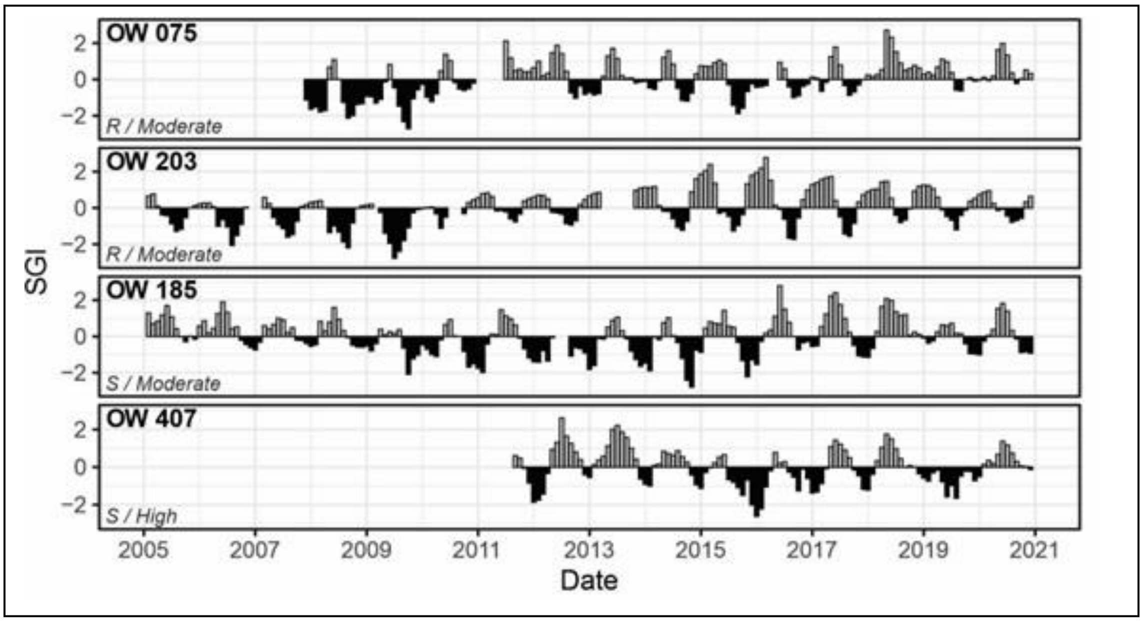
WATER SCIENCE SERIES

Indicators of Groundwater Drought in British Columbia

April Gullacher, Diana M. Allen, Jonathan D. Goetz



January 2023

BRITISH COLUMBIA

SFU SIMON FRASER UNIVERSITY

No. 2023-01

The **Water Science Series** are scientific technical reports relating to the understanding and management of B.C.'s water resources. The series communicates scientific knowledge gained through water science programs across B.C. government, as well as scientific partners working in collaboration with provincial staff. For additional information visit: http://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-science-data/water-science-series.

ISBN: 978-1-0399-0016-5

Citation:
Gullacher, A., D.M. Allen, and J.D. Goetz. 2023. Indicators of Groundwater Drought in British Columbia. Water Science Series, WSS2023-01. Prov. B.C., Victoria.

Author's Affiliation:
A. Gullacher, MSc. Student
Department of Earth Sciences
Simon Fraser University

D.M. Allen, P.Geo., Professor
Department of Earth Sciences
Simon Fraser University

J.D. Goetz, P.Ag.
River Forecast Centre
Ministry of Forests, Victoria, B.C.

Cover Image:
Standardized Groundwater Level Index for several Province of British Columbia Observation Wells.

Acknowledgements

Funding for this research was provided by the Canadian Mountain Network, and the Province of British Columbia as a B.C. Groundwater Science Project. The authors thank Dr. Jesse Halm (Simon Fraser University), Julie-Ann Ishikawa (B.C. Water, Land and Resource Stewardship) and Dr. Carl Mendoza (Emeritus Professor University of Alberta) for their feedback.

EXECUTIVE SUMMARY

In recent years, many parts of British Columbia (B.C.) have experienced unprecedented drought conditions. While the start of the Water Year on October 1 is typically marked by wetter conditions, 12 different water basins across B.C. experienced Level 4 or Level 5 drought conditions through the end of November in 2022 due to an unusually dry summer and fall. The most obvious indicator of drought is reduced streamflow, but groundwater levels can also drop.

Drought levels in B.C. are informed by indicators based on 1) core early season indicators (basin snow measures and seasonal runoff forecasts), and 2) core drought season indicators (7-day average streamflow, 30-day percent of average precipitation). Currently, aquifer levels are only used as a supplemental indicator of drought with no quantitative threshold(s). Moreover, although streamflow is one of the core indicators during the drought season, the hydraulic connection between the surface water and groundwater is not considered. Due to the varied nature of the response mechanisms of aquifer-steam systems, as described in Gullacher et al. (2021), these hydraulic connections should be considered when using groundwater levels as a drought indicator. The groundwater drought indicator should also be applicable to the wide range in climatology and physiography of the province.

Unfortunately, there is no widely acceptable indicator for groundwater drought. The majority of the existing groundwater drought indicators used in different jurisdictions worldwide are after-the-fact indicators, relying on past observed groundwater levels. What is needed is a method that can predict if a groundwater drought may occur, and then, during the drought season use an indicator of current groundwater drought conditions.

The main purpose of this study is to contribute to our understanding of groundwater drought in mountainous regions and develop a set of decision-making tools for assessing groundwater drought in B.C. The objectives were three-fold:

1) classify the response mechanism for aquifers monitored by provincial observation wells in B.C. (reported in Gullacher et al., 2021);
2) develop early season and drought season core indictors of groundwater drought that can be used for drought-related decision-making in B.C. (this report); and
3) develop an approach for mapping the drought susceptibility of aquifers and demonstrating this approach in the Okanagan Basin (this report).

Objective 2 focuses on three different study areas in the province: 1) South Central B.C., primarily in the Okanagan Basin, 2) the Fraser Valley, and 3) the Gulf Islands. These areas were chosen to represent three different geologic and hydroclimatic regions: unconsolidated aquifers in a snowmelt-dominated region (South Central B.C.), unconsolidated aquifers in a rainfall-dominated region (Fraser Valley), and consolidated/bedrock aquifers in a rainfall-dominated region (Gulf Islands). For Objective 3, the Okanagan Basin is selected as a case study area. This region was chosen because the Basin experiences a water deficit (evapotranspiration is higher than precipitation) during the summer and, as a result, the Okanagan Basin is a water stressed region that has experienced severe droughts.

Groundwater levels from the Provincial Groundwater Observation Well Network (PGOWN) in each region were first examined seasonally (a preliminary analysis) to identify individual climate and hydrological predictor variables (e.g., precipitation amount, snow water equivalent (SWE), minimum and maximum daily temperatures, streamflow) that appear to influence summer groundwater levels. Due to the complexity of responses revealed through this preliminary analysis, generalized additive models (GAMs) were used to explore associations between predictor variables and summer groundwater levels. Various sensitivity analyses were conducted to explore associations between individual predictor

variables and summer groundwater levels, and to explore different options for incorporating the predictor variables into the GAMs. The associations with the Niño 3.4 index representing the El Niño Southern Oscillation (ENSO), and the Pacific Decadal Oscillation (PDO) were also explored.

Based on the individual predictor variables that resulted in the most statistically robust GAMs, the predictor variables were combined to create multi-parameter GAMs for each study region. GAMs that used summer predictor variables (e.g., summer maximum daily temperature) or annual conditions (e.g., annual Niño 3.4 index) ultimately were not selected because the goal was to identify predictor variables that could be used prior to the summer season to "predict" if groundwater drought might occur. In South Central B.C., maximum spring temperature, maximum snow water equivalent, and the winter ENSO 3.4 index was the best combination of climate predictor variables. In the Fraser Valley, the maximum spring temperature, winter precipitation, and spring streamflow was the best combination of climate predictor variables. For the Gulf Islands, the GAMs did not produce well fitted summer groundwater levels.

The GAMs were validated by comparing the standardized values for each seasonal predictor variable against the percentage of wells that had summer groundwater levels in different percentile ranges. In South Central B.C., years with a combination of above average maximum spring temperature, below average maximum SWE, and a positive Niño 3.4 index corresponded with a larger number of wells with average summer groundwater levels lower than the 15th percentile. In the Fraser Valley, years with a combination of above average maximum spring temperature, below average winter precipitation, and below average streamflow corresponded with a larger number of wells with water levels lower than the 15th percentile.

Several provincial observation wells were identified as potential groundwater drought indicator wells. These wells all had high r^2 values for the GAM when only using climate and hydrological variables from the winter and spring previous to the summer groundwater levels.

In addition to identifying predictor variables of groundwater drought, the use of the standardized groundwater level index (SGI) was explored as a potential drought season core indicator of groundwater drought. The SGI was tested in South Central B.C. and the Fraser Valley, and found to be effective at indicating which wells had pronounced responses to periods of drought in each region. However, the SGI was shown to be affected by water use in aquifers, and as such may not be best used in aquifers with a high well density or negative groundwater trends if only climate-related drought (and not anthropogenic drought) is of interest. Overall, the SGI appears to be a good indicator to retroactively check how the groundwater levels responded to periods of drought and to non-drought years.

Finally, aquifer susceptibility to drought was examined for the Okanagan Basin. An aquifer drought susceptibility matrix was created using published hydraulic diffusivity values for different aquifer types, as well as the well density of each aquifer. The classification identified five highly susceptible aquifers and 23 moderately susceptible aquifers. Additionally, these classifications were consistent with observations of surface water and groundwater problems made by participants of a workshop in October 2019. Aquifers classified as high susceptibility should be carefully monitored and considered for use curtailment during the summer based on the core early season predictor variables identified in this study. Aquifers classified as moderate susceptibility, with a moderate well density should be monitored to ensure that further development of the aquifer (i.e., an increase in well density) does not adversely affect the groundwater levels, particularly during droughts. Furthermore, the amount of water being abstracted, as well as the timing of abstractions, should also be noted if there is non-domestic water use in the aquifer.

CONTENTS

FIGURES

TABLES

1. INTRODUCTION

British Columbia (B.C.) has experienced significant periods of drought, the most recent of which occurred in the summer of 2022, with 12 different water basins experiencing Level 4 or Level 5[1] drought conditions in late November[2]. B.C. also experienced significant drought in the summer of 2015, with Level 4[3] drought conditions in South Central B.C. and along the South Coast. While drought conditions are typically manifested in very low streamflow, groundwater levels too can drop. For example, on August 24, 2015, the B.C. Ministry of Forests, Lands and Natural Resource Operations (now the Ministry of Forests (FOR)) issued a Fact Sheet to well owners in B.C. urging them to continue to conserve water as many provincial observation wells were showing lower than normal groundwater levels earlier in the season than in previous years. Notably, although 2015 was very dry, the drought conditions had largely dissipated by October 1, compared to the continued drought conditions extending to the end of November in 2022.

Drought levels in B.C. are informed by indicators based on 1) core early season indicators (basin snow measures and seasonal runoff forecasts), and 2) core drought season indicators (7-day average streamflow, 30-day percent of average precipitation) (B.C. Ministry of Land, Water and Resource Stewardship (B.C. LWRS), 2022). Supplemental indicators can include aquifer levels, individual hydrometric results, multi-year trends, reservoir inflows, and wildfire danger class ratings (B.C. LWRS, 2022). However, currently there is no aquifer (groundwater) level indicator in B.C. that can be widely used for drought warning and response planning.

Unfortunately, there is no widely acceptable indicator for groundwater drought (Bloomfield and Marchant, 2013). Furthermore, the complexity of surface water and groundwater interactions in mountainous regions makes the use of standardized indicators more difficult. Widely used drought indicators, such as the Standardized Precipitation Index (SPI), do not consider the complex interactions between aquifers and streams – they use only precipitation and temperature as inputs (Hayes et al. 1999). Understanding the response mechanism of a well, that is, whether the groundwater level responds to a change in streamflow (streamflow-driven) or whether the groundwater response to recharge drives changes in streamflow (recharge-driven) is important for understanding the hydraulic connection between aquifers and streams and how these aquifer-stream systems might respond to drought. As well, and perhaps more importantly, groundwater levels in B.C. are only monitored in 217 Provincial Observation Wells, despite over 1,100 aquifers extending over more than 30,000 km^2 having been mapped and registered[4]. This means that only a small fraction of aquifers has regularly monitored groundwater level information. Thus, there is a need for a groundwater drought indicator that considers the complex response mechanisms of aquifer-stream systems in mountainous regions, which can be used to identify drought conditions and potentially forecast groundwater droughts. Moreover, there is a need for information on what types of aquifers are more susceptible to drought so that aquifers that are not currently monitored can be prioritized for future monitoring.

---

[1] Current drought level system.

[2] Historical British Columbia Drought Information.

[3] Old drought level system

[4] Understanding Aquifers.

The main purpose of this study is to contribute to our understanding of groundwater drought in mountainous regions and develop a set of decision-making tools for assessing groundwater drought in B.C. The objectives were three-fold:

1) classify the response mechanism for aquifers monitored by provincial observation wells in B.C. (reported in Gullacher et al., 2021);
2) develop early season and drought season core indictors of groundwater drought that can be used for drought-related decision-making in B.C. (this report); and
3) develop an approach for mapping the drought susceptibility of aquifers and demonstrating this approach in the Okanagan Basin (this report).

It is hoped that the approaches developed in this project can be applied to other mountainous areas and provide insight on drought warning and planning policies with these complex aquifer-stream systems.

This project was funded by the Canadian Mountain Network as part of a project titled "Managing Groundwater Resources in Mountainous Areas: Planning for and Adapting to Drought Conditions" led by Dr. Diana Allen. The project is also supported by the British Columbia Ministry of Water, Land and Resource Stewardship (WLRS) under the Groundwater Science Program.

2. BACKGROUND

2.1 What is Drought?

Drought is defined as a shortage in water due to a lack of precipitation (Wilhite and Glantz, 1985). There are four main categories of drought (Wilhite and Glantz 1985; Mishra and Singh, 2010):

- Meteorological drought – a period of time with a lack of precipitation over a region
- Hydrological drought – a period of time in which there is a deficit in surface and subsurface water for established water uses.
- Agricultural drought – a period of time in which there is a reduction in soil moisture or an irregular evapotranspiration deficit.
- Socio-economic drought – a reduction in water supply that limits the supply of an economic good.

Drought can propagate through the water cycle. For example, a deficit in precipitation, or a meteorological drought, can become a soil moisture drought and a hydrological drought (Peters et al., 2003; Han et al., 2019). Groundwater droughts occur when groundwater recharge decreases (Bryant et al., 1994), followed by decreases in groundwater levels and groundwater discharge (Peters et al., 2001, 2003, 2005). These decreases are brought on by a deficiency in precipitation and can occur on different time scales of months to years (Van Lanen and Peters, 2000; Mishra and Singh, 2010). Consequently, a decrease in groundwater level is often used to signify a groundwater drought, such that if the groundwater levels in an aquifer have decreased below a critical level over a selected period of time, a groundwater drought has occurred (Chang and Teoh, 1996; Eltahir and Yeh, 1999).

Groundwater drought has been observed in many regions around the world. For example, California experienced a multi-year drought from 2012 to 2016 that resulted in widespread groundwater level declines (Lund et al., 2018; Ojha et al., 2019). As a result of this drought, numerous wells were deepened due to the declined groundwater levels throughout the state (Levy et al., 2020). A significant drought occurred in Europe in 2015 due to preceding dry periods and a dry summer (Van Loon et al., 2017).

Drought is an important aspect of hydrology and can have huge impacts on people and the environment. A study in the Sierra Nevada, found that wells completed in fractured bedrock in areas of higher elevation that are primarily recharged by precipitation are at a higher risk to water shortages during periods of drought (Levy et al., 2020). If there is a significant decrease in the groundwater level, wells may need to be deepened (Levy et al., 2020). Additionally, declining groundwater levels can also negatively impact local ecosystems. Groundwater droughts can cause a decline in the amount of baseflow in streams during summer lows, negatively impacting the fish and other aquatic species that depend on sustained streamflow (Douglas, 2006).

A complicating factor is that groundwater droughts can be exacerbated or caused by human activities such as surface and subsurface water abstraction (Van Loon et al., 2016). Whether a drought is natural or has been exacerbated by humans is critical to drought management as there is a need to focus on either adapting to the changing climate and the resulting natural climate-induced drought, or alternatively focus on how to alleviate the causes of human-induced drought (Van Loon et al., 2016). Therefore, it is important to consider human impacts when assessing periods of drought.

2.2 Drought in British Columbia

The Province of B.C. has identified 32 different drought regions[5]. These regions represent the diverse physiography and climatology of the province. Most of B.C. lies in the Cordilleran, which has a complex geologic history. Due to tectonics and episodic glaciation, the physiography of B.C. is a system of mountain ranges and plateaus and valleys with mainstem lakes and river systems (Church and Ryder, 2010). Given the diverse physiography and climatology of B.C., drought conditions can vary considerably across the province in any particular year. For example, Level 4 droughts were declared in 2016 in the East Vancouver Island region, and in 2017 in nine different drought regions as early as August and as late as October[3].

The British Columbia Drought and Water Scarcity Response Plan outlines drought management responsibilities, as well as the drought response levels, indicators, and actions for when a drought occurs (B.C. LWRS, 2022). The B.C. Drought Response Plan was updated in 2021 from four to six successive levels of drought (B.C. LWRS, 2022). These new drought levels range from Average or Wetter than Average (0) to Exceptionally Dry (5) and are based on core indicators and supplemental indicators (Table 1). As mentioned previously, the core indicators are separated into early season indicators (basin snow measures, and seasonal volume runoff forecasts) and drought season indicators (7-day average streamflow, 30-day percent of average precipitation) (B.C. LWRS, 2022) (Table 2). Supplemental indicators can include aquifer (groundwater) levels, individual hydrometric results, multi-year trends, reservoir inflows and wildfire danger class ratings, and may be used throughout the early season or during the drought season as appropriate (B.C. LWRS, 2018).

---

[5] B.C. Drought Information Portal

Table 1: Drought level classifications and response measures used in B.C. (Source: B.C. LWRS, 2022)

Level	Conditions	Impacts	General Response Measure
0: Green	Average or Wetter than Average	There is sufficient water to meet socioeconomic and ecosystem needs	Preparedness
1: Yellow	Starting to Become Dry	Adverse impacts to socio-economic or ecosystem values are **rare**	Conservation
2: Peach	Becoming Very Dry	Adverse impacts to socio-economic or ecosystem values are **unlikely**	Conservation Local water restrictions where appropriate
3: Orange	Becoming Severely Dry	Adverse impacts to socio-economic or ecosystem values are **possible**	Conservation Local water restrictions likely
4: Red	Extremely Dry Conditions	Adverse impacts to socio-economic or ecosystem values are **likely**	Conservation and local water restrictions Regulatory action possible
5: Maroon	Exceptionally Dry Conditions	Adverse impacts to socio-economic or ecosystem values are **almost certain**	Conservation and local water restrictions Regulatory action likely Possible emergency response

Table 2: Drought indicator criteria used to assist decision makers with establishing drought levels and responses (Source: B.C. LWRS, 2022).

	Timing of Use	
	Early Season	**Drought Season**
Core Indicators	• Basin snow measures • Seasonal volume runoff forecasts	• 7-Day average streamflow • 30-day percent of average precipitation
Supplemental Indicators (May be used throughout early season or drought season as appropriate)	• Air temperatures • Stream water temperature • Aquifer levels • Community or commercial operations responding to low snowpack or low water supplies • Forecasts of stream flows from hydrologic models • Groundwater levels and soil moisture deficits • Indicator aquatic species • Individual indicator hydrometric station results • Measured flows at discontinued WSC or provincial hydrometric stations multi-year trends • Percent mean annual discharge (% MAD)	• Precipitation deficits at longer timescales (2-6 months) • Reports of fish stress and other ecosystem impacts • Reports of low flows • Reservoir inflows, storage, or lake levels • Scientific drought indicators (e.g., Palmer Drought Severity Index, Standardized Precipitation Index) • Short- and long-term weather forecasts • Streamflow characteristics at longer timescales (e.g., cumulative streamflow over 1-6-month periods) • Wildfire danger class ratings and wildfire “Drought Codes”

Currently, aquifer levels are only used as a supplemental indicator of drought, with no quantitative threshold(s). Moreover, although streamflow is one of the core indicators during the drought season, the hydraulic connection between the surface water and groundwater is not considered. Due to the varied nature of the response mechanisms of aquifer-steam systems, as described in Section 2.5, these hydraulic connections should be considered when using groundwater levels as a drought indicator in B.C. and other mountainous regions. The groundwater drought indicator should also be applicable to the wide range in climatology and physiography of the province.

Moreover, the majority of the existing groundwater drought indicators are after-the-fact indicators, relying on past observed groundwater levels. What is needed is a method that can predict if a groundwater drought may occur. Readily available climate variables, such as temperature and streamflow data, can potentially be used as predictor variables for groundwater drought. This will require knowing which climate and hydrological variables are associated with summer groundwater levels in the different hydroclimatic regions of B.C.

2.3 Drought Indicators

There are numerous drought indicators. Table 3 outlines drought indicators used globally; they are categorized by the type of drought: meteorological, agricultural, and hydrological. Drought indices are used to assess drought parameters such as intensity and duration, as well as the effects of a drought (Mishra and Singh, 2010). Drought indices can use one variable, such as precipitation, or a combination of variables to form a composite or multivariate indicator (Hao and Singh, 2015). A time scale of a year or a month is most often used in drought analysis (Mishra and Singh, 2010). Some of these drought indicators have been classified as easy to use, while others are more difficult to use (Table 4). Due to differences in climates and basins, research and analyses should be done to determine which indicator would work best for specific regions (World Meteorological Organization and Global Water Partnership (WMO and GWP), 2016).

