties of Fine Sand (Table C4).

Table 4C: Fine Sand material properties in HELP used for the generalized method.

Property	Value	Units
Total Porosity	0.457	vol/vol
Field Capacity	0.083	vol/vol
Wilting Point	0.033	vol/vol
Sat. Hyd. Conductivity	10	cm/hr
Subsurface inflow	0	mm/year

Generally, the range for the soil thickness of the Grand Forks Aquifer (Figure C4) is estimated to be about 0.4 to 1.6 m thick (Scibek and Allen, 2004; Figure 6). For modelling purposes and simplicity, soil thickness was assumed to be 1.0 m in all percolation columns for both the generalized and localized studies.

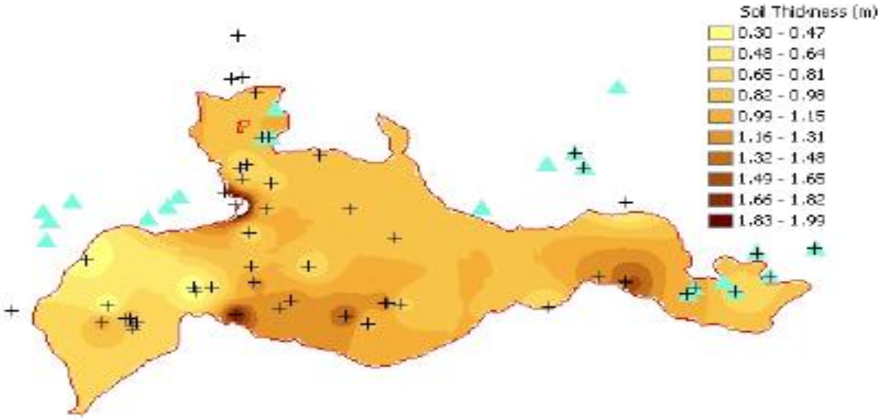


Figure C4: Soil thickness across the Grand Forks Aquifer. Used with permission from Scibek and Allen (2004).

b. Water Table Depth

The localized method mapped water table depth in the aquifer using data from 285 wells. Depth to water table ranged from 1.5 m to 46.8 m, with median of 10.1 m, a mean of 11.4 m, standard deviation of 8.8 m, and quartile values of 6.1 m and 12.9 m. The depth classes were assigned: 0 to 6 m, 6.1 to 10 m, 10.1 to 12.9 m, 13 to 47 m. Representative columns were assigned as average for each range: 3, 8, 11, and 25 m in depth to water table. A mean of 11.4 m was used when recreating the profile.

The generalized method used a value of 36.7m.

APPENDIX D: HELP SENSITIVITY ANALYSIS

A targeted sensitivity analysis was completed on the BGCZ Coastal Douglas Fir (CDF) to further investigate why the CDF had high annual recharge rates as well as relative monthly values in excess of 100%.

First, the Abbotsford-Sumas profile was run with only the precipitation data from the months of April and May, which had the highest monthly recharge percentages, the other months were assigned zero precipitation for each year of the simulation. The only variable was K_{sat} of the soil.

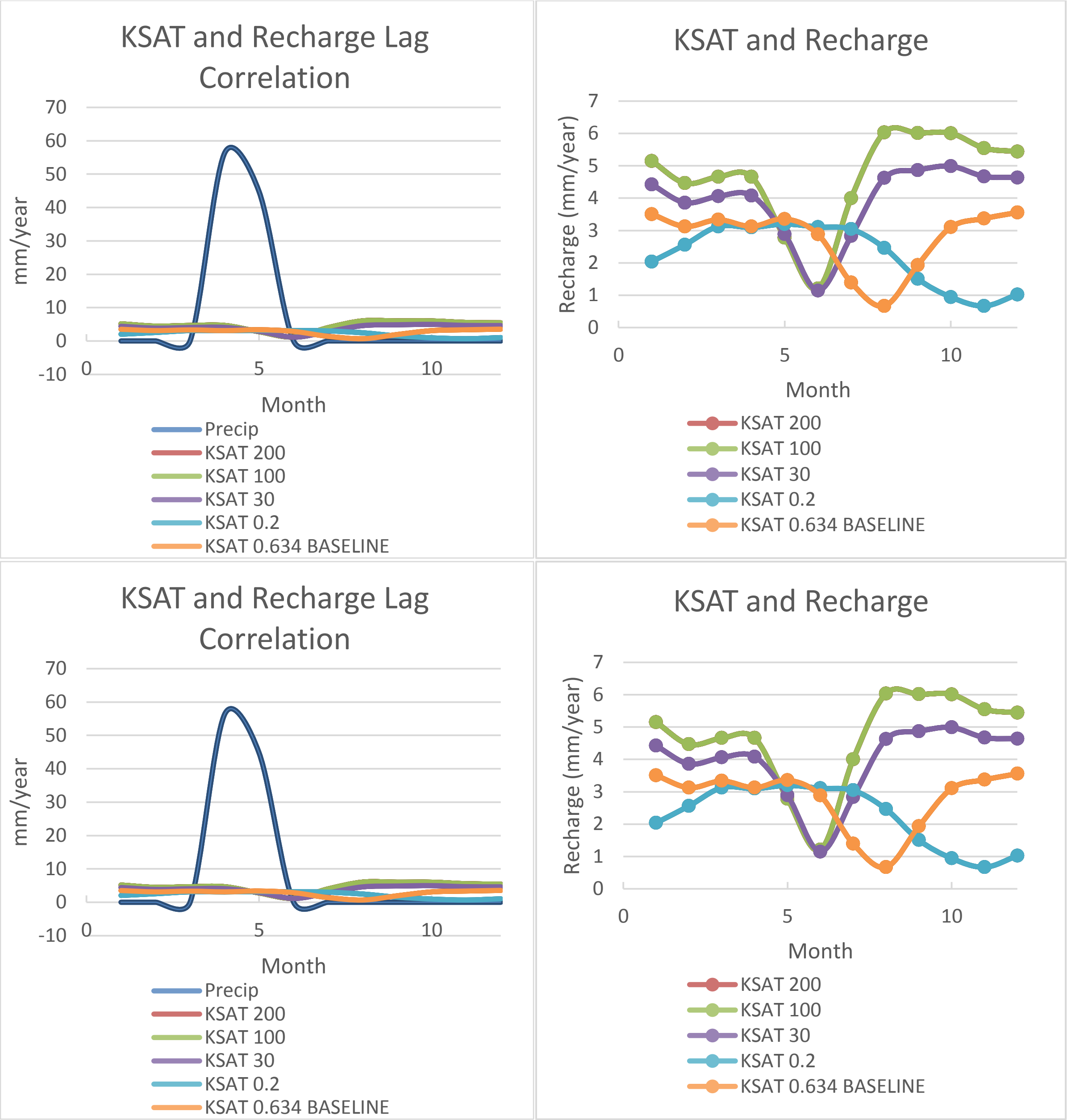


Figure D1: (left) Ksat and recharge lag correlation. (right) Ksat and recharge relationship.

In order to observe the results more clearly, the precipitation was removed from the graph to focus more closely on the response of the recharge values, which is illustrated in Figure D1.

The largest drop in precipitation is shown during the sixth month as shown in Figure D1. In contrast, in Figure D1, the lowest point of recharge for the baseline K_{sat} (green) does not occur until about month eight. The lag time is the longest for the lowest K_{sat} values. These results suggest that the lower the K_{sat} of the overlying soil, the longer a peak in precipitation will take to recharge to the aquifer. This leads to months with low precipitation accounting for the high levels of precipitation that may have happened several months before which then leads monthly values of over 100%.

Second, a broader sensitivity analyses of the BGCZ Coastal Douglas Fir (CDF) were focused on parameters of the weather generator, soil properties and water table depth. The parameters altered in the Weather Generator included relative humidity, wind speed, temperature, precipitation and growing season.

Relative humidity had a moderate effect on recharge; an increase to 50% caused a 9% increase in recharge and a 50% decrease in recharge led to a reduction in recharge by 12%. The weather generator parameter with the greatest influence on recharge was precipitation, where a 50% increase caused a 62% increase in recharge and a 50% decrease caused a 58% percent decrease in recharge.

Factors with no noticeable or very small change included (<5%), (1) stand of grass, (2) wilting point, (3) field capacity, and (4) initial moisture content. Factors with moderate effect on recharge included (1) soil thickness and (2) porosity of layer. Parameters with strong effect on recharge included (1) depth of vadose zone, (2) soil type and (3) K_{sat} of vadose zone.