Two widely used drought indicators are the Standardized Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI). The SPI was developed by Mckee et al. (1993) and uses a monthly precipitation data set and a specified time scale. The historical precipitation record at the chosen time scale is fitted to the Gamma function to compute a probability of precipitation, which allows for comparisons of the frequency of severely and extremely dry conditions between locations (Mckee et al., 1993). The only input to the SPI is precipitation, which allows for its ease of use, but the indicator does not consider the overall water balance (Bloomfield and Marchant, 2013).

Table 3: Summary of drought indicators as well as the parameters used, ease of use, and the original study. The ease of use is ranked as green (easiest to use), yellow, or red (more complicated) (WMO and GWP, 2016). Ease of use is described in Table 4.

Drought Indicators	**Type of Drought**	**Parameters Used ***	**Ease of Use** (WMO and GWP 2016)	**Limitations** (WMO and GWP 2016)	**Original Studies**
Standard Precipitation Index	Meteorological	P	**Green**	• precipitation is the only input	Mckee et al. (1993)
Palmer Drought Severity Index	Meteorological	P, T, AWC	**Orange**	• assumes all precipitation falls as rain (Hayes et al. 1999) • underestimates runoff (Hayes et al. 1999)	Palmer (1968)
Standardized Precipitation Evapotranspiration Index	Meteorological	P, T	**Orange**	• requires serially complete datasets • monthly index, may not identify drought fast enough	Vicente-Serrano et al. (2010)
Soil Moisture Deficit Index	Soil Moisture	modelled	**Red**	• requires Soil and Water Assessment Tool (SWAT) modelling	Narasimhan and Srinivasan (2005)
Soil Moisture Anomaly	Soil Moisture	P, T, AWC	**Orange**	• difficult to calculate • ET estimates vary by region	Bergman et al. (1988)
Soil Water Storage	Soil Moisture	AWC, R, Soil Type, SWD	**Red**	• can have variations over small spatial extents in areas without soil homogeneity	B.C. Ministry of Agriculture (2015)
Palmer Hydrological Drought Index	Hydrological	P, T, AWC	**Orange**	• human impacts not considered	Palmer (1965)
Standardized Streamflow Index	Hydrological	SF	**Orange**	• only uses streamflow	Modarres (2007)
Surface Water Supply Index	Hydrological	P, R, SF, Snowpack	**Orange**	• different basins cannot be compared	Shafer and Dezman (1982)
Streamflow Drought Index	Hydrological	SF	**Orange**	• only uses streamflow • skewed results due to no flow periods	Bhuiyan (2004)
Standardized Water Level Index	Hydrological	GW	**Orange**	• interpolation between points may not be accurate	Bhuiyan (2004)

* P = precipitation, T = Temperature, AWC = available water content, R = reservoir, SF = streamflow, SWD = soil water deficit, GW = groundwater levels.

Table 4: Ease of use descriptions for drought indicators (WMO and GWP, 2016).

Ease of Use	Description
Green	• A code or program to run the index is readily and freely available • Daily data are not required • Missing data are allowed for • Output of the index is already being produced operationally and is available online
Orange	• Multiple variables or inputs are needed for calculations • A code or program to run the index is not available in a public domain • Only a single input or variable may be needed, but no code is available • The complexity of the calculations needed to produce the index is minimal
Red	• A code would need to be developed to calculate the index based upon a methodology given in the literature • The index or derivative products are not readily available • The index is obscure index, and is not widely used, but may be applicable • The index contains modelled input or is part of the calculations

2.4 Groundwater Drought Indicators

Three drought indicators that consider groundwater levels are the Standardized Water-level Index (SWI), the Groundwater Resource Index (GRI), and the Standardized Groundwater Level Index (SGI). Only the SWI was included in the review of drought indicators by WMO and GWP (2016) (Table 3).

The SWI was developed in India as a methodology to assess groundwater recharge deficits (Bhuiyan, 2004). The only input parameter for the SWI is groundwater levels. The SWI has also been used in other studies including Yarmouk basin, Jordan (Mohammad et al., 2018); Vistula basin, Poland (Kubiak-Wójcicka and Bąk, 2018); Dhar and Mewat Districts, India (Sahoo et al., 2015).

The GRI uses a water balance model for drought monitoring and forecasting and was developed and tested in the Calabria region of Italy (Mendicino et al., 2008). The model produces a groundwater detention value, while also considering the aquifer lithology by separating the study area into lithological categories (Mendicino et al., 2008). The GRI value is then calculated using the groundwater detention minus the mean of the groundwater detention values, divided by the standard deviation for the month using at least 30 years.

The SGI builds upon the SPI and is estimated using a non-parametric normal score transform for each calendar month of groundwater level (Bloomfield and Marchant, 2013). Bloomfield & Marchant (2013) developed the SGI using groundwater levels from 14 sites in unconfined consolidated aquifers across the UK and compared their results to the SPI using precipitation data. The SGI was used to classify hydrographs of 74 observation boreholes in England situated in flat generally low-lying areas. These observation boreholes were organized into clusters of similar changes in their SGI time series. The hydrographs were normalized using SGI for each month and merged to form a continuous SGI time series. Additionally, the SPI was estimated for precipitation accumulation periods of 1, 2, …, 36 months. The correlation between the SGI and SPI was analyzed for each cluster. The authors found that the catchment and hydrogeological factors were the dominant control of the cluster groups. It was also determined that groundwater droughts were longer in duration than meteorological droughts (Bloomfield et al., 2015).

Each groundwater indicator has limitations that may make it not applicable to drought in mountainous regions. For example, the SGI was developed in low lying areas, and in predominately chalk aquifers across the UK (Bloomfield and Marchant, 2013). The SWI was developed in a mountainous region of India, although the geology of the area was gneiss, schist, and phyllites. Additionally, the stream channels in the region where the SWI was developed experience dry periods for most of the year. The GRI is a complicated index as it involves a water balance model and so may be difficult to implement.

One potential limitation of these indicators is that they do not take into consideration the hydraulic connection between the surface water and groundwater, which may be complex due to the diverse hydroclimatology of mountain regions (Winter et al., 1999). These hydraulic connections allow water to flow from surface water to the groundwater and the other way around and can vary temporally and spatially (Winter et al., 1999). Moreover, the hydraulic connections can be more complex in mountainous environments due to the spatial and temporal differences in streamflow, which can subsequently influence the spatial and temporal variability of groundwater levels (Winter et al., 1999; Viviroli et al., 2003). The hydraulic connection between aquifers and surface water bodies, such as streams, should be considered when investigating groundwater drought. Therefore, this study first classified the response mechanism of the aquifer-stream system (see Section 2.5), following the approach by Allen et al. (2010).

2.5 Considering Hydraulic Connectivity

In the context of characterizing the interactions between groundwater and surface water in mountainous regions, Allen et al. (2010) classified aquifer-stream system types using a two end-member system representing the response mechanism: recharge-driven systems and streamflow-driven systems (Figure 1). In recharge-driven systems, diffuse recharge over an aquifer footprint causes groundwater levels to rise, with a subsequent increase in the contribution of groundwater to the stream. Thus, the groundwater level response leads the streamflow response. In streamflow-driven systems, increases and decreases in the streamflow (stage) cause increases and decreases in the groundwater levels. In these systems, the streamflow response leads the groundwater level response. The response mechanism can be determined using hysteresis plots of groundwater levels versus streamflow and through a cross correlation analysis as illustrated in Figure 1.

A detailed discussion of the aquifer-stream classification methodology and classification results for provincial observation wells can be found in Gullacher et al. (2021) along with associated hysteresis and cross correlation plots (Appendix A of Gullacher et al., 2021). Table 5 summarizes the results. Of the 220 provincial observation wells, 149 had sufficient data to generate plots. Of these 149, only 124 wells could be classified as either recharge-driven (34%) or streamflow-driven (66%). The remaining 26 wells were classified as indeterminant because either (or both) the hysteresis plot or the cross-correlation plot yielded indeterminant results. For most of these indeterminant cases (22 wells), it was the hysteresis plot that could not be interpreted. For nine (9) wells, the hysteresis plot and cross-correlation plot yielded conflicting classification results. For these, local hydrogeological conditions were examined to classify the well. Wells with a nearby hydrometric station that did not have sufficient overlap between the periods of record of the hydrometric data and groundwater level data were not classified due to lack of data. In general, the hysteresis plots for recharge-driven systems tend to be "messier" than those of streamflow-driven systems which are smoother. In some cases, the direction changed (CCW to CW or vice versa) from one year to the next, and in many cases the hysteresis direction was clear for one year and unclear for other years.

Gullacher et al. (2021) discussed the limitations of the classification, noting that the most important limitation of this analysis is the lack of hydrometric stations on streams that intersect the aquifers with the observation wells. In most cases, the nearest hydrometric station was used, but in cases where the nearest hydrometric station was not situated in a stream adjacent to the aquifer in which the observation well is located, an alternative hydrometric station at a greater distance from the well was used in the analysis. Oftentimes, an ideal hydrometric station was nearby, but it was no longer active, or the period of record did not overlap with the groundwater level data. As a result of this data limitation, some of the classification results may not be correct.

There are various potential uses of the classification results (see Section 5.5 in Gullacher et al., 2021). In this research, the classification results are used to better understand the drought response of aquifers, as described in this report.

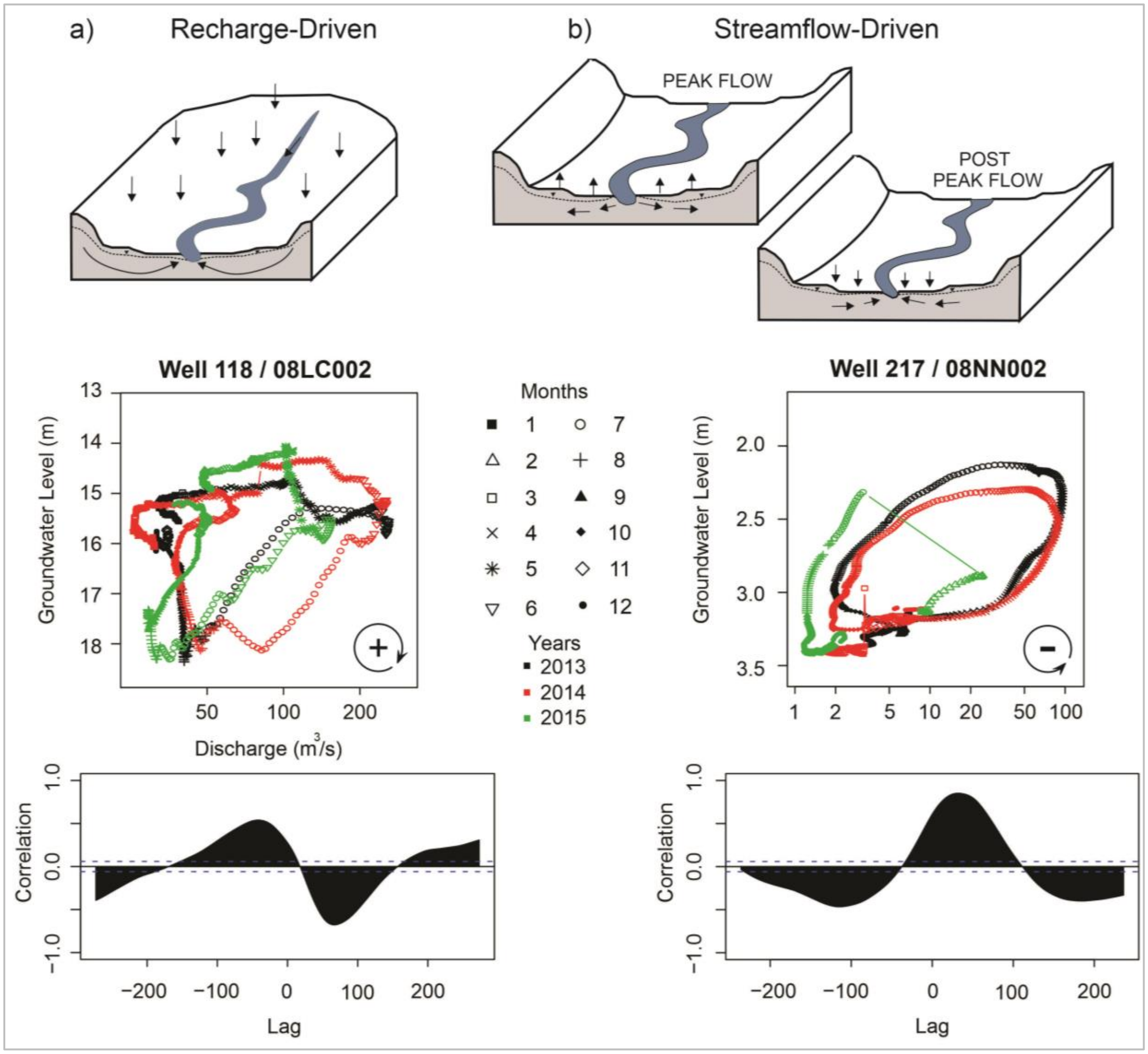


Figure 1: Schematic diagram showing the two end-members of aquifer-stream systems: a) recharge-driven systems and b) streamflow-driven systems. Below each schematic are example hysteresis and cross correlation plots used to characterize the response mechanisms. In recharge-driven systems, changes in streamflow lag behind changes in groundwater level creating a positive or clockwise hysteresis loop. In streamflow-driven systems, the water flows from the stream to the aquifer during peak flow, and from the aquifer to the stream post peak flow. Therefore, changes in the groundwater level lag behind changes in the streamflow, creating a negative or counter-clockwise hysteresis loop (data from Province of B.C. Observation wells 118 and 217, and Environment and Climate Change Canada hydrometric stations 08LC002 and 08NN002).

Table 5: The number of observation wells per each resource region that were classified as recharge-driven or streamflow-driven. Aquifer type is defined in Wei et al. (2009).

Resources Area	Aquifer Type	Recharge-driven	Streamflow-driven
North Natural Resource Area	1a	1	0
	1b	0	1
	4b	3	1
	5a	2	2
	6b	1	0
	unmapped	0	1
	Total	***7 (58%)***	***5 (42%)***
West Coast Region	1b	4	1
	1c	1	0
	4b	6	16
	5a	1	7
	6b	0	6
	unmapped	0	2
	Total	***12 (27%)***	***32 (73%)***
South Natural Resource Area	1a	2	2
	1b	1	3
	1c	1	3
	2	0	1
	3	0	2
	4a	3	4
	4b	10	4
	6b	0	2
	bedrock	2	1
	unmapped	0	1
	Total	***19 (45%)***	***23 (55%)***
South Coast Region	1a	0	2
	1b	1	0
	3	1	0
	4a	0	10
	4b	1	7
	4c	0	2
	5a	0	1
	6b	1	0
	Total	***4 (15%)***	***22 (85%)***
	Grand Total	**42 (34%)**	**82 (66%)**

1a – Unconfined fluvial or glaciofluvial aquifers along major higher order rivers
1b – Unconfined fluvial or glaciofluvial aquifers along moderate order rivers
1c – Unconfined fluvial or glaciofluvial aquifers along lower order streams where lateral extent is limited
2 – Unconfined deltaic aquifers
3 – Unconfined alluvial fan or colluvial aquifers
4a – Unconfined glaciofluvial outwash or ice contact aquifers
4b – Confined aquifers of glacial or pre-glacial origin
4c – Confined aquifers associated with glaciomarine environments
5a – Fractured sedimentary bedrock aquifers
6b – Crystalline granitic, metamorphic, metasedimentary, meta-volcanic, and volcanic rock aquifers

3. SCOPE OF THIS REPORT AND STUDY REGIONS

This report focuses on Objectives 2 and 3 as described in the Introduction:

Objective 2) Developing early season (Section 4) and drought season (Section 5) core indictors of groundwater drought that can be used for drought-related decision-making in B.C.; and

Objective 3) Developing an approach for mapping the drought susceptibility of aquifers and demonstrating this approach in the Okanagan Basin.

Each objective was met in a specific region of B.C.

Objective 2 focused on three different study areas in the province: 1) South Central B.C., primarily in the Okanagan Basin, 2) the Fraser Valley, and 3) the Gulf Islands (Figure 2). These areas were chosen to represent three different geologic and hydroclimatic regions: unconsolidated aquifers in a snowmelt-dominated region (South Central B.C.), unconsolidated aquifers in a rainfall-dominated region (Fraser Valley), and consolidated/bedrock aquifers in a rainfall-dominated region (Gulf Islands).

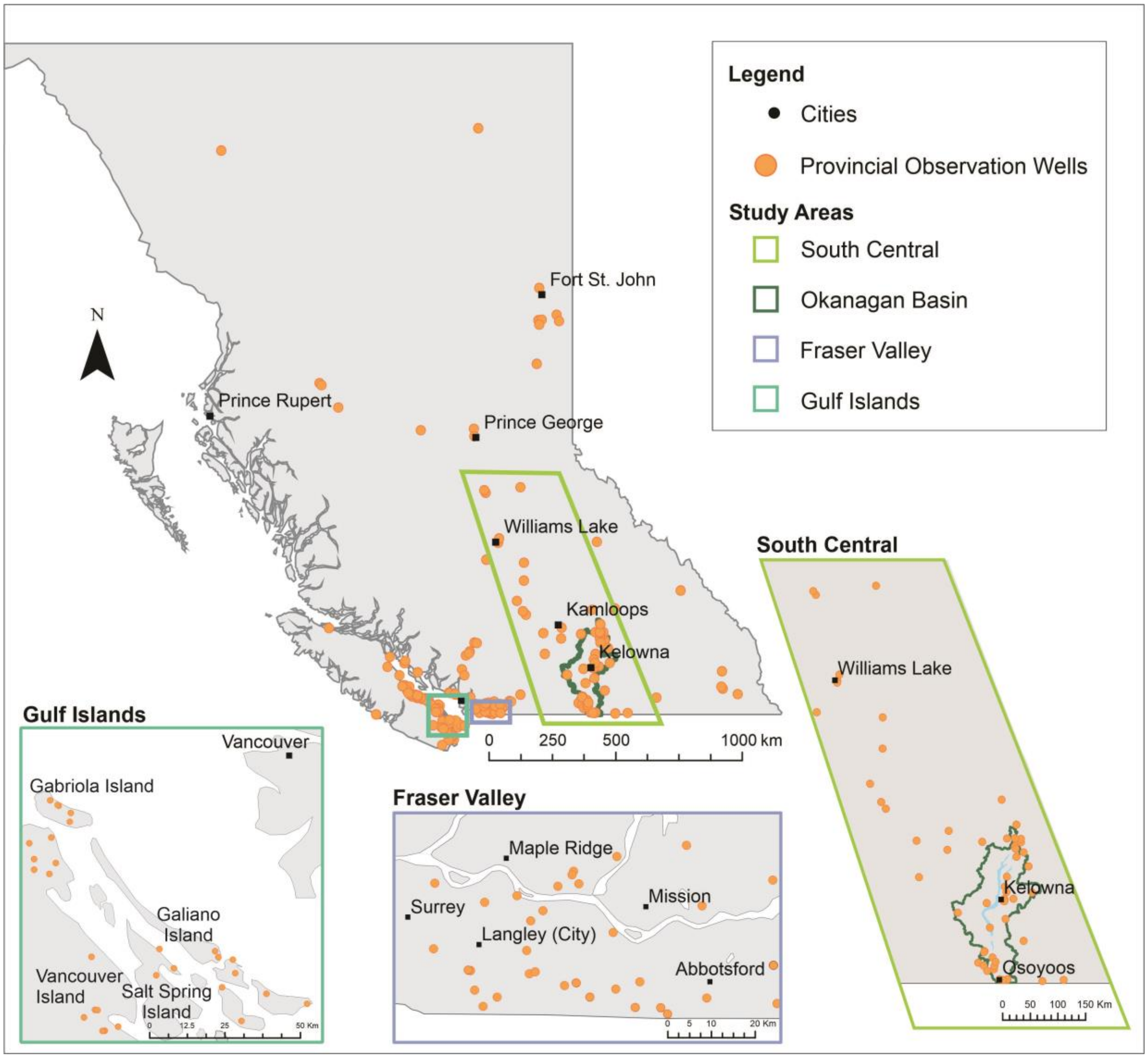


Figure 2: Map of British Columbia showing the three study areas and the Okanagan Basin itself. The locations of wells in the provincial observation well network are shown in orange.

For Objective 3, the Okanagan Basin is selected as a case study area (Figure 2). The Okanagan Basin is located in the rain shadow of the Coast Mountains causing the basin to receive little precipitation (Okanagan Water Stewardship Council, 2008). Furthermore, a large portion (80%) of water in the Okanagan Basin is lost due to evapotranspiration and evaporation from lakes (Figure 1 in Summit Environmental Consultants, 2010). Streams in the Okanagan are primarily snowmelt-dominated, meaning that the streamflow is highest (freshet) in the spring or early summer due to the melting snow and icepack at higher elevation (Okanagan Water Stewardship Council, 2008). During the summer, the Basin experiences a water deficit (evapotranspiration is higher than precipitation). As a result, the Okanagan Basin is a water stressed region that has experienced severe droughts (e.g., in 2015; B.C. River Forecast Centre, 2015). For example, a Level 4 drought was declared in the Okanagan and the surrounding basins in 2015 and in 2021 (B.C. FOR, 2021). Another limiting factor for water management of the Okanagan Basin is that even though there are large deep lakes there is still a lack of water storage options (Okanagan Water Stewardship Council, 2008). Additionally, a large portion (~90%) of streams in the Okanagan have met or are past their license capacity for water withdrawal (Okanagan Water Stewardship Council, 2008). Water demand is at its highest in the summer months when the streamflow tends to be the lowest, causing a summer water shortfall (Okanagan Water Stewardship Council, 2008).