Increasing by up to 200% both the water table depth (profile thickness) and soil thickness had negligible influence on the recharge for the profile (<0.01%) as shown in Table D3.

Table D1: Soil Properties sensitivity analysis results as % change of annual recharge

	50% Decrease	50% Increase
Field Capacity	-1.6344	3.020058
Sat. Hydraulic Conductivity	0.921247	1.533033
Total Porosity	3.142027	-2.89859
Wilting Capacity	3.424308	-2.47036

Table D2: Aquifer properties sensitivity analysis results as % change of annual recharge

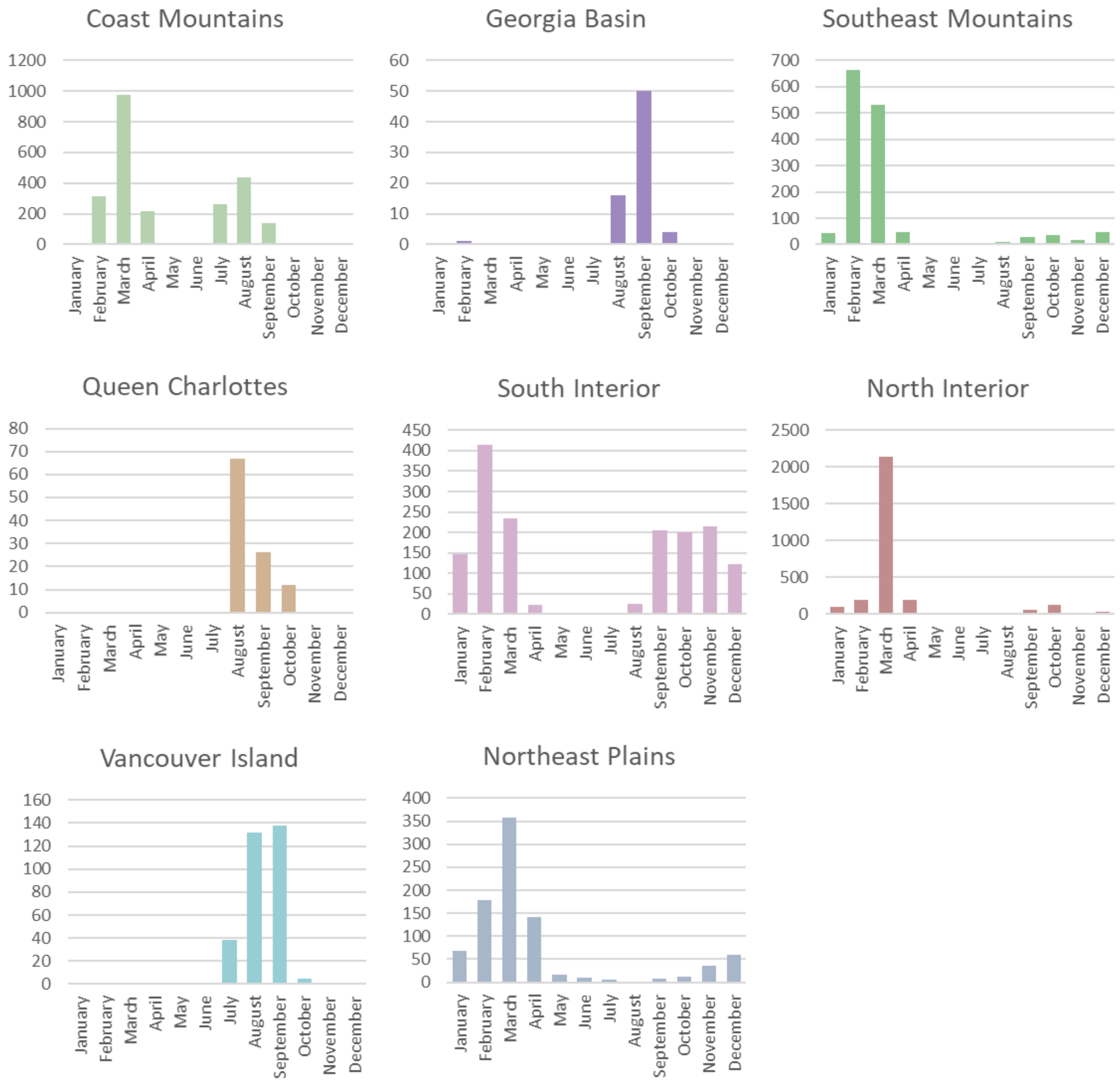
	50% Decrease	50% Increase
Field Capacity	1.16	1.151959
Sat. Hydraulic Conductivity	1.16110	1.168094
Total Porosity	1.187784	1.183713
Wilting Capacity	1.190141	1.186519

Table D3: Water table depth and soil thickness sensitivity analysis results as % change of annual recharge

Input Change (%)	Recharge Change (%)
75% Increase in Soil Thickness	-0.012
75% Increase Water Table	0.037
100% Increase in Soil Thickness	-0.030
100% Increase in Water Table	0.019
200% Increase in Soil Thickness	-0.037
200% Increase in Water Table	0.039

APPENDIX E: E_{LF} - MONTHLY LOW FLOWS

When deriving ELF, the minimum modelled annual mean monthly flows were plotted for each low flow zone (Figure E1.). Low flow zones are illustrated in Figure E2.



Coast Mountains

Georgia Basin

Southeast Mountains

Queen Charlottes

South Interior

North Interior

Vancouver Island

Northeast Plains

Figure E1. Low flow seasons based on frequency of months for cells ($100km^2$) of minimum modelled mean monthly flow.

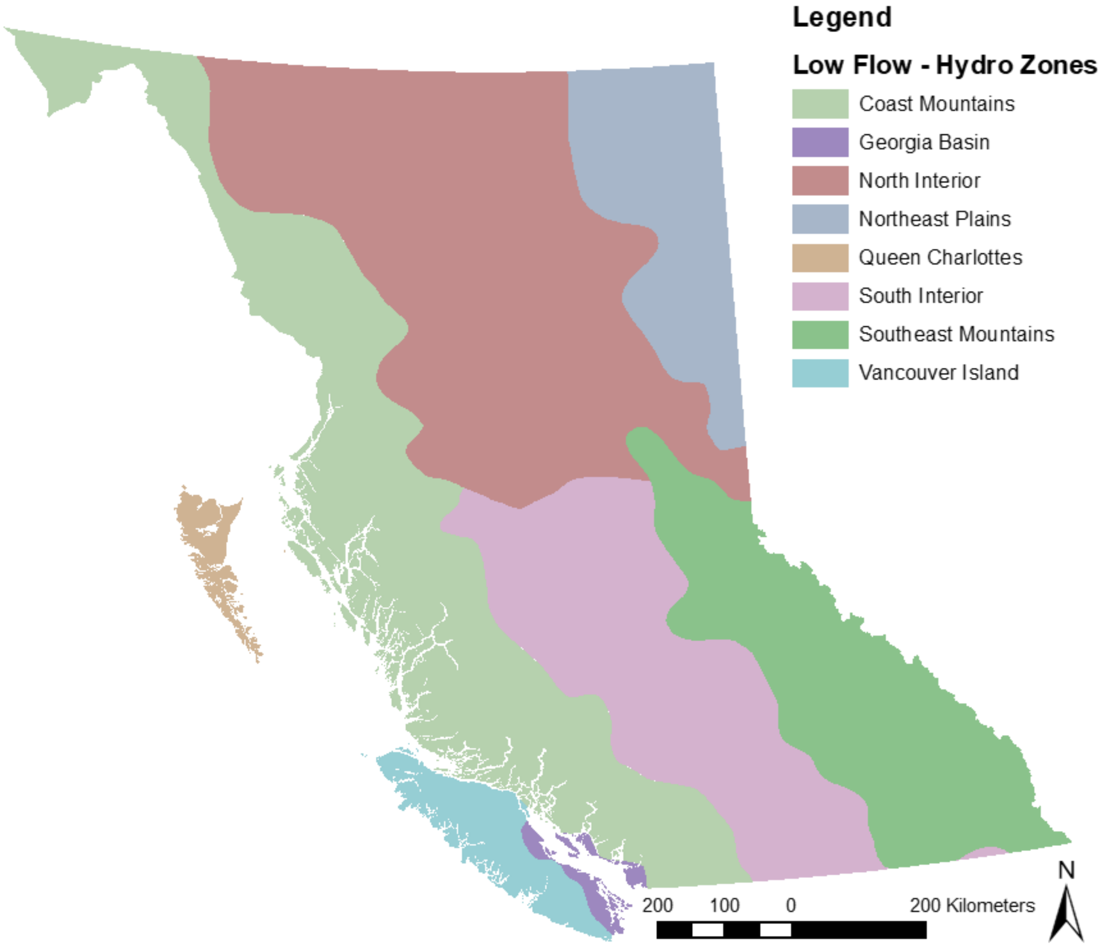


Figure E2. Low flow zones for British Columbia.