4. EARLY SEASON CORE INDICATORS OF GROUNDWATER DROUGHT

4.1 Overview of the Approach

Groundwater levels from the Provincial Groundwater Observation Well Network (PGOWN) were first examined seasonally (a preliminary analysis) to identify individual climate and hydrological predictor variables (e.g., precipitation amount, snow water equivalent (SWE), minimum and maximum daily temperatures, streamflow) that appear to influence summer groundwater levels. Summer groundwater levels were examined because drought conditions are observed during the summer in B.C.

Due to the complexity of responses revealed through this preliminary analysis, generalized additive models (GAMs) were used to explore associations between predictor variables and summer groundwater levels. Various sensitivity analyses were conducted to explore associations between individual predictor variables and summer groundwater levels, and to explore different options for incorporating the predictor variables into GAMs. The associations with the Niño 3.4 index representing the El Niño Southern Oscillation (ENSO), and the Pacific Decadal Oscillation (PDO) were also explored.

Based on the individual predictor variables that resulted in the most statistically robust GAMs, the predictor variables were combined to create multi-parameter GAMs for each study region. The best GAM was identified for each region. GAMs that used summer predictor variables (e.g., summer maximum daily temperature) or annual conditions (e.g., annual Niño 3.4 index) ultimately were not selected because the goal was to identify predictor variables that could be used prior to the summer season to “predict” if groundwater drought might occur. In addition to identifying predictor variables of groundwater drought, this chapter also explores the use of the standardized groundwater level index (SGI) as a potential drought season indicator of groundwater drought.

This report focuses on the main findings. Details about the methodologies are provided in Gullacher (2022).

4.2 Data Sources and Processing

All groundwater level data were obtained from the PGOWN database. Hourly data were downloaded from October 1, 2005 to September 30, 2020. The year 2005 was chosen as the starting year because this was the year that data loggers were installed to record hourly data. Some wells did not have complete records either because the well became part of the PGOWN at a later start date or due to missing data. Figure 3, Figure 4 and Figure 5 show the locations of the final subset of observation wells in South Central B.C., the Fraser Valley and the Gulf Islands, respectively.

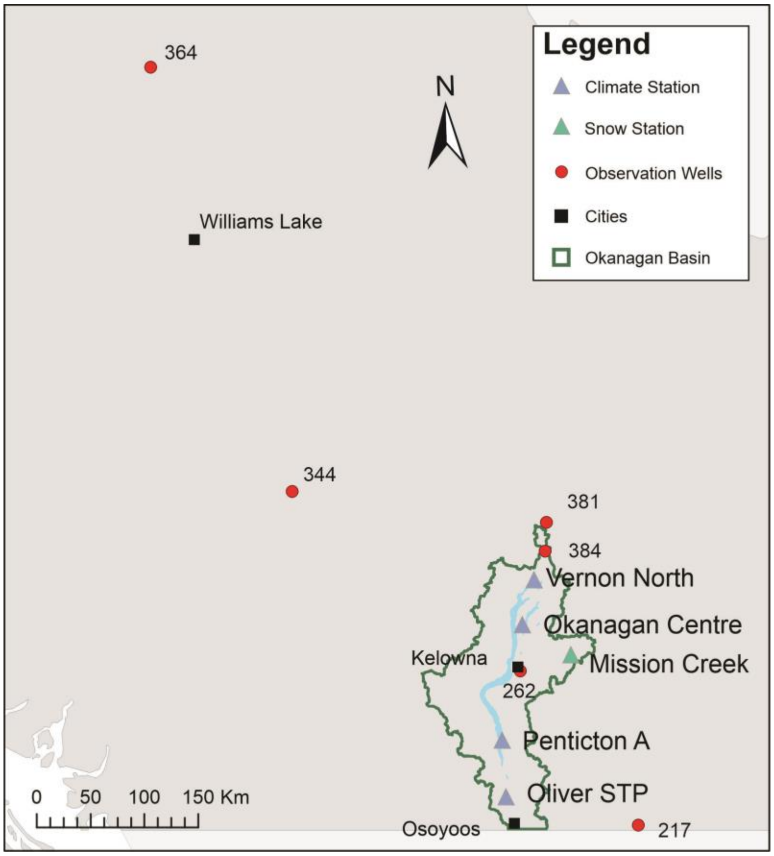


Figure 3: Map showing the locations of the observation wells, climate stations (Vernon North #1128583, Penticton A #1126150, Okanagan Centre #1125700, Oliver STP #1125766), and the Mission Creek snow station (#2F05P) for the South Central B.C. region.

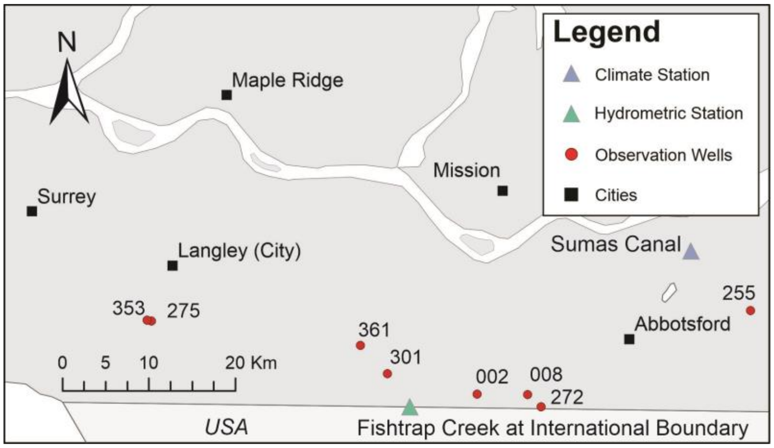


Figure 4: Map showing the locations of the observation wells, the Sumas Canal climate station (#1107785), and the Fishtrap Creek at International Boundary hydrometric station (#08MH153) for the Fraser Valley region.

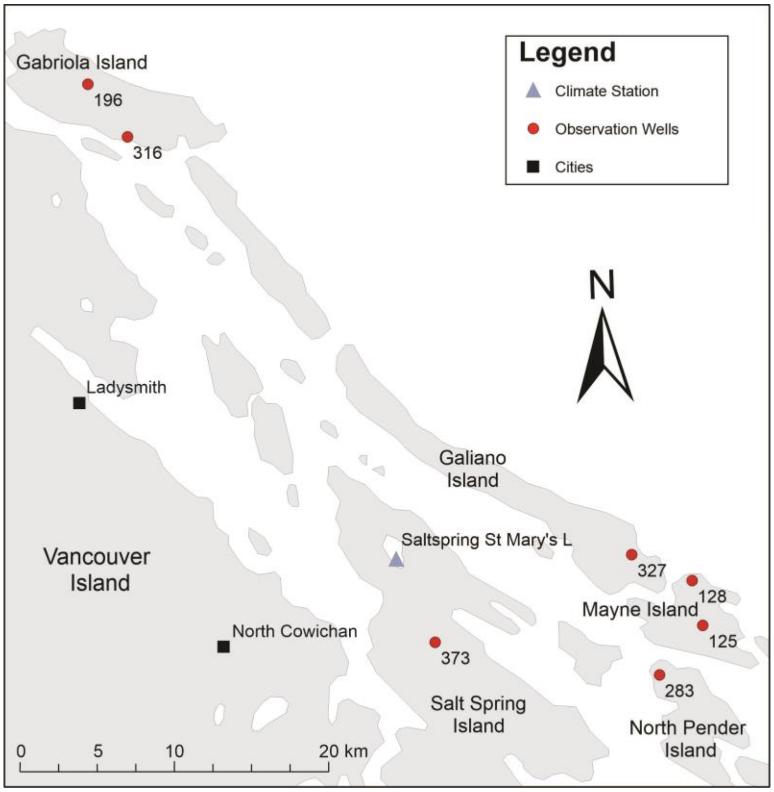


Figure 5: Map showing the locations of the observation wells and the St Mary's L climate station (#1016995) for the Gulf Islands.

The hydrographs for all provincial observation wells were visually examined for any irregularities such as trends in the groundwater level, and inconsistent hydrograph shapes from year to year. These irregular wells were removed from the analysis (Table 6). The period of record for each well was then examined, and the number of missing days in each water year and each summer season (July, August, September – JAS) were computed. Wells that were missing 23 or more days of data (25% of the total number of days) for the summer months were excluded from the analysis. In addition, wells that had missing data from the 2015 drought year were also removed as 2015 was a significant drought year across the province. Some wells did not have complete records either because the well became part of the PGOWN at a later start date or due to missing data. The analysis results for these wells were interpreted with caution. For South Central B.C., six wells were used in the analysis with the period 2008-2016. In the Fraser Valley, eight wells were used with the period 2011-2019.

The observation wells were separated by the response mechanism (recharge driven and streamflow driven) based on Gullacher et al. (2021). Observation wells were then grouped by aquifer type (Wei et al., 2009).

For the South Central B.C. region, climate data were obtained from Environment and Climate Change Canada (ECCC) (Figure 3). Four climate stations were selected: Vernon North (#1128583), Penticton A (#1126150), Okanagan Centre (#1125700), and Oliver STP (#1125766). Snow water equivalent (SWE) data were obtained from the Ministry of Environment and Climate Change Strategy (ENV) Mission Creek snow station (#2F05P). For the Fraser Valley region, climate data were obtained from the ECCC Sumas Canal (#1107785) climate station (Figure 4). B.C. Federal-Provincial Hydrometric Network streamflow data were obtained from ECCC for Fishtrap Creek (#08MH153) hydrometric station. For the Gulf Islands, climate data were obtained from the ECCC Salt Spring St Mary's L (#1016995) climate station (Figure 5).

Table 6: All observation wells available in each region. Wells retained for analysis are in bold type and are shown in Figure 3, Figure 4 and Figure 5.

South Central B.C.		Fraser Valley		Gulf Islands	
OW045	OW332	**OW002**	OW452	OW058	OW320
OW047	**OW344**	**OW008**	OW453	OW060	**OW327**
OW074	OW356	**OW255**	OW456	OW065	OW337
OW075	OW362	**OW272**	OW457	OW071	OW338
OW096	OW363	**OW275**	OW458	**OW125**	OW343
OW117	**OW364**	OW299	OW459	**OW128**	OW345
OW118	OW375	**OW301**	OW461	**OW196**	OW355
OW122	OW376	**OW353**	OW490	OW197	OW371
OW154	**OW381**	OW354		OW204	OW372
OW172	**OW384**	OW357		OW211	**OW373**
OW185	OW400	OW359		OW233	
OW203	OW405	OW360		OW240	
OW217	OW407	**OW361**		OW258	
OW236	OW409	OW406		OW265	
OW260	OW410	OW414		OW281	
OW262	OW412	OW415		**OW283**	
OW294	OW422	OW440		OW284	
OW296	OW442	OW441		OW290	
OW302	OW444	OW446		OW312	
OW306	OW468	OW447		**OW316**	
OW309		OW450		OW319	

The Niño 3.4 index data were obtained from the Global Climate Observing System Working Group on Surface Pressure (GCOS-WGSP, 2021). The Pacific Decadal Oscillation index data were obtained from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO, 2021).

The climate and groundwater level data were standardized using the 2005 to 2020 data period using the ‘scale’ R base function (R Core Team, 2020). The scale function subtracts the mean seasonal value from each yearly seasonal average and divides by the standard deviation for the same period. Standardization was done to enable comparison of groundwater level anomalies among the wells. Water years (WY) were used instead of calendar years; a WY extends from October 1st of the previous year to September 30th of the following year (e.g., the 2015 water year starts October 1st 2014 and ends September 30th, 2015). The data were divided quarterly into seasons by WY: fall (October, November and December), winter (January, February and March), spring (April, May and June), and summer (July, August and September). The seasons were divided such that they fall within a single WY. An R script by was used to calculate the water year (Rong, 2015).

4.3 Preliminary Analysis

A preliminary analysis involved plotting the annual and seasonal groundwater level data alongside plots of various climate variables (seasonal temperatures, seasonal precipitation, and SWE) and visually comparing records between drought and non-drought years with the goal of identifying which climate variables the summer groundwater levels seemed most sensitive to. The R packages seas (Toews et al., 2007), dplyr (Wickham et al., 2022), lubridate (Grolemun and Wickham 2011), openair (Carslaw and Ropkins, 2012), and ggplot2 (Wickham, 2016) were used for data manipulation and visualization.

The preliminary analysis identified SWE and temperature as the dominant controls on summer groundwater levels. However, each aquifer type and response mechanism (streamflow driven and recharge driven) seemed to be related to these variables differently. Therefore, a statistical approach, using generalized additive models (GAMs), was used to determine the associations between potential predictor variables and the summer groundwater level.

4.4 Generalized Additive Models (GAMs)

Generalized additive models (GAMs) are statistical models that use sums of smoothed functions of covariates (or predictor variables) to infer associations with a univariate response variable (Hastie and Tibshirani, 1986). The non-linear "smooth" functions (e.g., splines) are able to model and capture the non-linearities in the data. The response variable in this study is summer groundwater level. The predictor variables included, for each season, the maximum and minimum daily temperatures, precipitation, SWE, streamflow, and the Niño 3.4 index.

The 'gam' function from the mgcv R Package was used to create the GAMs (Wood, 2011; 2017). The 'summary.gam' function from the mgcv package was used to obtain the p values (significance) for each predictor variable and the r^2 value (explained variance) for the GAMs. The Akaike Information Criterion (AIC) value, an estimate of the model's predictive accuracy, was also used to compare the different models. The AIC takes into account the sample size as well as the number of model parameters (Wagenmakers et al., 2004). A low AIC indicates the more accurate model with the fewest parameters. The gratia R Package (Simpson, 2022) was used to visualize the effects of each of the smoothed predictor variables on the summer groundwater levels.

The GAM analysis proceeded in two main steps:

1) Comparing the effects of individual climate and hydrological variable on summer groundwater levels (Single Predictor Variable GAMs; Section 4.4.1); and
2) Based on the individual predictor variables that resulted in the most statistically robust GAMs, combining the predictor variables to create multi-parameter GAMs for each study region (Multiple Predictor Variable GAMs, Section 4.4.2).

Several sensitivity analyses were also done to: 1) test if downscaled historical gridded climate data are sufficient for the analysis in the absence of climate station data; 2) explore the effect of climate teleconnections such as Niño 3.4 index and Pacific Decadal Oscillation (PDO); and 3) the effect of different time period lengths to see if the data period length has a significant effect. The results of the sensitivity analysis are described in detail in Gullacher (2022).

For each analysis, each well was analyzed separately. A graph showing the response (observed summer groundwater levels) versus the fitted (modeled) summer groundwater levels was generated. Figure 6 shows an example of the results of a GAM that included the maximum spring temperature as the predictor variable for well 262. The AIC and r^2 value were recorded, as well as the p values of the smoothed predictor terms for each parameter.

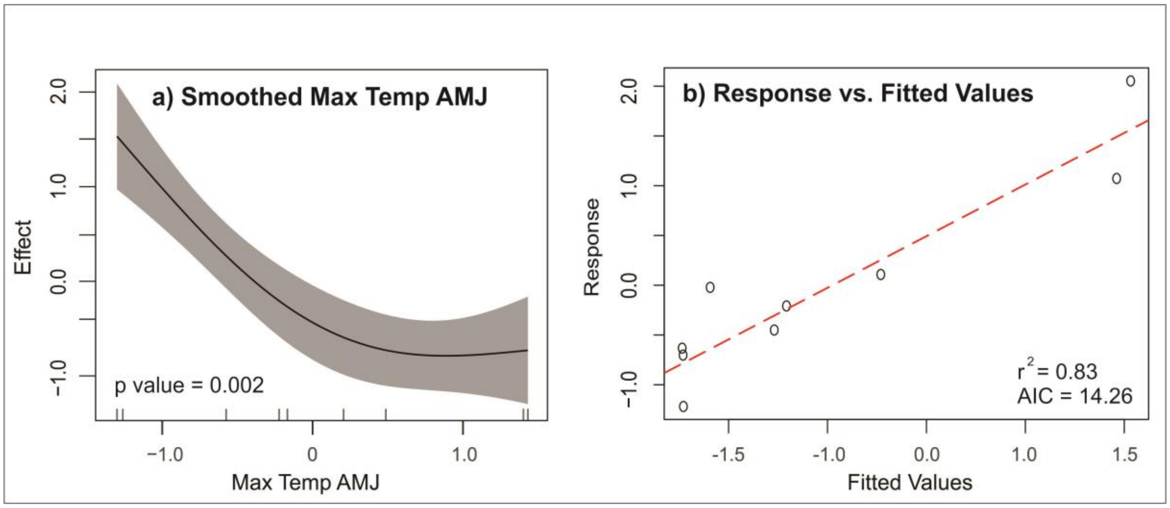


Figure 6: The results of a generalized additive model (GAM) using the maximum spring (April, May, June; AMJ) temperature as the only predictor for the summer groundwater level response of Provincial Observation Well 364. A) The effects of the smooth function for maximum spring temperature, and the significance value (p value). B) The response (observed summer groundwater levels) vs the fitted (modeled) results. The dashed red line shows a 1:1 ratio and would indicate a perfect model.

4.4.1 Single Predictor Variable GAMs

Single predictor GAMs were created for each groundwater well in each study region (Table 7). Different variables were used to account for the different hydroclimatic regimes. For the snow-dominated South Central B.C. region SWE was included for both the current and previous year. SWE was not used in the rainfall-dominated Fraser Valley and Gulf Islands. Additionally, streamflow data were included in the GAMs for South Central B.C. and Fraser Valley; however, several of the wells in South Central B.C. did not have a nearby hydrometric station and so GAMs could be generated for these wells. Streamflow was also excluded in the Gulf Islands region due to the lack of hydrometric stations.

The p values were for each predictor variable, and the AIC and r^2 values for each GAM can be found in Appendix A.1. These statistics were examined to identify which parameters resulted in the “best” GAMs, particularly identifying GAMs with low p values (< 0.1) for the individual predictor variables and r^2 values > 0.5 for the models. The AIC values were generally similar among models. Even though a number of parameters had sufficiently low p values, the summer and yearly variables were eliminated because the data would not yet be available (in spring, for example) to predict summer groundwater levels, as summer would not yet have occurred.

For South Central B.C., maximum spring temperature, maximum SWE, spring streamflow and winter Niño 3.4 resulted in the best single predictor variable GAMs based on the statistics (red dots in Table 7). In the Fraser Valley, maximum spring temperature, winter precipitation, and spring streamflow resulted in the best single predictor GAMs, while in the Gulf Islands, the maximum spring temperature and precipitation resulted in the best GAMs.

Table 7: The predictor variables used in GAMs for each study region. The black filled in circles indicate the predictor climate variables that had p values < 0.1 and r2 values > 0.5. The red filled in circles indicate climate variables that were used in combination for the best fitted GAM for each region.

	South Central B.C.	Fraser Valley	Gulf Islands
Max Temp JFM	○	●	○
Max Temp AMJ	🔴	🔴	●
Max Temp JAS	○	○	○
Min Temp JFM	○	○	○
Min Temp AMJ	○	○	○
Min Temp JAS	●	○	○
Precip JFM	○	🔴	○
Precip AMJ	○	○	●
Precip JAS	○	○	○
Max SWE	🔴		
Max SWE Prev Year	○		
Streamflow JFM	○	○	
Streamflow AMJ	🔴	🔴	
Streamflow JAS	○	○	
Nino 3.4	○	○	○
Nino 3.4 JFM	🔴	●	○
Total number	16	14	11

4.4.2 Multiple Predictor Variable GAMs

The combined influences of climate and hydrological variables on the summer groundwater levels in each region were tested using multi-parameter GAMs. Different combinations of the individual predictor variables identified in the single predictor variable GAMs were tested.

For South Central B.C., summer groundwater levels for six provincial observation wells (217, 364, 381, 262, 344, 384) were used as the response variable for seven different GAMs in South Central B.C. (Table A3). The climate data were obtained from the Okanagan Center climate station (ECCC station #1125700). As this region is snowmelt-dominated, the SWE from the Mission Creek headwaters (ENV station #2F05P) was included in the predictor variables. Three different aquifer types are represented: 1b (n=2), 4a (n=1), and 4b (n=3).

For the Fraser Valley, groundwater level data from eight provincial observation wells (002, 008, 272, 275, 301, 353, 361, 255) were used as the response variable for six different GAMs (Table A5). For this region, streamflow data from the Fishtrap Creek hydrometric station at the international border (ECCC station #08MH153) and the SWE from the Chilliwack River headwaters (ENV station #1D17P) were added to the predictor variables. Three different aquifer types are represented: 4a (n=6), 4c (n=1), and 6b (n=1) all of which were classified as streamflow driven.

For the Gulf Islands, groundwater level data from seven provincial observation wells (327, 196, 125, 128, 283, 316, 373) were used as the response variable for seven different GAMs (Table A7). The climate data were obtained from the Saltspring St Mary's L climate station (ECCC #1016995). Two different aquifer types are represented: 4b (n=1) and 5a (n=6). Of these wells, only two (316 and 373) were classified as streamflow driven, while the others could not be classified.