APPENDIX F: PCR-GLOBWB STREAMFLOW COMPARISON TO B.C. STATION OBSERVATIONS

The following section provides the data for the streamflow comparison complete based on the streamflow discharge data output from PCR-GLOBWB and 79 stream gauges.

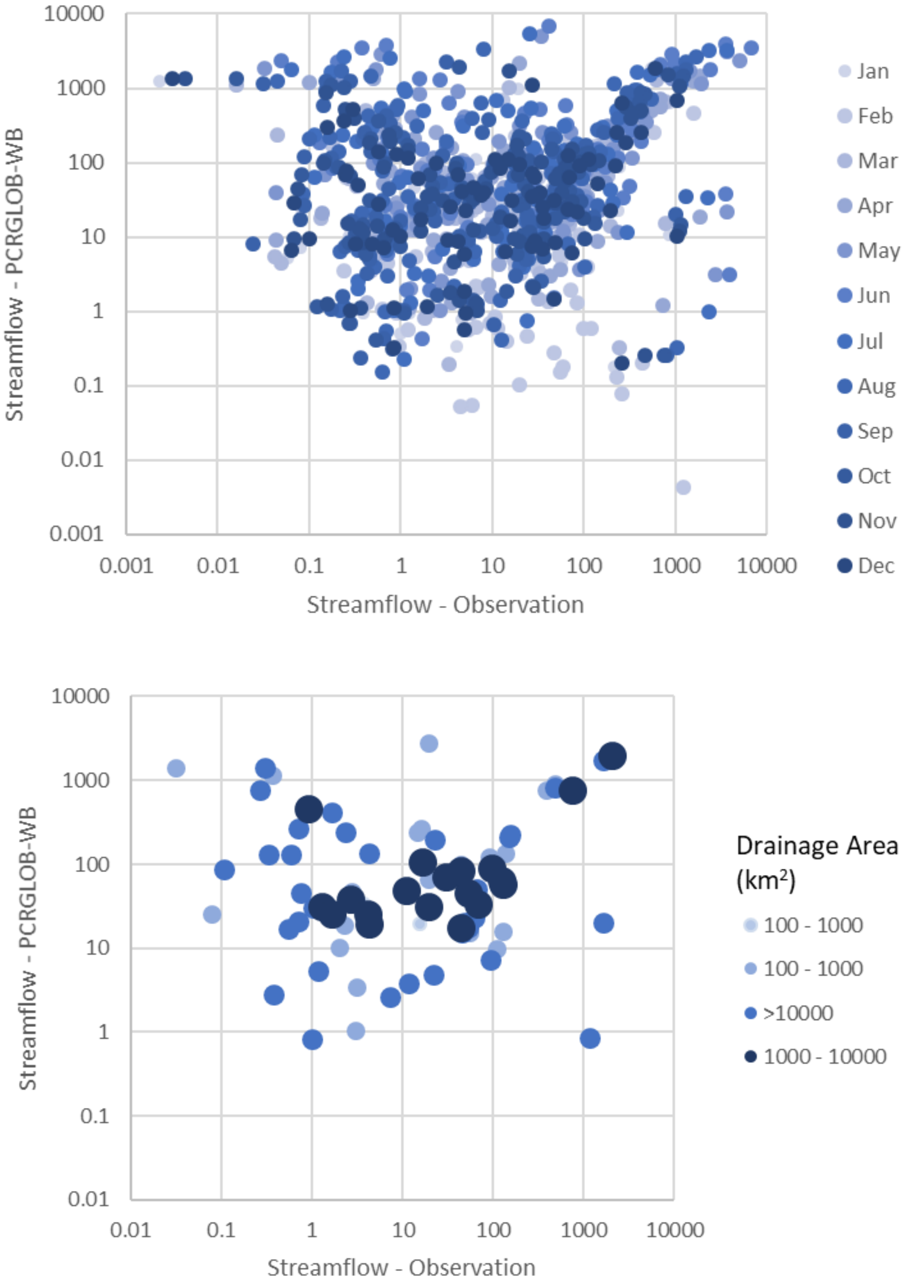


Figure F1. Observation stream gauges versus PCR-GLOBWB modelled streamflow based on mean monthly flow (above), and drainage area (below).