Appendix A.2 (Table A4, Table A6 and Table A8) show the statistical results of the different combinations tested in each GAM. Gullacher (2022) describes these results in detail. Section 4.4.3 following below summarizes the results.

4.4.3 *Final Early Season Predictor Variables for Groundwater Drought*

Generally, GAM 2, which includes the maximum spring and summer temperatures, had the highest r^2 values in the South Central region. However, GAM 2 includes summer maximum temperature, a variable that would not be available until the end of the summer. Therefore, GAM 6 was selected for South Central B.C., which included maximum SWE, maximum spring temperature, and winter Niño 3.4, all of which are available in the spring (Table 8). GAM 6 is broadly applicable across all the aquifer types represented in the analysis and both response mechanisms (Table A4). Due to the limited number of wells in South Central B.C. with a nearby hydrometric station, streamflow was only included in GAM 7. GAM 7 resulted in the highest r^2 values for wells classified as streamflow-driven but performed poorly for wells classified as recharge-driven (Table A4). These results suggest that if streamflow data are available, streamflow should be included as a predictor of summer groundwater levels for streamflow-driven wells.

The best fitting GAM for the Fraser Valley region was GAM 5, which included maximum spring temperature, winter precipitation, and spring streamflow data. This GAM had the highest r^2 values – all were greater than 0.75 (Table A6).

No best fitting GAM was identified for the Gulf Islands (Table A8).

Table 8: Early season predictor variables from the best fitting GAMs for the South Central B.C. and Fraser Valley regions.

South Central B.C.	Fraser Valley
GAM 6:	GAM 5:
Max Temp – AMJ	Max Temp – AMJ
Max SWE	Precip – JFM
ENSO 3.4 – JFM	Streamflow – AMJ

4.4.4 *Validating the GAM Results*

To validate the results of the GAMs, a retrospective analysis was undertaken. The climate variables were standardized in R using the scale function, using data spanning 2005 and 2020 from 31 wells for the South Central B.C. In the Fraser Valley, precipitation data were missing for 2008-2011 and temperature data were missing from 2007-2010, so data spanning 2011-2020 from 13 wells were used in the analysis. The 5th, 10th, and 15th percentiles of the average summer groundwater levels for each well were calculated.

In South Central B.C., years with a combination of above average maximum spring temperature, below average maximum SWE, and a positive Niño 3.4 index corresponded with a larger number of wells with average summer groundwater levels lower than the 15th percentile (Figure 7). For example, in the summer of 2015 in South Central BC, the maximum spring temperature was the highest recorded over the entire 2005-2020 study period. Additionally, the maximum SWE was the lowest in 2015. Over half (15 of 29) of the wells with available data had summer groundwater levels lower than the 15th percentile, with eight wells having levels lower than the 5th percentile. In 2012, a low maximum spring temperature, higher maximum SWE, and a negative Niño 3.4 index corresponded with only two wells (OWW 122 and 405) with water levels lower than the 15th percentiles.

In the Fraser Valley, years with a combination of above average maximum spring temperature, below average winter precipitation, and below average streamflow corresponded with a larger number of wells with water levels lower than the 15th percentile (Figure 8). For example, the maximum spring temperature was highest in 2015 and 2018. In 2019, the winter precipitation was the lowest for the time period examined and nine wells had water levels lower than the 15th percentiles. Spring streamflow was the lowest in 2015 and 2016. Over half (7 of 12) of the wells with available data were lower than the 15th percentile of the summer groundwater levels in 2015, 2016, and 2019.

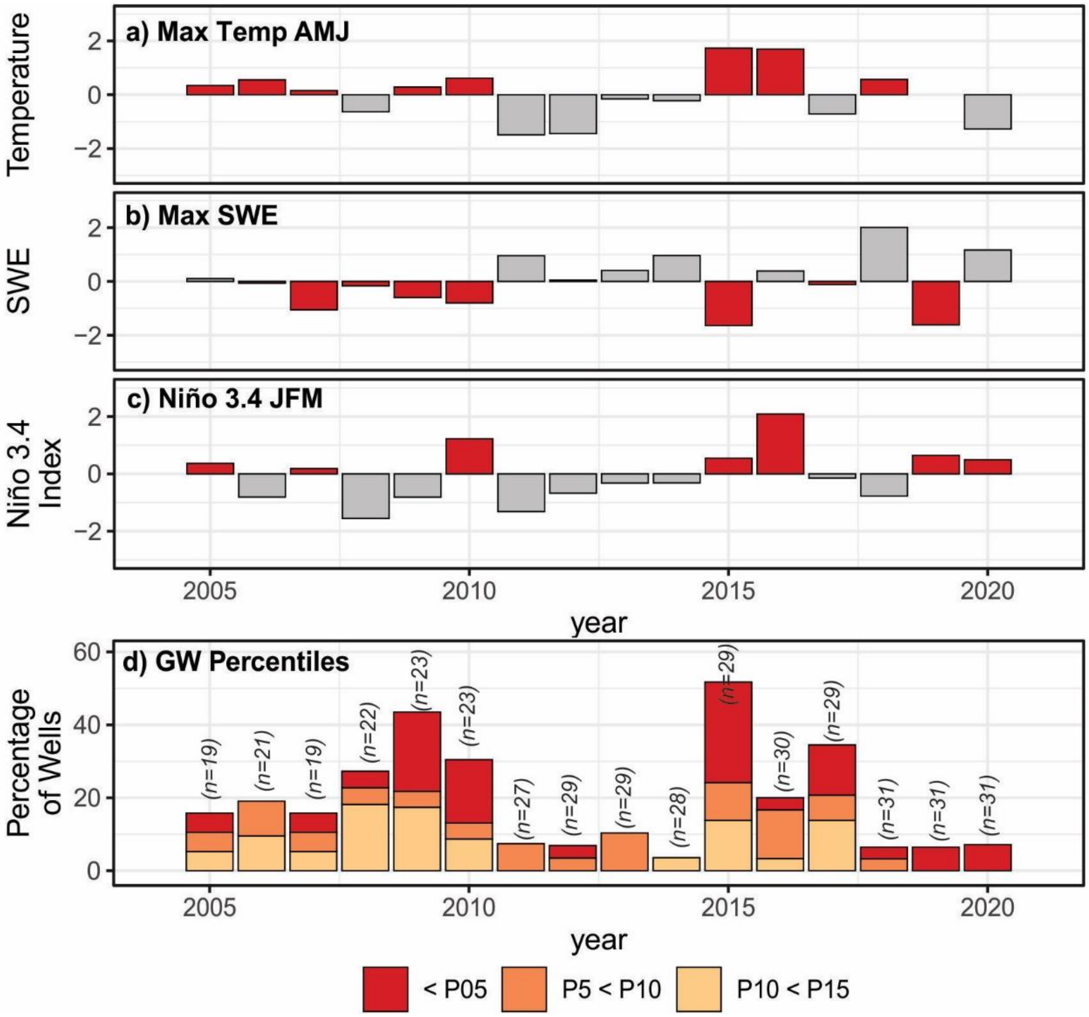


Figure 7: The top three graphs show the selected standardized climate predictor variables for the South Central B.C. region. Red shading reflects above average (in plots a and d) or below average (in plot b) standardized values. The percentage of wells with available data within each summer groundwater level percentile category per year is shown in the bottom graph. The number of wells with available data for each year is labelled in italics.

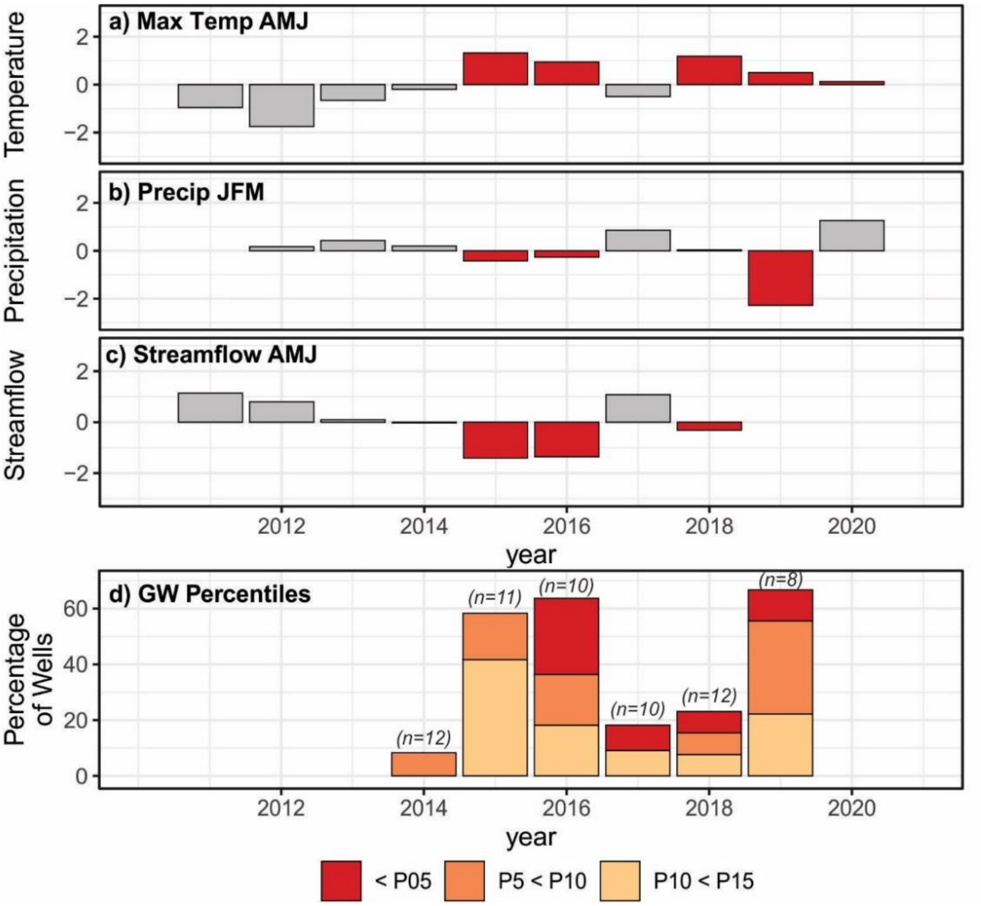


Figure 8: The top three graphs show the selected standardized climate predictor variables for the Fraser Valley region. Red shading reflects above average (in plots a and d) or below average (in plot b) standardized values. The percentage of wells with available data within each summer groundwater level percentile category per year is shown in the bottom graph. The number of wells with available data for each year is labelled in italics.

4.5 Recommended Groundwater Drought Indicator Wells

Based on the findings the analyses conducted in this study, several provincial observation wells were identified as potential groundwater drought indicator wells (Table 9). These wells all had high r^2 values for the GAM when only using climate and hydrological variables from the winter and spring previous the summer groundwater levels. As such, these wells could be used to track groundwater levels starting in late spring if the associated standardized winter and spring predictor variables for the region point to potential drought conditions during the summer (see Figure 7 and Figure 8). Other wells were not as sensitive to the climate and hydrological predictor variables. This may be due to interferences, such as water use and land usage, that resulted in ill-fitting GAMs. The exclusion of wells that did not have robust GAMs does not imply that groundwater drought does not occur in these aquifers, but rather that the summer groundwater levels are not easily associated with the climate and hydrological predictor variables. The climate and hydrological variables may be used by the B.C. Drought Response Team and water managers to anticipate groundwater droughts based on readily available climate and hydrological data prior to the beginning of the drier summer months.

Table 9: Recommended groundwater drought indicator wells in the South Central B.C. and Fraser Valley regions. Aquifer types are listed in Table 5.

South Central B.C.			**Fraser Valley**		
Predictor Variables	**Well #**	**Aquifer Type**	**Predictor Variables**	**Well #**	**Aquifer Type**
Max Temp – AMJ **Max SWE** **ENSO 3.4 – JFM**	217	1b	**Max Temp – AMJ** **Precip – JFM** **Streamflow – AMJ**	002	4a
	364	1b		008	4a
	381	4a		272	4a
	344	4b		275	4a
	384	4b		301	4a
				353	4a

5. DROUGHT SEASON CORE INDICATOR

5.1 Standardized Groundwater Level Index (SGI)

Various indicators of groundwater drought have been proposed in the literature. These indicators are retrospective, in the sense that observed groundwater levels are used to calculate the index. One example is the Standardized Groundwater Level Index (SGI), which has been used to explore the effects on precipitation on groundwater levels in China and Poland (Liu et al., 2016; Kubicz and Bąk, 2019).

The SGI uses a non-parametric normal score transform for each calendar month of average groundwater level (Bloomfield and Marchant, 2013). The monthly SGI for each well was calculated in R. Groundwater levels from 2005-2020 for the South Central B.C. region, 2011-2020 for the Fraser Valley, and 2007-2020 for the Gulf Islands were used in the analysis and months with more than 7 days of missing groundwater levels were excluded. The SGI values were plotted for each well and grouped by aquifer type, with the aquifer-stream system response mechanism noted. Additionally, the aquifer well density (low, moderate, high) as reported on the B.C. Aquifer Fact Sheets is noted to account for anthropogenic factors on the groundwater levels.

Figure 9 shows an example plot of the SGI values for the aquifer type 1a (unconfined glaciofluvial aquifers along major rivers) wells from the South Central B.C. region. Most of the wells fluctuate between periods of drought as defined by Bloomfield and Marchant (2013) as SGI < 0 (shown in black) and non-drought with SGI > 0 (shown in grey). Bloomfield and Marchant (2013) simply classify drought vs non-drought according to the sign of the SGI. The “intensity” of drought can be inferred by how negative the SGI index is. Appendix B includes plots for all aquifer types. General findings for the South Central B.C., the Fraser Valley and the Gulf Islands study regions are provided below.

South Central B.C.

In South Central B.C., the SGI was compared between a drought (2015) and non-drought (2020) year. In 2015, 23 of the 30 wells had at least one negative SGI value in the summer months of July, August, and September (JAS). During summer 2020, 19 of the wells had positive SGI values for each month, indicating a non-drought year, with only three wells having an SGI values less than -1.

Considering aquifer type, the 4b aquifers had the lowest SGI values for 2015, with half of the wells having an SGI value of less than -2. The type 1b aquifers had high overall SGI values in summer of 2015, with the lowest being -0.6, occurring September of 2015 in well 302. Well 381 (type 4b) had positive SGI values for both the drought (2015) and non-drought (2020) years. Well 262 had the lowest summer 2015 SGI (-2.75), although the well density in this aquifer is low, there are high-capacity wells that could be modifying the drought level in this well. Additionally, wells 344 and 422 have a high aquifer well density, and low SGI values (< -1).

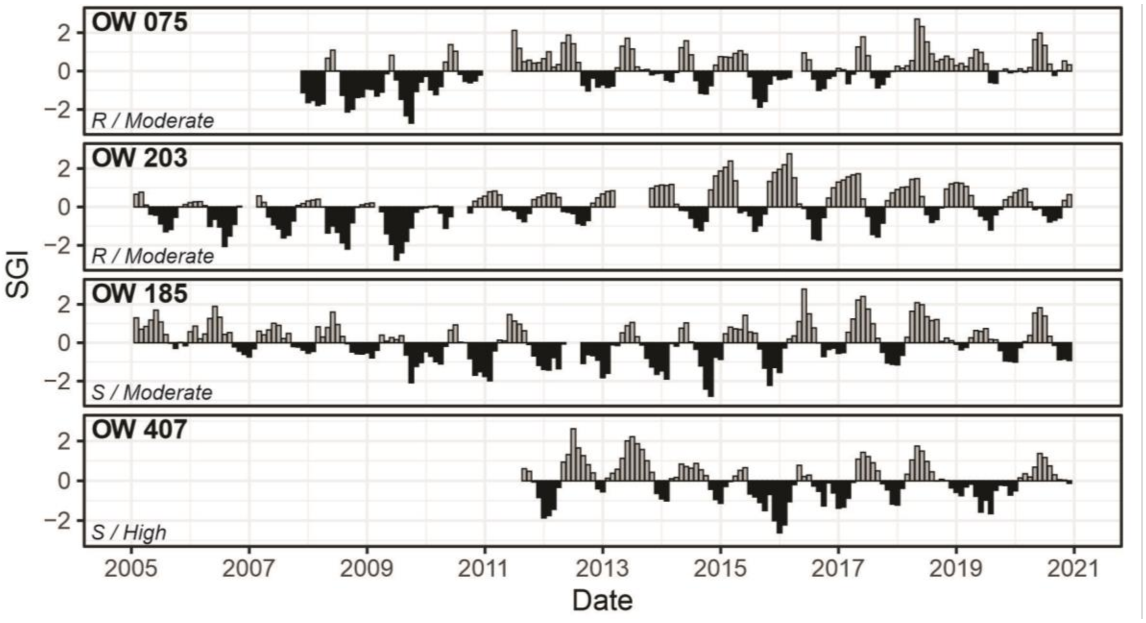


Figure 9: The SGI values for aquifer type 1a from the South Central B.C. region. The response mechanism for each well is labelled in italics (R for recharge driven and S for streamflow driven) as well as the reported well density of the aquifer (Low, Moderate, High).

Fraser Valley

In the Fraser Valley, the SGI was compared between a drought year (2015) and a non-drought year (2011). In the summer of 2015, all the 12 wells in the Fraser Valley had negative SGI values indicating a drought year. In the summer of 2011, the non-drought year, all but two wells had negative SGI values for all three summer months. However, the SGI values were less negative than in the drought year. SGI values ranged from -0.7 to 1.2. The lowest SGI (-1.1) was for well 301. All of the wells, with the exception of wells 375 and 359, are located in aquifers with a high well density.

Gulf Islands

In the Gulfs Islands, the SGI was compared between a drought of level 4 (2015) and a drought of level 2 (2019). In the summer of 2015, 6 of the 8 wells, had SGI values less than -1.0, with four wells having SGI values less than -2.0. The SGI values for the summer of 2019 were greater than the 2015 summer values in all wells except for wells 058 and 327. The lower drought level year (2019) had SGI values ranging from -2.0 to 0.04, while the level 4 drought year (2015) had SGI values ranging from -2.7 to 0.35. The lowest SGI (-2.7) was for well 125 located on Mayne Island.

5.2 Applicability of SGI as a Core Drought Season Indicator of Groundwater Drought

The SGI was able to highlight which wells in each region had experienced periods of drought. The SGI showed that 2015 was a period of groundwater drought in both the South Central and Fraser Valley regions. Well 262, which is located in Aquifer 464, had many months with negative SGI values from 2011 to 2019 (Figure B6). Notably, this aquifer has many high-capacity wells (Aquifer Mapping Report), and a negative trend in groundwater level (-0.13 m/year). As such, the SGI may not be the best used for wells completed in aquifers that have a high well density or high-capacity wells or with negative trends in groundwater level if only climate-related drought is of interest.

Overall, the SGI appears to be a good indicator to retroactively check how the groundwater levels responded to periods of drought and to non-drought years.

6. AQUIFER SUSCEPTIBILITY TO DROUGHT

6.1 Approach

Aquifer susceptibility to drought was only examined for the Okanagan Basin. An aquifer drought susceptibility matrix was created using published hydraulic diffusivity values for different aquifer types, as well as the well density of each aquifer. The Standardized Groundwater Level Index (SGI) values of the observation wells were used to supplement the aquifer susceptibility to drought classification. Ultimately, each aquifer in the Okanagan Basin was mapped according to its susceptibility to drought. The mapping results are compared qualitatively to a map generated during a workshop held in the Okanagan in October 2019. The workshop participants identified aquifers or streams in the Okanagan that have had past or ongoing water problems.

6.1.1 Hydraulic Diffusivity

Hydraulic diffusivity influences how fast groundwater stresses, such as drought, propagate through an aquifer; the higher the hydraulic diffusivity, the more rapidly hydraulic stresses propagate through the aquifer (Barlow and Leake, 2012). Hydraulic diffusivity is calculated as the ratio of transmissivity (T) to storativity (S) or equivalently, hydraulic conductivity (K) to specific storage (Ss).

Hydraulic diffusivity values were compiled from Kuang et al. (2020) and Rathfelder (2016). Rathfelder (2016) had compiled T and S values for different aquifer types in B.C.; therefore, these values were used directly. Kuang et al. (2020) compiled K and Ss values for different aquifer media internationally. Therefore, these were associated with the aquifer types in B.C. based on whether the values were from: 1) unconfined unconsolidated aquifers, 2) confined unconsolidated aquifers, or 3) bedrock. The aquifer types were grouped into three categories based on the compiled hydraulic diffusivities and then ranked: low, moderate, high (Table 10). Appendix C reports the original T, S, K and Ss values from Rathfelder (2016) and Kuang et al. (2020) for each aquifer type.

Table 10: Compiled hydraulic diffusivity values from Rathfelder (2016) and Kuang et al. (2020) for each aquifer type. Table 5 identifies aquifer types.

Diffusivity Rank	**Aquifer Type**	**Rathfelder 2016 T/S (m^2/day)**	**Kuang et al. 2020 K/Ss (m^2/day)**
High	**4b**	7.75E+05	6.5E+05
Moderate	**1a**	2.25E+04	2.6E+05
	1b	1.29E+04	2.6E+05
	1c	na	2.6E+05
	2	1.43E+04	2.6E+05
	3	2.10E+04	2.6E+05
	4a	1.63E+04	2.6E+05
Low	**5a**	2.50E+02	na
	6a	4.70E+01	7.7E+03
	6b	4.70E+01	2.9E+04

The well density of each aquifer in the Okanagan Basin was also examined to take anthropogenic drought into consideration in the drought susceptibility matrix. The well densities were obtained for each aquifer from the aquifer mapping reports. Where the well density was not reported, it was calculated using the number of wells correlated to the aquifer divided by the aquifer area (km^2) as reported in GWELLS. The well densities were then classified and assigned a density rank (Table 11).