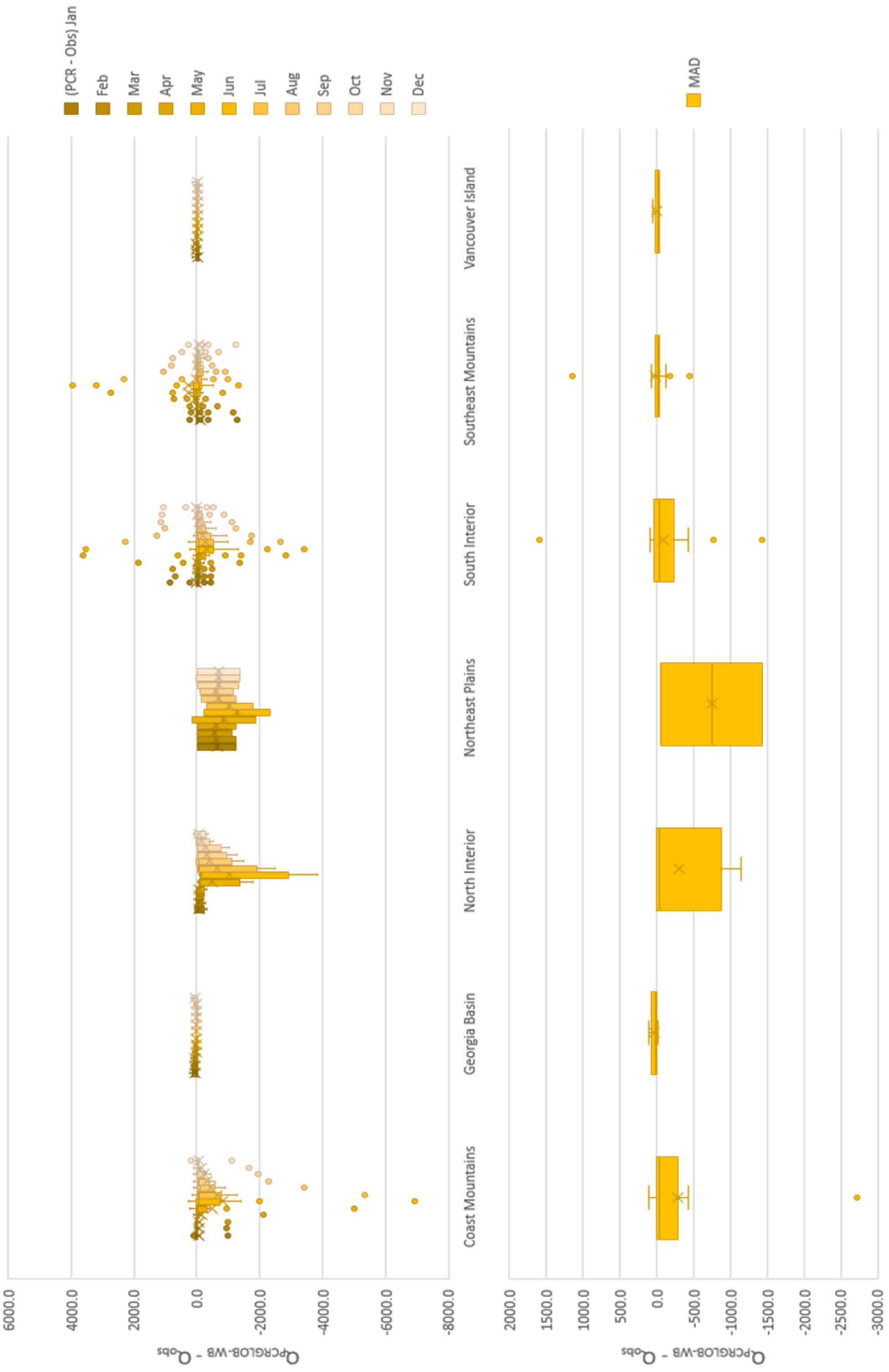


Figure F2. Difference in mean monthly modelled flow from PCR-GLOBEWB and observed streamflow gauges.