Table 11: Classified well density and rank.

Well Density (wells/km²)	Density Rank
> 4	low
4 < 20	moderate
> 20	high

The SGI values were grouped by aquifer type and histograms were made of the summer (July, August, September) SGI values. Examples of histograms for each group are shown in Figure 10; all other graphs can be found in Appendix D. The SGI histograms for each aquifer type were then classified: low, moderate, and high (Table 12).

Table 12: Classified Standardized Groundwater Level Index (SGI) values and rank.

SGI Values	SGI Rank
<-1	high
-1 < 1	moderate
>1	low

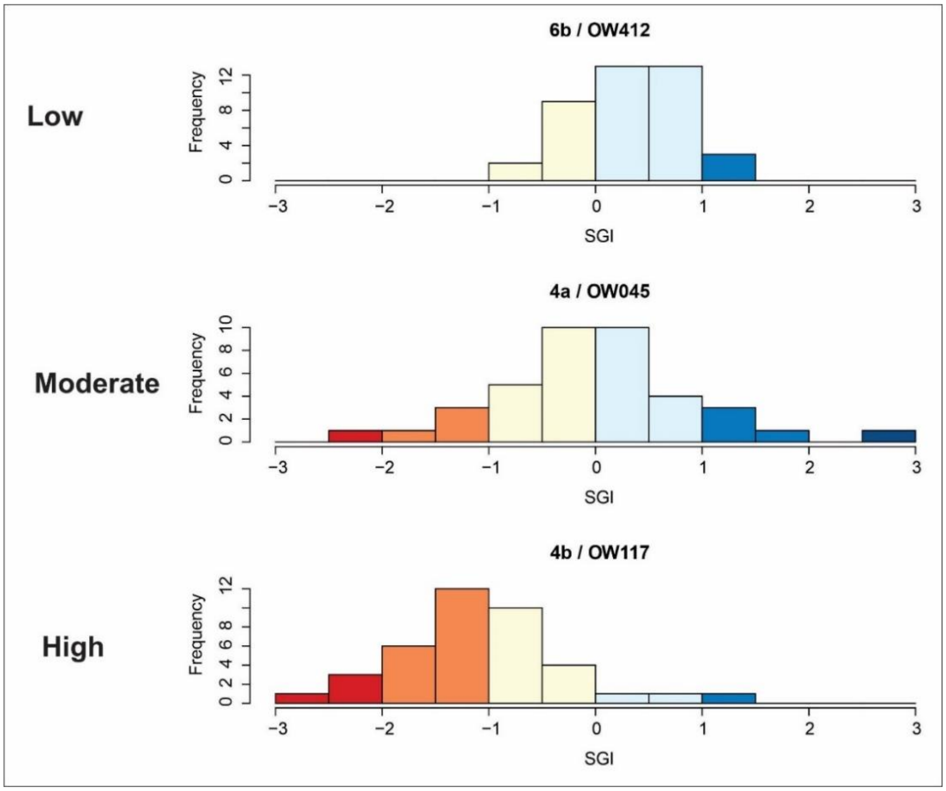


Figure 10: Histograms of summer (July, August, and September) SGI values for three observation wells in different aquifer types showing the three different classes based on the SGI values.

An aquifer drought susceptibility matrix was created using hydraulic diffusivity and well density (Table 13). Values were assigned to each rank for each variable. The rank values for diffusivity are numerically higher than the values for well density to give a higher weight to the diffusivity, which is considered to more strongly influence rate of drought propagation. These rank values are then multiplied together to determine the susceptibility of the aquifer to drought. For example, Aquifer #257, which is a 4b aquifer, has a high diffusivity rank (4) and a moderate well density (2) giving an aquifer susceptibility value of 8 indicating that it is moderately susceptible to groundwater drought. The susceptibility of the aquifers to drought were then mapped in ArcMap.

Table 13: Groundwater drought susceptibility matrix showing the values corresponding to the rank of each variable. The diffusivity and well density ratings are multiplied to obtain the susceptibility to drought. Values between 2 to 4 indicate low susceptibility, 6 to 8 indicate moderate susceptibility, and 9 to 12 indicate high susceptibility.

		Well Density		
		low (1)	moderate (2)	high (3)
Diffusivity	low (2)	**2**	**4**	**6**
	moderate (3)	**3**	**6**	**9**
	high (4)	**4**	**8**	**12**

6.2 Drought Susceptibility Mapping Results

The aquifer susceptibility to drought was determined for 100 mapped aquifers in the Okanagan Basin. In total, 71 aquifers were classified as low susceptibility, 23 as moderate susceptibility, and 5 as high susceptibility (Table 14). Table 15 shows the number of aquifers of each aquifer type classified as low, moderate and high susceptibility to drought.

Of the 61 mapped aquifers in the northern part of the Okanagan, 44 (75%) were classified as low susceptibility to drought, 13 (22%) as moderate susceptibility, and 2 (3%) as high susceptibility (Figure 11). The two aquifers classified as high susceptibility to drought are Aquifer #344, which is a type 4b aquifer and had a susceptibility score of 12, and Aquifer #353, which is a type 3 aquifer and had a susceptibility score of 9.

Of the 39 mapped aquifers in the southern part of the Okanagan Basin, 26 (67%) were classified as low susceptibility to drought, 10 (26%) as moderate susceptibility, and 3 (8%) as high susceptibility (Figure 12). The three aquifers classified as high susceptibility to drought are Aquifer #193 (type 4a), Aquifer #255 (type 1a), and Aquifer #860 (4a), all of which have a susceptibility score of 9.

Table 14: The number of aquifers for each susceptibility score and classification.

	Aquifer Susceptibility Value	**Number of Aquifers**
Low	2	20
	3	16
	4	36
	Total	**72**
Moderate	6	16
	8	7
	Total	**23**
High	9	4
	12	1
	Total	**5**

Table 15: Number of aquifers for each aquifer type for each drought susceptibility classification.

Aquifer Type	Low		Moderate		High		Total
1a	1	(33 %)	1	(33 %)	1	(33 %)	3
1b	1	(50 %)	1	(50 %)	0	(0 %)	2
1c	1	(50 %	1	(50 %)	0	(0 %)	2
2	2	(67 %)	1	(33 %)	0	(0 %)	3
3	2	(20 %)	7	(70 %)	1	(10 %)	10
4a	9	(56 %)	5	(31 %)	2	(13 %)	16
4b	19	(70 %)	7	(26 %)	1	(4 %)	27
5a	3	(100 %)	0	(0 %)	0	(0 %)	3
6a	1	(100 %)	0	(0 %)	0	(0 %)	1
6b	33	(100 %)	0	(0 %)	0	(0 %)	33

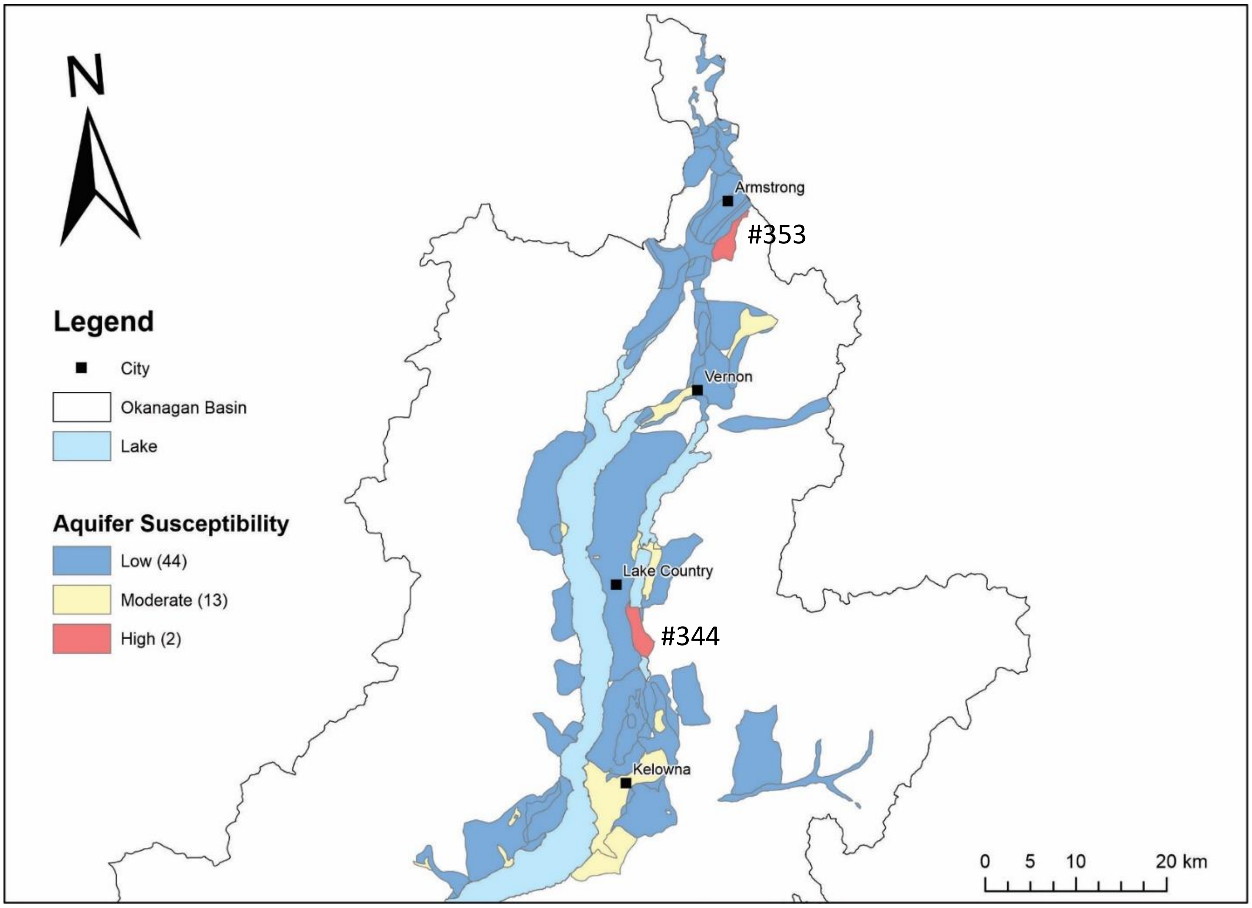


Figure 11: Map of the Aquifer Drought Susceptibility for the North Okanagan Basin.

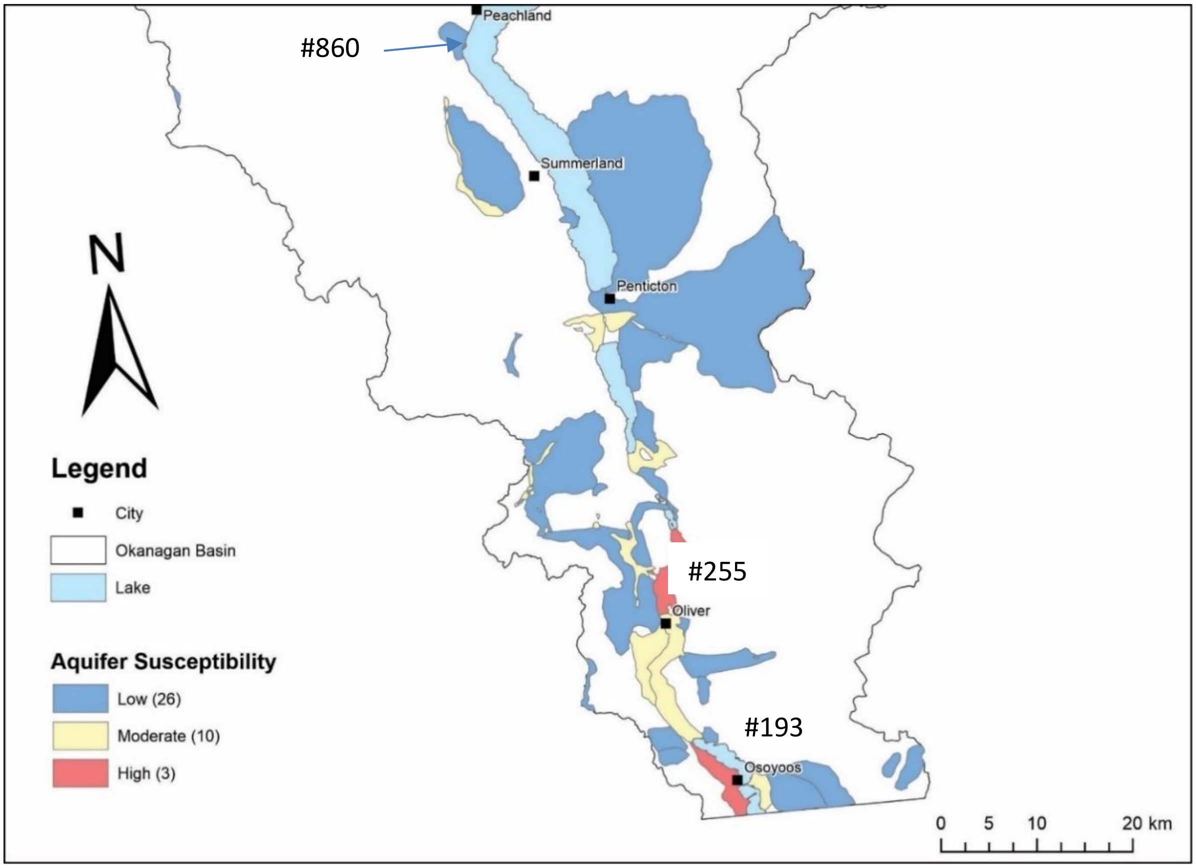


Figure 12: Map of the Aquifer Drought Susceptibility for the South Okanagan Basin. Aquifer #860 borders Okanagan Lake at the edge of Aquifer #861.

6.3 Discussion

All five aquifers that were determined to have a high susceptibility to drought (#344, #353, #193, #255, and #860) had high well densities. Aquifer type 4b had the highest diffusivity values, but only seven of the 27 aquifers (26%) were classified as moderately susceptible and one classified as highly susceptible. Five of the eight histograms of the summer SGI values for the 4b aquifers (Figure D7) had a positive skewness value, which indicates more negative values. All the bedrock aquifers, which have the lowest hydraulic diffusivity values, were classified as having low susceptibility to drought. This was reflected in the SGI histograms of the bedrock aquifers (Figure D8 and Figure D9), with all three histograms having skewness values ranging from -0.08 to 0.05.

A workshop was held in October of 2019 where a map of groundwater and surface water problems in the Okanagan Basin was generated (Figure 13 and Figure 14). Past and ongoing water problems were identified by the workshop participants, as well as three areas where no water problems have been observed.

In North Okanagan, the workshop participants identified eight locations with surface water problems and eight locations with groundwater problems (Figure 13; Table 16). The map index of areas without known water problems identified at workshop is shown in Table 17.

West Kelowna (#7 on Figure 13) has experienced both surface water and groundwater problems in the past. Located in this area are aquifers #301 and #302. Both of these aquifers are type 4a with moderate aquifer susceptibility, both resulting in a moderate aquifer drought susceptibility.

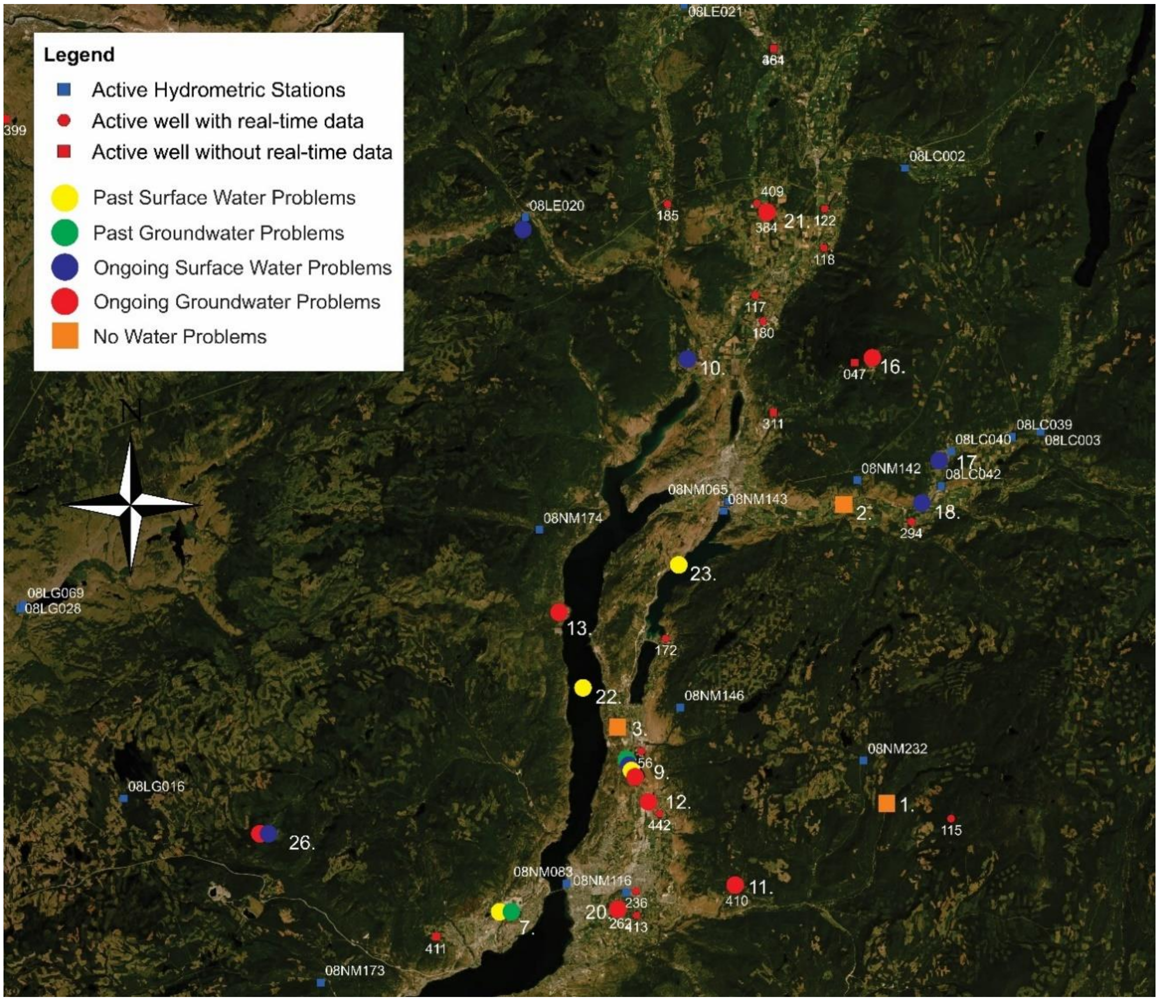


Figure 13: Map for the North Okanagan Basin showing past and current surface water and groundwater problems. The map was generated at a workshop held in Kelowna in October 2019.

Ellison Lake (#9 on Figure 13) was identified as having both, past and ongoing, surface water and groundwater problems. Aquifer 344 is located between Wood Lake and Ellison Lake and was determined to have a high drought susceptibility due to the high diffusivity and high well density.

An ongoing groundwater problem was identified in aquifer 473 (#11 on Figure 13). Aquifer #473 is a type 6b aquifer giving it a low diffusivity and the aquifer has a low well density. However, observation well 410 had an average SGI of -0.65 for the summer of 2015. Although the aquifer has a low well density, all the wells are concentrated in the lower half of the aquifer close to Mission Creek.

The Kelowna airport was also identified as an area of concern for ongoing groundwater problems (#12 on Figure 13). Aquifers #467 and #464 are located in this area. Aquifer #467 is type 1c with a moderate well density, resulting in a moderate drought susceptibility. Aquifer #464 is a type 4b with a low well density, resulting in a low aquifer susceptibility. Although aquifer #464 was classified as low susceptibility, it has a number of high-capacity wells, including municipal supply wells. Observation well 262 (#20 on Figure 13) was also identified as having ongoing groundwater problems. It is located in this aquifer (Aquifer #464) and had a summer 2015 SGI value of -2.64, indicating very low groundwater levels. Therefore, while the well density can be a good indicator of water use, the type of use and overall water demand should also be considered.

Table 16: Map index of water problems identified at a workshop held in Kelowna in October 2019.

Number	Dot Colour	Location name
1	blue	Shingle Creek
2	blue	Inkaneep Creek
3	blue	Vaseaux Lake
4	blue	Shuttleworth Creek
5	yellow, green	Okanagan Falls
6	yellow, green	Twin Lakes
7	yellow, green	West Kelowna
8	green	West of Summerland
9	blue, yellow, green, red	Ellison Lake
10	blue	Okanagan Indian Band – Vernon
11	red	Joe Rich
12	red	Airport
13	red	Fintry
14	red	Anarchist Mtn
15	blue	Osoyoos Lake
16	red	Silver Star
17	blue	Bessette Creek
18	blue	Duteau Creek
19	blue	Faulkland
20	red	Observation well 262
21	red	Observation well 384
22	yellow	Okanagan Lake
23	yellow	Kalamalka Lake
24	yellow	Okanagan River
25	yellow	McIntyre Dam
26	blue, red	Pennask Plateau

yellow = past surface water problems; green = past groundwater problems;
blue = ongoing surface water problems; red = ongoing groundwater problems

Table 17: Map index of areas without known water problems identified at a workshop held in Kelowna in October 2019.

Number	Dot Colour	Location name	Notes
1	orange square	Upper Mission Creek	
2	orange square	Lavington	
3	orange square	Between Windfield and Okanagan Lake	springs

Fintry (#13 on Figure 13) was identified as having ongoing groundwater problems. Fintry is located on aquifer #358 a type 3 fan aquifer with a moderate well density classified as having a moderate drought susceptibility. Silver Star was also identified as having ongoing groundwater problems (#16 on Figure 13). Silver Star is located on aquifer #351, which has a low drought susceptibility due to the aquifer type (6b) and low well density. Observation well 047 is completed in this aquifer and had a SGI value of -0.01 in the summer of 2015, which does not indicate a dry period had occurred. Observation well 384 (#21 on Figure 13) had experienced ongoing groundwater problems. The observation well is in aquifer #102 and is a type 4b with a low well density, resulting in a low drought susceptibility. However, the SGI rank for the summer of 2015 was high, indicating very low groundwater levels.

Bessette and Duteau Creeks (#17 and #18, respectively, on Figure 13), located near Lumby, were both identified as having ongoing surface water problems. Aquifer #316 is a 1c aquifer with a moderate well density resulting in a moderate drought susceptibility. Observation well 294 is located in this aquifer and was classified as a streamflow-driven system with Bessette Creek and is likely hydraulically connected to Duteau Creek as well (Aquifer #316).

Another past surface water problem was identified at Kalamalka Lake (#23 on Figure 13). Three aquifers are located between Kalamalka Lake and Wood Lake: aquifers #345, #1238, and #1239. Aquifer #345 is a type 4a aquifer with a moderate well density and was determined to have a moderate drought susceptibility. Aquifers #1238 and #1239 are both type 3 aquifers with moderate well density and were also classified as being moderately susceptible to drought.

In South Okanagan, the workshop participants identified eight locations with surface water problems and four locations with groundwater problems (Figure 14; Table 16). Okanagan Falls (#5 on Figure 14) was identified as having both past surface water and groundwater problems. Located at Okanagan Falls is aquifer # 264, which is a type 4a aquifer with a moderate well density resulting in a moderate aquifer susceptibility and hydraulic connection to surface water is likely (Aquifer #264 Factsheet). Vaseaux Lake is regulated by the McIntyre dam on the Okanagan River (#3, #24, and #25 on Figure 14) and all of which were identified as having surface water problems. Aquifer #255 is a type 1a streamflow-driven aquifer with a high well density resulting is a high susceptibility to drought. Observation well 407 is located in this aquifer and had SGI value of -0.85 in the summer of 2015.

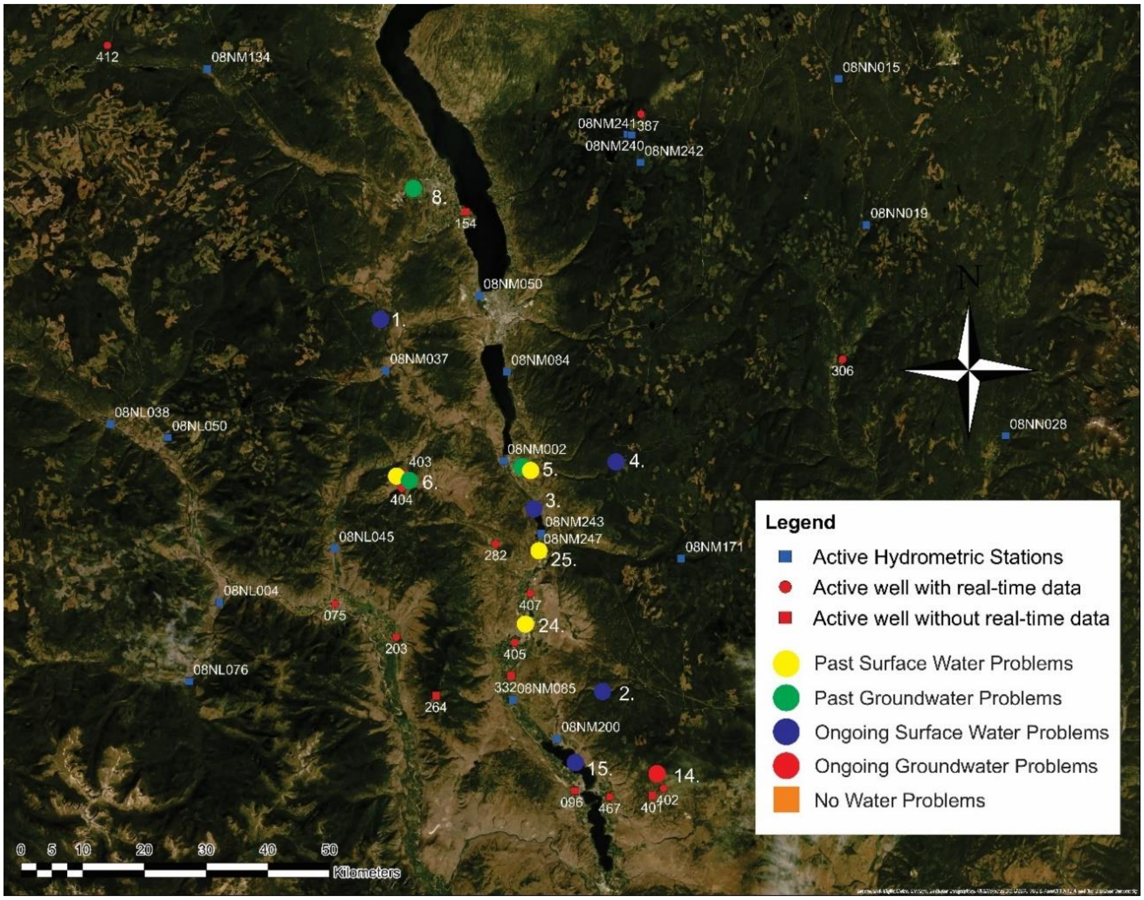


Figure 14: Map for the South Okanagan Basin showing past and current surface water and groundwater problems. The map was generated at a workshop held in Kelowna in October 2019.

Additionally, surface water problems were also identified at Osoyoos Lake (#15 on Figure 14). Aquifer #193 is located to the west of Osoyoos Lake, while Aquifer #194 is located on the east. Aquifer #193 has a high well density, while #194 has a moderate well density, resulting in high and moderate drought susceptibilities, respectively.

Twin Lakes (#6 on Figure 14) is located west of Okanagan Falls and was identified as having past surface water and groundwater problems. Aquifer #261 underlies the lakes and is a 4a aquifer with a moderate well density, resulting in a classification of moderate drought susceptibility. Additionally, Anarchist Mountain is located east of Osoyoos Lake (#14 on Figure 14) and has experienced ongoing groundwater problems. Aquifers #808 and #936 are both type 6b with moderate well densities, both being classified as low drought susceptibility. However, both aquifers extend past the US-Canada International border and may be affected by water use south of the border.

Additionally, three locations were identified as not having any water problems: Upper Mission Creek, Lavington, as well as areas between Winfield and Okanagan Lake. The aquifers located in upper Mission Creek (#461), and between Winfield and Okanagan Lake (#471) were both classified as having low drought susceptibility. Aquifer #461 is a 4b aquifer but has a low well density. Aquifer #471 is a 6b aquifer with a low well density. Aquifer #352 is located at Lavington and is a 4b aquifer with a low well density, resulting in a low drought susceptibility.

Overall, the aquifer drought susceptibility classification results are generally consistent with the observations made by the workshop participants.

CONCLUSIONS AND RECOMMENDATIONS

Early Season Core Indicators of Groundwater Drought

The GAMs identified combinations of predictor climate variables that are associated with summer groundwater levels in both the South Central B.C. and Fraser Valley study areas. In South Central B.C., maximum spring temperature, maximum snow water equivalent, and the winter ENSO 3.4 index was the best combination of climate predictor variables. In the Fraser Valley, the maximum spring temperature, winter precipitation, and spring streamflow was the best combination of climate predictor variables. For the Gulf Islands, the GAMs did not produce well fitted summer groundwater levels. This shows that each of the three study regions are uniquely influenced by different climate variables.

Drought Season Core Indicator of Groundwater Drought

The Standardized Groundwater Level Index (SGI) was tested in South Central B.C. and the Fraser Valley as a potential drought season core indicator. The SGI was effective at indicating which wells had pronounced responses to periods of drought in each region. However, the SGI was shown to be affected by water use in aquifers, and as such may not be best used in aquifers with a high well density or negative groundwater trends if only climate-related drought (and not anthropogenic drought) is of interest.

Overall, the SGI appears to be a good indicator to retroactively check how the groundwater levels responded to periods of drought and to non-drought years.

Aquifer Susceptibility to Drought

The aquifer susceptibility to drought classification adequately identified which aquifers may be more susceptible to drought in the Okanagan Basin. Aquifers were classified using both estimates of hydraulic diffusivity by aquifer type and the well density. In addition, the SGI was used to verify the classification.

The classification identified five highly susceptible aquifers and 23 moderately susceptible aquifers. Additionally, these classifications were consistent with observations of surface water and groundwater problems made by participants of a workshop in October 2019.

Aquifers classified as high susceptibility should be carefully monitored and considered for use curtailment during the summer based on the core early season predictor variables identified in this study. Aquifers classified as moderate susceptibility, with a moderate well density should be monitored to ensure that further development of the aquifer (i.e., an increase in well density) does not adversely affect the groundwater levels, particularly during droughts. Furthermore, the amount of water being abstracted, as well as the timing of abstractions, should also be noted if there is non-domestic water use in the aquifer.

REFERENCES

Allen, D.M., P.H. Whitfield, and A. Werner. 2010. Groundwater level responses in temperate mountainous terrain: regime classification, and linkages to climate and streamflow. Hydrological Processes, 24: 3392–3412. https://doi.org/10.1002/hyp.7757

Barlow, P.M., and S.A. Leake. 2012. Streamflow Depletion by Wells—Understanding and Managing the Effects of Groundwater Pumping on Streamflow. United States Geological Survey Circular 1376. Reston, Virginia

Bergman, K.H., P. Sabol and D. Miskus. 1988. Experimental indices for monitoring global drought conditions. Proceedings of 13th Annual Climate Diagnostics Workshop, United States Department of Commerce, Cambridge, MA.

B.C. Ministry of Agriculture. 2015. Soil Water Storage Capacity and Available Soil Moisture. Water Conservation Fact Sheet. https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/agriculture-and-seafood/agricultural-land-and-environment/soil-nutrients/600-series/619000-1_soil_water_storage_capacity.pdf. Accessed 5 Jan 2023.

B.C. Ministry of Forests (B.C. FOR). 2021. British Columbia Drought Information Portal. In: Province of British Columbia. https://governmentofbc.maps.arcgis.com/apps/MapSeries/index.html?appid=838d533d8062411c820eef50b08f7ebc. (Accessed 12 May 2022).

B.C. Ministry of Land, Water and Resource Stewardship (LWRS). 2022. British Columbia Drought and Water Scarcity Response Plan. Government of British Columbia. https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/drought-info/drought_response_plan_final.pdf (Accessed 5 December 2022).

B.C. River Forecast Centre. 2015. Snow Survey and Water Supply Bulletin - April 1st, 2015.

Bhuiyan, C. 2004. Various drought indices for monitoring drought condition in Aravalli Terrain of India. In: Proceedings of the XXth ISPRS Conference. International Society for Photogrammetry and Remote Sensing., Istanbul, Turkey. https://www.isprs.org/proceedings/XXXV/congress/comm7/papers/243.pdf (Accessed 1 June 2022).

Bloomfield, J.P., and B.P. Marchant. 2013. Analysis of groundwater drought building on the standardised precipitation index approach. Hydrology and Earth System Sciences, 17: 4769–4787. doi.org/10.5194/hess-17-4769-2013.

Bloomfield, J.P., B.P. Marchant, S.H. Bricker, and R.B. Morgan. 2015. Regional analysis of groundwater droughts using hydrograph classification. Hydrology and Earth System Sciences 19: 4327–4344. https://doi.org/10.5194/hess-19-4327-2015

Bryant, S.J., N. Arnell, and F.M. Law. 1994. The 1988–92 drought in its historical perspective. Water and Environment Journal, 8(1): 39-51. doi: 10.1111/j.1747-6593.1994.tb01091.x

Carslaw, D.C., and K. Ropkins. 2012. openair --- An R package for air quality data analysis. Environmental Modelling & Software 27–28: 52–61.

Chang, T.J., and C.B. Teoh. 1996. Use of the kirging method for studying characteristics of groundwater droughts. Water Resources Bulletin, 31: 1001–1007.

Church, M., and J.M. Ryder. 2010. Physiography of British Columbia. In: Pike, R.G., T.E. Redding R.D. Moore, et al. (eds) Compendium of Forest Hydrology and Geomorphology in British Columbia. B.C. Min. For. Range, For. Sci. Prog., Victoria, B.C

Douglas, T. 2006. Review of Groundwater-Salmon Interactions in British Columbia. https://watershedwatch.ca/wp-content/uploads/2011/02/Review_Groundwater_Salmon.pdf (Accessed 1 June 2022).

Eltahir, E.A.B., and P.J.F. Yeh. 1999. On the asymmetric response of aquifer water level to floods and droughts in Illinois. Water Resources Research, 35: 1199–1217. doi.org/10.1029/1998WR900071

Global Climate Observing System Working Group on Surface Pressure (GCOS-WGSP). 2021. Niño 3.4 SST Index. https://psl.noaa.gov/gcos_wgsp/Timeseries/Nino34/. (Accessed 1 November 2021)

Grolemun, G., and H. Wickham. 2011. Dates and times made easy with lubridate. Journal of Statistical Software 40: 1–25.

Gullacher, A. 2022. Groundwater Drought: Developing Quantitative Indicators and Mapping Drought Susceptible Aquifer - Stream Systems in British Columbia. MSc thesis, Simon Fraser University.

Gullacher, A., D.M. Allen, and J.D. Goetz. 2021. Classification of Groundwater Response Mechanisms in Provincial Observation Wells Across British Columbia. British Columbia Water Science Series, WSS2021-03, Prov. B.C., Victoria.

Han, Z., S. Huang, Q. Huang, G. Leng, H. Wang, Q. Bai, J. Zhao, et al. 2019. Propagation dynamics from meteorological to groundwater drought and their possible influence. Journal of Hydrology 578: 124102. https://doi.org/10.1016/j.jhydrol.2019.124102

Hao, Z., and V.P. Singh. 2015. Drought characterization from a multivariate perspective: a review. Journal of Hydrology, 527: 668–678. https://doi.org/10.1016/j.jhydrol.2015.05.031

Hastie, T and R. Tibshirani. 1986. Generalized additive models. Statistical Science, 1: 297–310. doi.org/10.1214/ss/1177013604

Hayes, M.J., M.D. Svoboda, D.A. Wilhite, and O. Vanyarkho. 1999. Monitoring the 1996 drought using the standardized precipitation index. Bull Am Meteorol Soc, 80: 429–438. doi.org/10.1175/1520-0477(1999)080<0429:MTDUTS>2.0.CO;2

Joint Institute for the Study of the Atmosphere and Ocean (JISAO). 2021. PDO Index. http://research.jisao.washington.edu/pdo/. (Accessed 1 June 2021)

Kuang, X., J.J. Jiam, C. Zheng, J.A. Cherry, and H. Li. 2020. A review of specific storage in aquifers. Journal of Hydrology, 581: 124383.

Kubiak-Wójcicka, K., and B. Bąk. 2018. Monitoring of meteorological and hydrological droughts in the Vistula basin (Poland). Environmental Monitoring and Assessment 190: 691. https://doi.org/10.1007/s10661-018-7058-8

Kubicz, J., and B. Bąk. 2019. The reaction of groundwater to several months' meteorological drought in Poland. Polish Journal of Environmental Studies 28: 187–195. https://doi.org/10.15244/PJOES/81691

Levy, Z.F., M.S. Fram, K.E. Faulkner, C.N. Alpers, E.M. Soltero, and K.A. Taylor. 2020. Effects of montane watershed development on vulnerability of domestic groundwater supply during drought. Journal of Hydrology, 583: 124567. doi.org/10.1016/j.jhydrol.2020.124567

Liu, B., X. Zhou, W. Li, C. Lu, and L. Shu. 2016. Spatiotemporal characteristics of groundwater drought and Its response to meteorological drought in Jiangsu Province, China. Water 2016, 8(11): 480. https://doi.org/10.3390/W8110480

Lund, J., J. Medellin-Azuara, J. Durand, and K. Stone. 2018. Lessons from California's 2012-2016 drought. Journal of Water Resources Planning and Management, 144: 04018067. doi.org/10.1061/(ASCE)WR.1943-5452.0000984

Mckee, T.B., N.J. Doesken, and J. Kleist. 1993. The relationship of drought frequency and duration to time scales. In: the 8th Conference on Applied Climatology. Anaheim, California, January 17-22, 1993, pp 179–184.

Mendicino, G., A. Senatore, and P. Versace, P. 2008. A Groundwater Resource Index (GRI) for drought monitoring and forecasting in a Mediterranean climate. Journal of Hydrology, 357: 282–302. doi.org/10.1016/j.jhydrol.2008.05.005

Mishra, A.K., and V.P. Singh. 2010. A review of drought concepts. Journal of Hydrology, 391: 202–216. doi.org/10.1016/j.jhydrol.2010.07.012

Modarres, R. 2007. Streamflow drought time series forecasting. Stochastic Environmental Research and Risk Assessment, 21: 223–233.

Mohammad, A.H., H.C. Jung, T. Odeh T, C. Bhuiyan, and H. Hussein. 2018. Understanding the impact of droughts in the Yarmouk Basin, Jordan: monitoring droughts through meteorological and hydrological drought indices. Arabian Journal of Geosciences 11: 103. https://doi.org/10.1007/s12517-018-3433-6

Narasimhan, B. and R. Srinivasan. 2005. Development and evaluation of Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) for agricultural drought monitoring. Agricultural and Forest Meteorology, 133(1): 69–88.

Ojha, C., S. Werth, and M. Shirzaei. 2019. Groundwater loss and aquifer system compaction in San Joaquin Valley during 2012–2015 drought. Journal of Geophysical Research: Solid Earth, 124: 3127–3143. doi.org/10.1029/2018JB016083

Okanagan Water Stewardship Council. 2008. Okanagan Sustainable Water Strategy - Action Plan 1.0. https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/agriculture-and-seafood/agricultural-land-and-environment/water/okanagan_sustainable_water_strategy_osws_action_plan.pdf (Accessed 1 June 2022)

Palmer, W.C. 1965. Meteorological Drought. Research Paper No. 45. United States Weather Bureau, Washington, DC.

Palmer, W.C. 1968. Keeping track of crop moisture conditions, nationwide: the Crop Moisture Index. Weatherwise, 21: 156–161.

Peters, E., H.A.I. Van Lanen, R.B. Bradford, J. Cruces de Abia, and L Martinez Cortina. 2001. Droughts derived from groundwater heads and groundwater discharge. In: Assessment of the Regional Impact of Droughts in Europe. Institute of Hydrology, University of Freiburg, pp 35–39.

Peters, E., P.J.I.F. Torfs, H.A.I. Van Lanen, and G. Bier. 2003. Propagation of drought through groundwater—a new approach using linear reservoir theory. Hydrological Processes, 17: 3023–3040. doi.org/10.1002/hyp.1274

Peters, E., H.A.I. Van Lanen, P.J.J.F. Torfs, and G. Bier. 2005. Drought in groundwater - Drought distribution and performance indicators. Journal of Hydrology, 306: 302–317. doi.org/10.1016/j.jhydrol.2004.09.014

R Core Team. 2020. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rathfelder, K. 2016. Modeling Tools for Estimating Effects of Groundwater Pumping on Surface Waters. British Columbia Water Science Series, WSS2016-09, Prov. B.C., Victoria.

Rong, N. 2015, Simple function in R to calculate water year. https://blogs.ubc.ca/nickrong/2015/09/22/simple-function-in-r-to-calculate-water-year/. (Accessed 1 June 2022)

Sahoo, R.N., D. Dutta, Khanna M, N. Kumar, and S.K. Bandyopadhyay. 2015. Drought assessment in the Dhar and Mewat Districts of India using meteorological, hydrological and remote-sensing derived indices. Natural Hazards 77: 733–751. https://doi.org/10.1007/s11069-015-1623-z

Shafer, B.A. and L.E. Dezman. 1982. Development of a Surface Water Supply Index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. Proceedings of the Western Snow Conference, Colorado State University, Fort Collins, CO, 164–175.

Simpson, G.L. 2022. gratia: graceful ggplot-based graphics and other functions for GAMs fitted using mgcv. https://rdrr.io/cran/gratia/ (Accessed 1 June 2022)

Summit Environmental Consultants. 2010. Okanagan Water Supply and Demand Project: Phase 2 Summary Report. https://www.obwb.ca/wsd/wp-content/uploads/2011/02/339_2011_summary_report.pdf (Accessed 5 January 2023).

Toews, M.W., P.H. Whitfield, and D.M. Allen. 2007. Seasonal statistics: The “seas” package for R. Computers and Geosciences 33: 944–951. https://doi.org/10.1016/j.cageo.2006.11.011

Van Lanen, H.A.J., and E. Peters. 2000. Definition, effects and assessment of groundwater droughts. In: Vogt JV, Somma F (eds) Drought and Drought Mitigation in Europe. Kluwer Academic Publishers, pp 49–61

Van Loon, A.F., T. Gleeson, J. Clark, A.I.J.M. Van Dijk, K. Stahl, J. Hannaford, G. Di Baldassarre, A.J. Teuling, et al. 2016. Drought in the Anthropocene. Nature Geoscience, 9: 89–91.