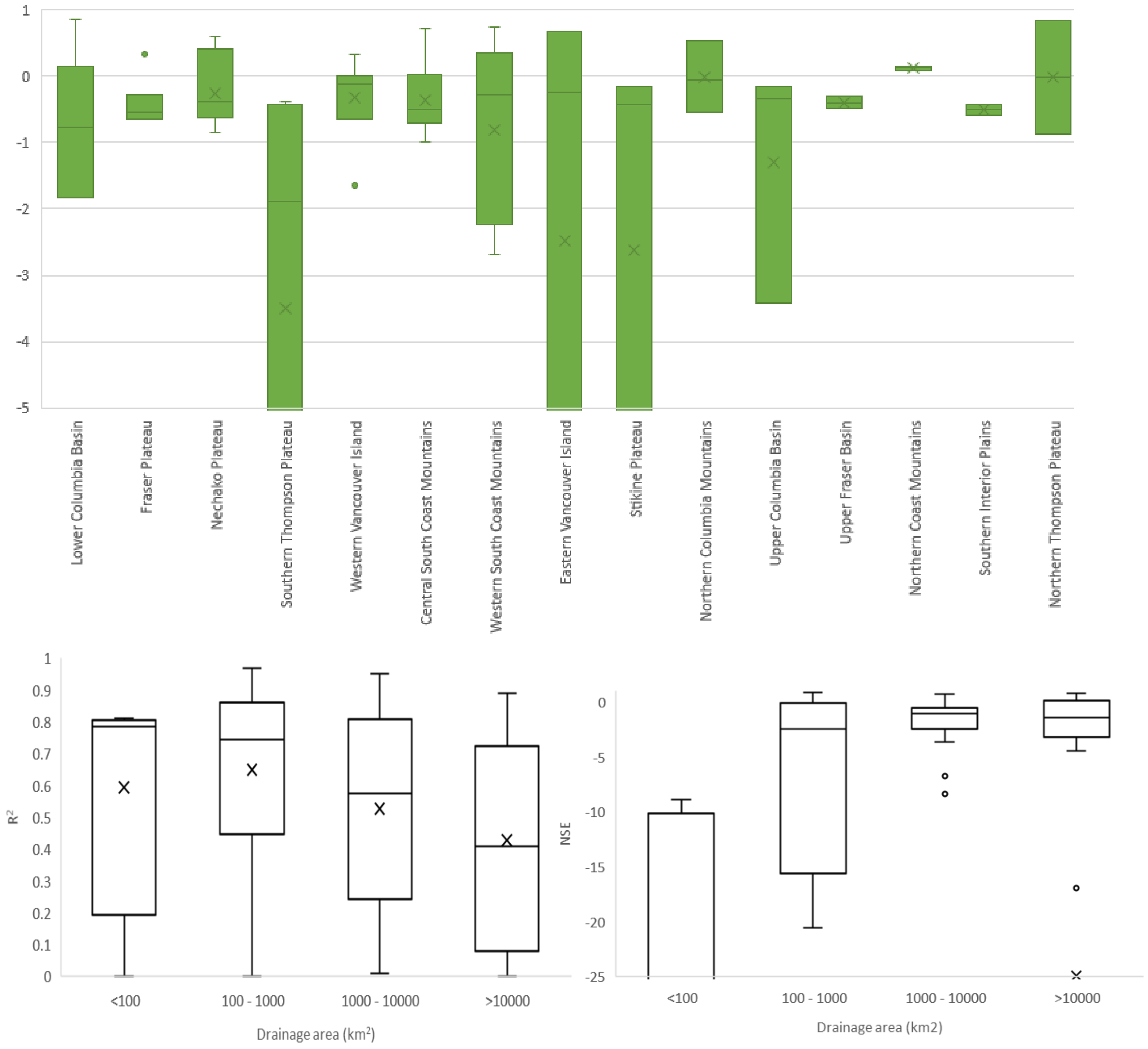


Figure F3. Nash-Sutcliff Efficiency (NSE) for observed modelled mean monthly flow and observed mean monthly flow from stream gauges. (top) NSE by low flow zones. (bottom, left) Mean squared error based on drainage area. (bottom, right) NSE based on drainage area.