Van Loon, A.F., R. Kumar, and V. Mishra. 2017. Testing the use of standardised indices and GRACE satellite data to estimate the European 2015 groundwater drought in near-real time. Hydrology and Earth System Sciences, 21: 1947–1971. doi.org/10.5194/hess-21-1947-2017

Vicente-Serrano, S.M., S. Begueria and J.I. Lopez-Moreno. 2010. A multi-scalar drought index sensitive to global warming: the Standardized Precipitation Evapotranspiration Index. Journal of Climate, 23: 1696–1718.

Viviroli, D., R. Weingartner, and B. Messerli. 2003. Assessing the hydrological significance of the world’s mountains. Mountain Research and Development 23: 32–40. https://doi.org/10.1659/0276-4741(2003)023[0032:ATHSOT]2.0.CO;2

Wagenmakers, E. -J., S. Farrell, and J. Wagenmakers. 2004. AIC model selection using Akaike weights. Psychonomic Bulletin & Review, 11: 192–196.

Wei, M., D.M. Allen, A. Kohut A, S. Grasby, K. Ronneseth, and B. Turner. 2009. Understanding the types of aquifers in the Canadian Cordillera Hydrogeologic Region to better manage and protect groundwater. Streamline, 13: 10–17.

Wickham, H. 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York

Wickham, H., R. Francois, L. Henry, and K. Muller. 2022. dplyr: A Grammar of Data Manipulation. https://dplyr.tidyverse.org/

Wilhite, D.A., and M.H. Glantz. 1985. Understanding the drought phenomenon: the role of definitions. Water International, 10(3): 111-120.

Winter, T.C., J.W. Harvey, O.L. Franke, and W.M. Alley. 1999. Ground Water and Surface Water: A Single Resource. U.S. Geological Survey, Denver, Colorado.

Wood, S.N. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. Journal of the Royal Statistical Society (B), 73(1): 3-36.

Wood, S. 2017. Generalized Additive Models: An Introduction with R, 2 edition. Chapman and Hall/CRC, New York, 496 pp.

World Meteorological Organization and Global Water Partnership (WMO and GWP), 2016. Handbook of Drought Indicators. (M. Svoboda and B.A. Fuchs). Integrated Drought Management Programme (IDMP), Integrated Drought Management Tools and Guidelines Series 2. Geneva.

APPENDIX A: GENERALIZED ADDITIVE MODEL (GAM) RESULTS

A.1 Single Predictor Variable GAMs

Table A1: Single predictor variable GAM results for the South Central B.C. study region. r^2 *values > 0.5 and p values < 0.1 are in bold.*

Aquifer Type		**1b**	**1b**	**4a**	**4b**	**4b**	**4b**
Response mechanism		**sf**	**sf**	**sf**	**r**	**r**	**r**
Observation Well #		**OW217**	**OW364**	**OW381**	**OW262**	**OW344**	**OW384**
Hydrometric Station #		**08NN002**		**08LE108**		**08LF002**	
Predictor Variable	**Statistics**						
Max Temp JFM	**AIC**	27.6	30.35	25.81	24.62	28.33	27.23
	r^2	0.25	-0.13	0.37	0.46	0.18	0.20
	p value	0.25	0.76	0.1	**0.09**	0.33	0.12
Max Temp AMJ	**AIC**	23.19	14.26	28.66	26.39	23.9	28.69
	r^2	**0.54**	**0.83**	0.10	0.34	**0.50**	0.06
	p value	**0.05**	**0.002**	0.28	0.15	**0.07**	0.25
Max Temp JAS	**AIC**	30.48	29.6	23.57	30.03	29.78	30.47
	r^2	-0.14	0.06	0.47	-0.09	-0.06	-0.14
	p value	0.98	0.53	**0.02**	0.57	0.48	0.93
Min Temp JFM	**AIC**	25.57	27.81	29.04	27.89	29.23	26.55
	r^2	0.39	0.21	0.03	0.21	0.10	0.26
	p value	0.12	0.22	0.31	0.25	0.46	**0.09**
Min Temp AMJ	**AIC**	29.52	20.84	29.69	27.29	28.88	25.02
	r^2	-0.03	0.65	-0.05	0.2	0.09	0.44
	p value	0.40	**0.02**	0.45	0.13	0.34	0.10
Min Temp JAS	**AIC**	30.19	26.89	25.92	20.61	28.77	22.5
	r^2	-0.11	0.23	0.37	**0.65**	0.06	**0.57**
	p value	0.65	0.11	0.14	**0.02**	0.27	**0.04**
Precip JFM	**AIC**	30.33	30.48	28.94	29.09	30.47	30.04
	r^2	-0.12	-0.14	0.04	0.02	-0.14	-0.09
	p value	0.74	0.99	0.29	0.32	0.92	0.57
Precip AMJ	**AIC**	25.07	30.44	30.37	30.4	29.13	28.41
	r^2	0.37	-0.14	-0.13	-0.13	0.11	0.09
	p value	**0.05**	0.86	0.78	0.81	0.45	0.22
Precip JAS	**AIC**	29.05	29.43	27.64	29.33	21.04	28.66
	r^2	0.12	-0.02	0.17	-0.01	0.64	0.13
	p value	0.43	0.38	0.15	0.36	**0.02**	0.32
Max SWE	**AIC**	26.53	27.74	28.97	27.89	30.14	30.37
	r^2	0.26	0.16	0.12	0.22	-0.1	-0.04
	p value	**0.09**	0.16	0.42	0.28	0.62	0.74
Max SWE Prev Year	**AIC**	29.9	30.47	27.42	18.54	28.52	31.79
	r^2	-0.07	-0.14	0.26	0.31	-0.16	0.02
	p value	0.52	0.93	0.24	0.23	0.89	0.53
Niño 3.4	**AIC**	29.71	29.8	23.43	23.2	27.62	28.06
	r^2	-0.05	-0.06	0.48	0.49	0.18	0.13
	p value	0.45	0.48	**0.02**	**0.02**	0.16	0.19

Table A1 Continued: Single predictor variable GAM results for the South Central B.C. study region.

Aquifer Type		**1b**	**1b**	**4a**	**4b**	**4b**	**4b**
Response mechanism		**sf**	**sf**	**sf**	**r**	**r**	**r**
Observation Well #		**OW217**	**OW364**	**OW381**	**OW262**	**OW344**	**OW384**
Hydrometric Station #		**08NN002**		**08LE108**		**08LF002**	
Predictor Variable	**Statistics**						
Niño 3.4 JFM	**AIC**	30	24.79	30.1	26.98	29.51	22.35
	r^2	-0.08	0.39	-0.1	0.29	-0.03	**0.58**
	p value	0.55	**0.04**	0.6	0.19	0.4	**0.04**
Streamflow JFM	**AIC**	27.95		16.05		24.38	
	r^2	-0.07		0.48		0.06	
	p value	0.49		0.15		0.44	
Streamflow AMJ	**AIC**	14.28		12.65		24.27	
	r^2	**0.83**		**0.65**		0.12	
	p value	**0.01**		**0.02**		0.49	
Streamflow JAS	**AIC**	15.59		20.00		22.90	
	r^2	**0.77**		0.09		0.19	
	p value	**0.03**		0.49		0.18	

sf = streamflow-driven response mechanism
r = recharge-driven response mechanism
JFM = January, February, March
AMJ = April, May, June
JAS = July, August, September
SWE = snow water equivalent

Table A2: Single predictor variable GAM results for the Fraser Valley study region. r^2 values > 0.5 and p values < 0.1 are in bold.

Aquifer Type		**4a**	**4a**	**4a**	**4a**	**4a**	**4a**	**4c**	**6b**
Response mechanism		**sf**	**sf**	**sf**	**sf**	**sf**	**sf**	**sf**	**sf**
Observation Well #		**2**	**8**	**272**	**275**	**301**	**353**	**361**	**255**
Hydrometric Station #		**08MH153**	**08MH029**	**08MH029**	**08MH155**	**08MH153**	**08MH155**	**08MH153**	**08MH001**
Predictor Variable	**Statistics**								
Max Temp JFM	**AIC**	23.13	23.52	27.20	17.18	21.21	5.03	21.30	26.33
	r^2	0.24	0.16	-0.17	0.19	0.48	0.42	**0.53**	0.00
	p value	0.13	0.18	0.98	0.15	**0.03**	**0.05**	**0.02**	0.35
Max Temp AMJ	**AIC**	18.91	18.63	23.68	26.24	19.35	26.95	30.24	25.14
	r^2	**0.68**	**0.69**	0.46	0.29	**0.67**	0.23	-0.11	0.37
	p value	**0.00**	**0.00**	**0.03**	**0.08**	**0.00**	0.11	0.68	**0.05**
Max Temp JAS	**AIC**	29.86	29.97	30.36	30.46	30.16	29.28	29.04	28.94
	r^2	-0.07	-0.08	-0.13	-0.14	-0.10	0.00	0.12	0.04
	p value	0.50	0.54	0.77	0.90	0.63	0.35	0.43	0.29
Min Temp JFM	**AIC**	24.45	24.46	27.19	18.66	23.55	6.59	22.67	25.89
	r^2	0.10	0.05	-0.17	0.10	0.36	0.36	0.44	0.06
	p value	0.23	0.28	0.93	0.40	0.13	0.16	**0.04**	0.28

Table A2 Continued: Single predictor variable GAM results for the Fraser Valley study region.

	Aquifer Type	**4a**	**4a**	**4a**	**4a**	**4a**	**4a**	**4c**	**6b**
	Response mechanism	**sf**	**sf**	**sf**	**sf**	**sf**	**sf**	**sf**	**sf**
	Observation Well #	**2**	**8**	**272**	**275**	**301**	**353**	**361**	**255**
	Hydrometric Station #	**08MH153**	**08MH029**	**08MH029**	**08MH155**	**08MH153**	**08MH155**	**08MH153**	**08MH001**
Predictor Variable	**Statistics**								
Min Temp AMJ	**AIC**	26.80	25.47	28.06	27.99	28.46	30.06	28.79	28.68
	r^2	0.31	0.40	0.13	0.21	0.17	0.01	0.05	0.06
	p value	0.19	0.12	0.19	0.29	0.35	0.64	0.27	0.25
Min Temp JAS	**AIC**	28.72	29.61	30.42	28.16	28.68	30.08	30.09	30.42
	r^2	0.15	0.06	-0.14	0.20	0.15	0.00	-0.08	-0.14
	p value	0.38	0.53	0.84	0.31	0.37	0.65	0.61	0.84
Precip JFM	**AIC**	16.54	17.64	25.51	7.34	22.25	6.55	24.81	27.48
	r^2	**0.70**	**0.64**	0.06	**0.79**	0.47	0.36	0.34	-0.15
	p value	**0.02**	**0.04**	0.28	**0.01**	0.11	0.16	0.20	0.78
Precip AMJ	**AIC**	27.07	27.16	29.47	29.50	25.09	28.78	28.86	27.65
	r^2	0.22	0.21	-0.02	0.07	0.37	0.14	0.13	0.17
	p value	0.12	0.12	0.39	0.52	**0.05**	0.39	0.39	0.15
Precip JAS	**AIC**	27.38	27.15	24.94	30.09	29.11	30.59	28.24	30.33
	r^2	0.19	0.21	0.38	-0.09	0.02	-0.12	0.19	-0.12
	p value	0.13	0.12	**0.04**	0.60	0.32	0.94	0.30	0.74
Niño 3.4 Year avg	**AIC**	25.19	25.36	28.63	21.53	26.05	20.47	28.88	29.92
	r^2	0.38	0.39	0.07	**0.61**	0.30	**0.66**	0.04	-0.07
	p value	**0.05**	**0.07**	0.25	**0.03**	**0.07**	**0.02**	0.28	0.52
Niño 3.4 JFM	**AIC**	22.52	23.50	30.10	20.77	18.91	21.00	27.81	25.82
	r^2	**0.53**	0.47	-0.06	**0.65**	**0.68**	**0.64**	0.15	0.32
	p value	**0.02**	**0.02**	0.64	**0.02**	**0.00**	**0.02**	0.16	0.07
Streamflow JFM	**AIC**	26.29	26.60	25.91	22.89	27.38	26.72	24.91	27.84
	r^2	-0.15	-0.15	-0.04	0.38	-0.17	0.14	0.22	-0.06
	p value	0.86	0.97	0.42	0.17	0.97	0.43	0.22	0.48
Streamflow AMJ	**AIC**	6.66	11.79	25.79	18.14	-2.34	23.29	22.75	26.30
	r^2	**0.90**	**0.82**	-0.02	**0.62**	**0.97**	0.38	0.37	0.13
	p value	**0.00**	**0.00**	0.40	**0.01**	**0.00**	**0.06**	**0.07**	0.22
Streamflow JAS	**AIC**	25.55	25.58	26.35	23.48	26.68	21.92	26.96	27.24
	r^2	-0.06	-0.04	-0.10	0.34	-0.07	**0.52**	-0.07	0.01
	p value	0.50	0.42	0.56	0.20	0.49	**0.08**	0.50	0.34

sf = streamflow-driven response mechanism
r = recharge-driven response mechanism
JFM = January, February, March
AMJ = April, May, June
JAS = July, August, September
SWE = snow water equivalent

A.2 Multiple Predictor Variable GAMs

Table A3: Predictor variables used for each of the seven GAMs in the South Central B.C. region.

GAM 1	**GAM 2**	**GAM 3**	**GAM 4**	**GAM 5**	**GAM 6**	**GAM 7**
Max SWE	Max SWE	Max SWE	Max SWE	Max SWE	Max SWE	Max SWE
Max Temp AMJ	Max Temp AMJ	Min Temp AMJ	Min Temp AMJ	Max Temp AMJ	Max Temp AMJ	Max Temp AMJ
Max Temp JAS	Max Temp JAS	Min Temp JAS	Min Temp JAS			
	Niño 3.4 JFM		Niño 3.4 JFM		Niño 3.4 JFM	
						Streamflow AMJ

Table A4: r^2 results from GAMs for each observation well in the South Central B.C. region. The highest r^2 values for each well are indicated in bold. NA = analysis not completed.

Aquifer Type	**1b**	**1b**	**4a**	**4b**	**4b**	**4b**
Response Mechanism	**Streamflow**	**Streamflow**	**Streamflow**	**Recharge**	**Recharge**	**Recharge**
Observation Well #	**217**	**364**	**381**	**262**	**344**	**384**
GAM 1	0.77	0.79	0.65	**0.78**	**0.99**	0.18
GAM 2	0.89	**0.94**	**0.97**	0.77	0.98	0.83
GAM 3	0.07	0.63	0.58	**0.78**	-0.20	0.77
GAM 4	0.07	0.61	0.62	0.70	-0.10	**0.90**
GAM 5	0.58	0.80	0.16	0.38	0.47	0.01
GAM 6	**0.90**	0.87	0.57	0.75	0.93	0.81
GAM 7	0.92	NA	**1.00**	NA	-0.11	NA

Table A5: Predictor variables used for each of the six GAMs in the Fraser Valley region.

GAM 1	**GAM 2**	**GAM 3**	**GAM 4**	**GAM 5**	**GAM 6**
Max Temp AMJ	Max Temp AMJ	Max SWE	Max SWE	Max Temp AMJ	Max Temp AMJ
Precip JFM	Precip AMJ	Max Temp AMJ	Max Temp AMJ	Precip JFM	Streamflow AMJ
	Nino 3.4 JFM		Nino 3.4 JFM	Streamflow AMJ	

Table A6: r^2 results from GAMs for each observation well in the Fraser Valley region. All wells in this region are classified as streamflow. The highest r^2 values for each well are indicated in bold.

Aquifer Type	**4a**	**4a**	**4a**	**4a**	**4a**	**4a**	**4c**	**6b**
Observation Well #	**002**	**008**	**272**	**275**	**301**	**353**	**361**	**255**
GAM 1	0.931	0.936	0.739	0.761	0.721	0.703	0.246	0.425
GAM 2	0.76	**0.979**	0.696	0.909	0.977	0.741	**0.98**	0.76
GAM 3	0.666	0.668	0.374	0.242	0.116	0.145	-0.112	0.318
GAM 4	0.746	0.72	0.384	0.799	0.902	0.846	0.478	0.269
GAM 5	0.93	0.893	**1**	**0.957**	**1**	**0.96**	0.76	**0.799**
GAM 6	**0.935**	0.9	0.722	0.588	0.985	0.252	0.746	0.401

Table A7: Predictor variables used for each of the seven GAMs in the Gulf Islands region.

GAM 1	**GAM 2**	**GAM 3**	**GAM 4**	**GAM 5**	**GAM 6**	**GAM 7**
Max Temp AMJ	Max Temp AMJ	Max Temp JAS	Max Temp JAS	Max Temp AMJ	Max Temp AMJ	Max Temp AMJ
Precip JFM	Precip AMJ	Precip JFM	Precip AMJ	Nino 3.4 Year	Precip JFM	Precip JFM
					Nino 3.4 Year	Nino 3.4 JFM

Table A8: r^2 results from GAMs for each observation well in the Gulf Islands region. The highest r^2 values for each well are indicated in bold.

Aquifer Type	**4b**	**5a**	**5a**	**5a**	**5a**	**5a**	**5a**
Response Mechanism	**n/a[1]**	**n/a**	**n/a**	**n/a**	**n/a**	**Streamflow**	**Streamflow**
Observation Well #	**327**	**196**	**125**	**128**	**283**	**316**	**373**
GAM 1	0.0817	0.605	0.225	0.685	0.0191	0.67	0.58
GAM 2	-0.197	0.693	-0.196	0.659	0.619	0.496	0.591
GAM 3	0.146	0.191	0.216	0.0976	0.63	0.143	**0.801**
GAM 4	-0.117	0.702	0.0338	0.616	**0.869**	0.502	0.741
GAM 5	-0.21	0.566	**0.652**	0.674	-0.0265	0.507	0.469
GAM 6	**0.311**	**0.766**	0.627	0.632	0.476	**0.85**	0.766
GAM 7	-0.0816	0.743	0.395	**0.738**	0.325	0.624	0.48

[1] n/a – classification results are not available.

APPENDIX B: STANDARDIZED GROUNDWATER LEVEL INDEX (SGI)

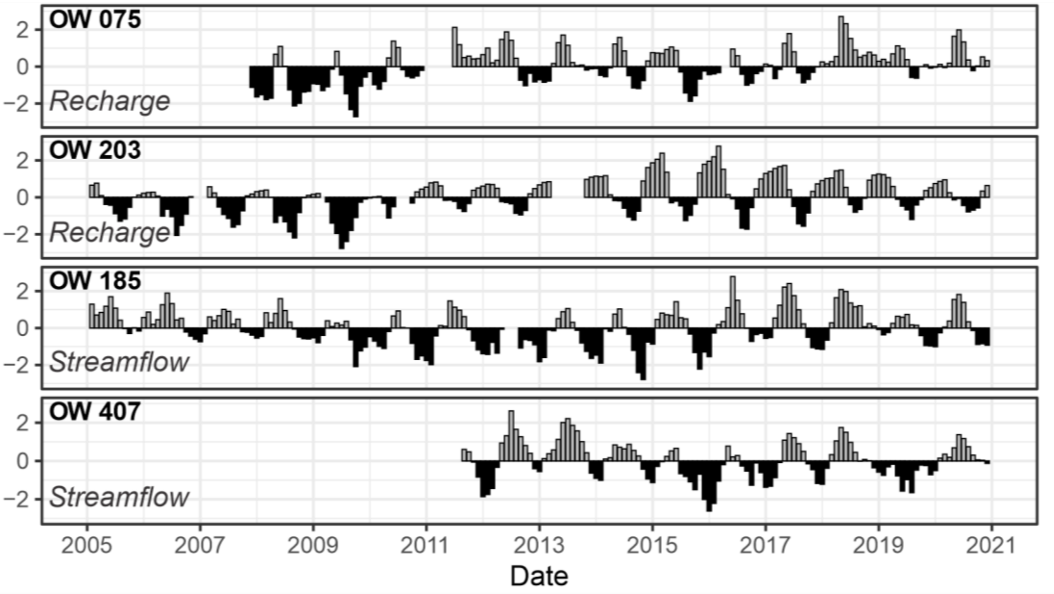


Figure B1: SGI values for type 1a aquifers in the South Central B.C. study area. The response mechanism for each well is denoted in italics.

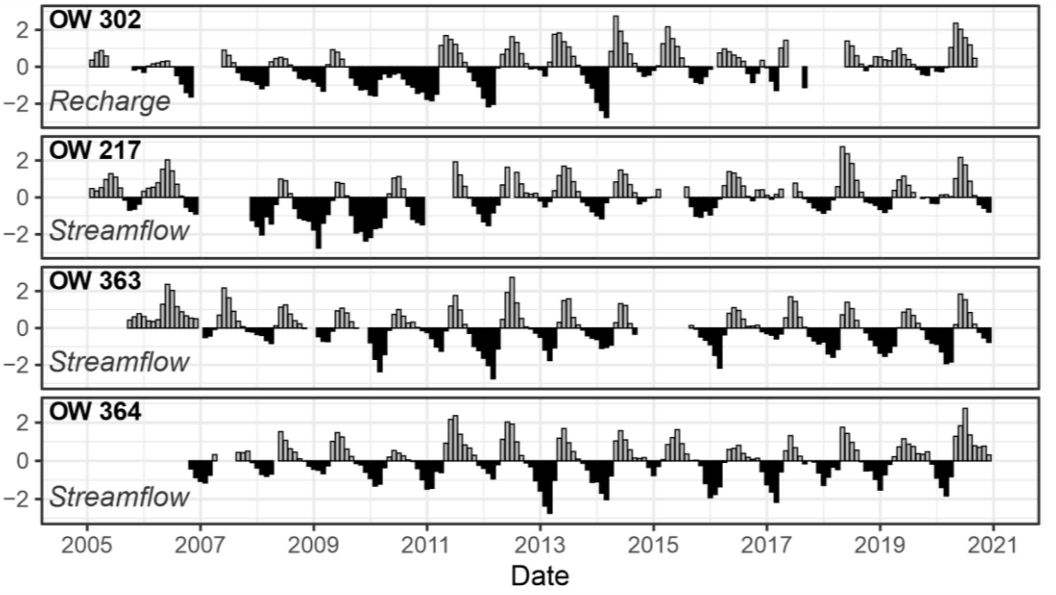


Figure B2: SGI values for type 1b aquifers in the South Central B.C. study area. The response mechanism for each well is denoted in italics.

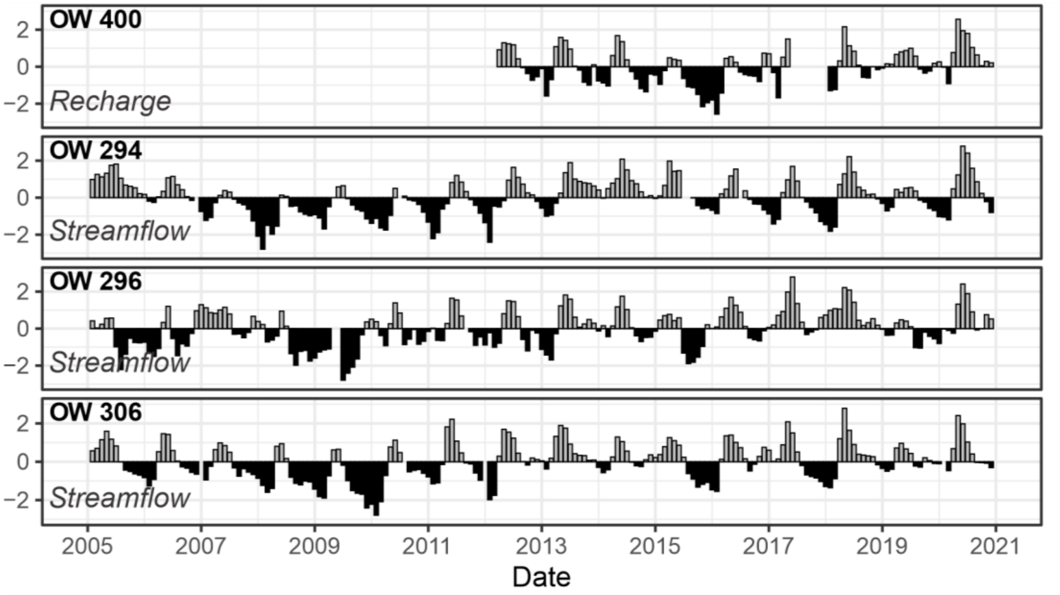


Figure B3: SGI values for type 1c aquifers in the South Central B.C. study area. The response mechanism for each well is denoted in italics.

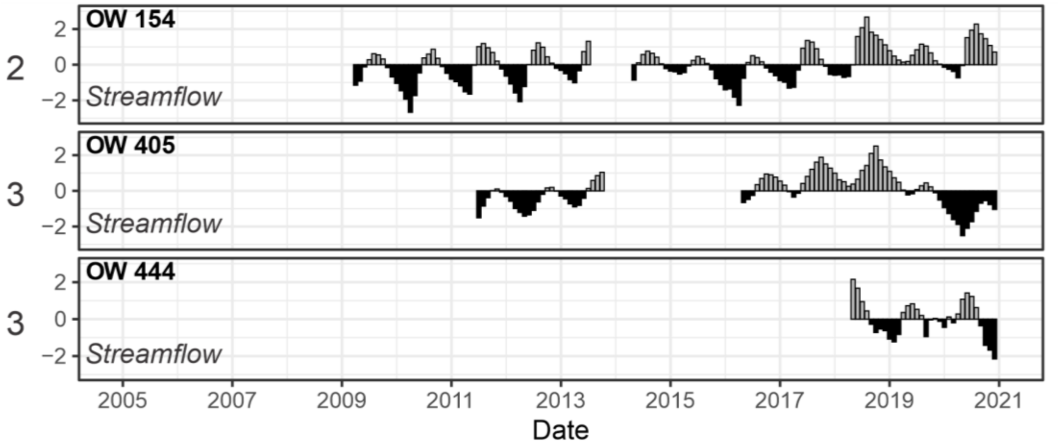


Figure B4: SGI values for types 2 & 3 aquifers in the South Central B.C. study area. The response mechanism for each well is denoted in italics.

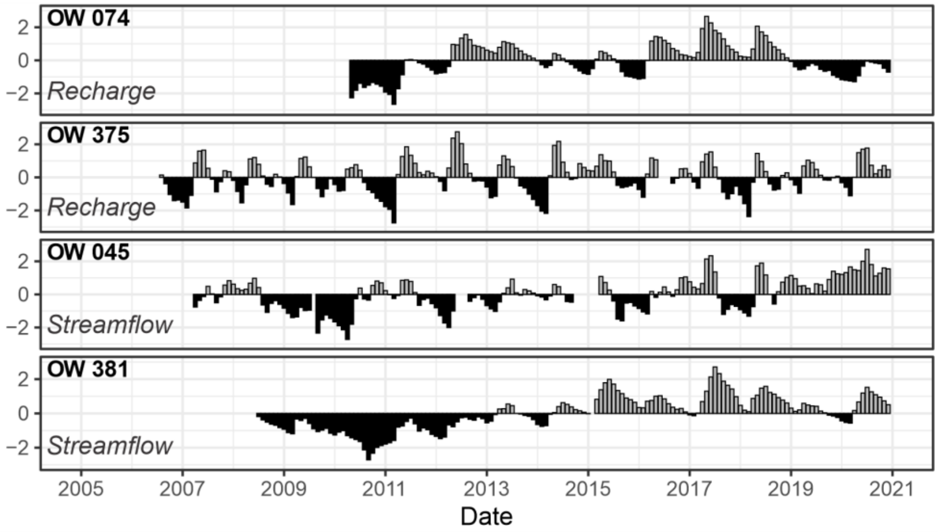


Figure B5: SGI values for type 4a aquifers in the South Central B.C. study area. The response mechanism for each well is denoted in italics.

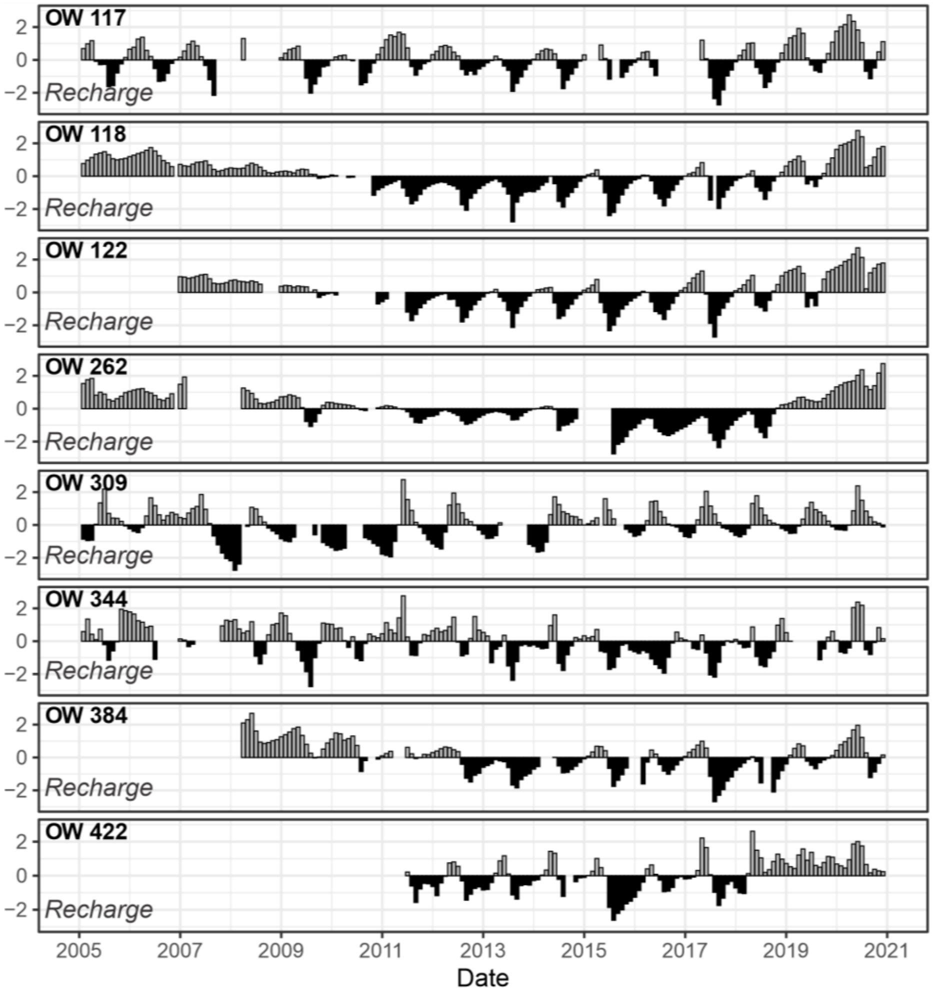


Figure B6: SGI values for type 4b aquifers in the South Central B.C. study area. The response mechanism for each well is denoted in italics.

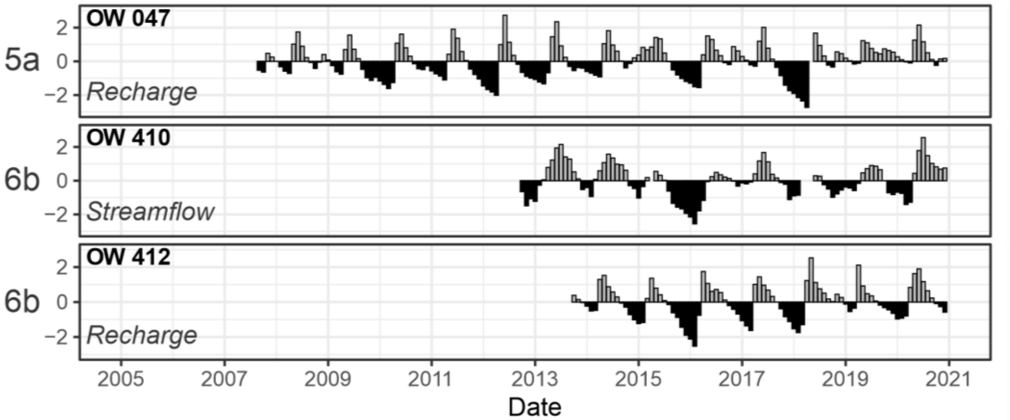


Figure B7: SGI values for types 5a & 6b aquifers in the South Central B.C. study area. The response mechanism for each well is denoted in italics.

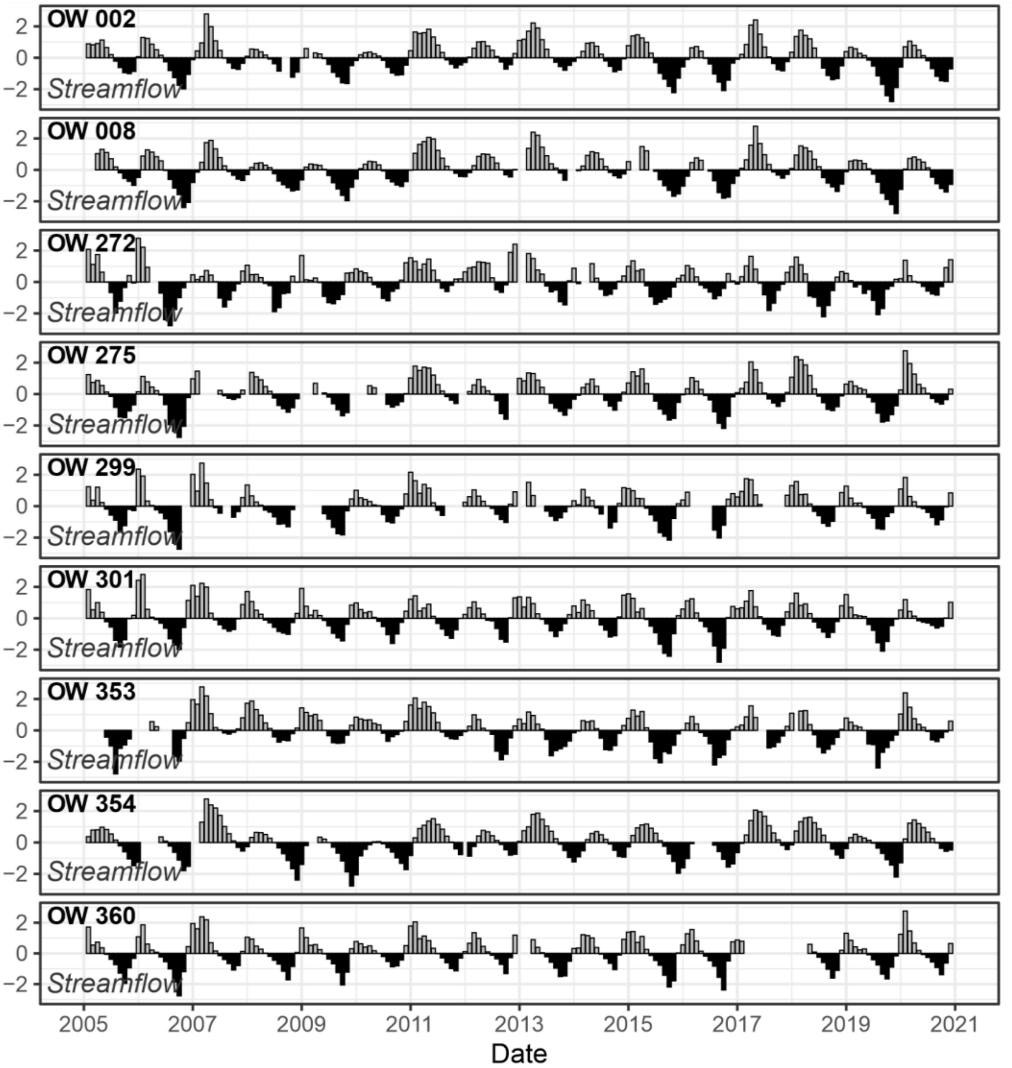


Figure B8: SGI values for type 4a aquifers in the Fraser Valley study area. The response mechanism for each well is denoted in italics.

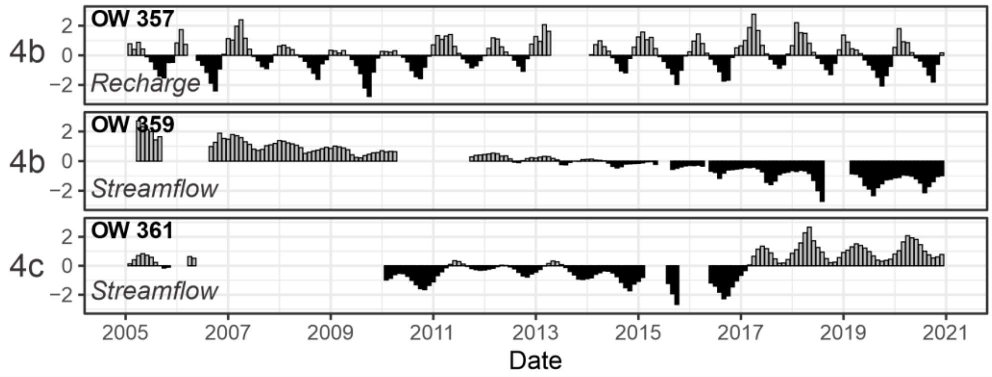


Figure B9: SGI values for type 4b aquifers in the Fraser Valley study area. The response mechanism for each well is denoted in italics.

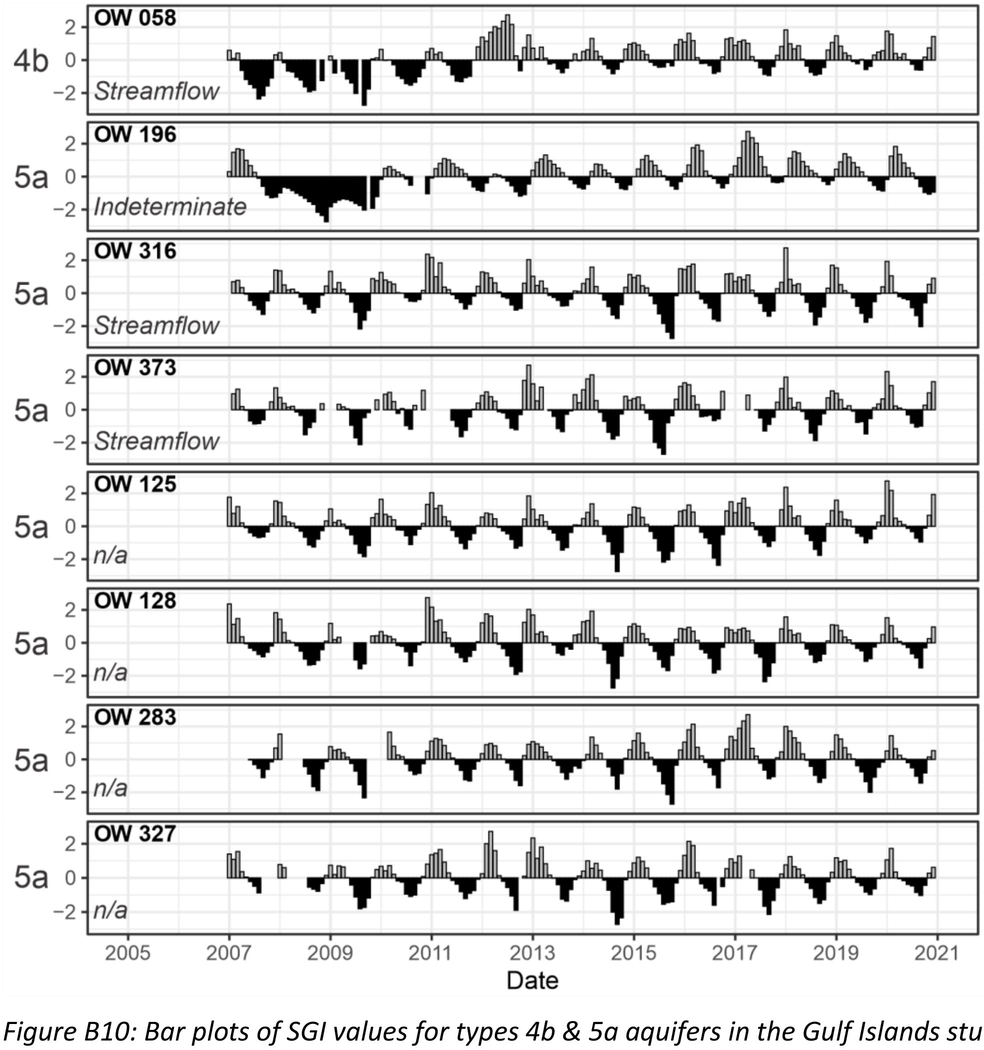


Figure B10: Bar plots of SGI values for types 4b & 5a aquifers in the Gulf Islands study region. The response mechanism for each wells is denoted in italics.

APPENDIX C: HYDRAULIC DIFFUSIVITY VALUES

Table C1: Representative values of hydraulic diffusivity and stream depletion factors in B.C. (From: Table 2-1 in Rathfelder, 2016).

Aquifer Type	Transmissivity (m^2/day)	Storativity (-)	Diffusivity (m^2/day)
1a - Unconfined or partially confined fluvial and glaciofluvial aquifers along high-order rivers	4,500 (1)	0.2 (2)	22,500
1b - Unconfined or partially confined fluvial and glaciofluvial aquifers along moderate-order rivers	1,800 (3)	0.14 (4)	12,900
2 - Unconfined deltaic aquifers formed in river deltas	1,000 (5)	0.07 (6)	14,300
3 - Unconfined alluvial fan aquifers	420 (3)	0.02 (4)	21,000
4a - Unconfined aquifers of glaciofluvial origin	650 (3)	0.04 (4)	16,300
4b - Confined aquifers of glaciofluvial origin	340 (3)	0.00044 (4)	775,000
5a - Fractured sedimentary bedrock aquifers	0.86 (7)	0.0034 (7)	250
6b - Granitic, metamorphic, meta-sedimentary, meta-volcanic, and volcanic rock	0.4 (3)	0.0085 (4)	47

(1) Geometric mean reported in Wei, M., D. Allen, K. Ronneseth, A. Kohut, S. Grasby, and B. Turner. 2014. Cordilleran Hydrogeological Region. Chapter 9, Canada's Groundwater Resources, Geological Survey of Canada.
(2) Typical value of specific yield reported in Freeze and Cherry (1979).
(3) Geometric mean of pumping test results in the Okanagan Basin (Carmichael et al., 2009)
(4) Median value of pumping test results in the Okanagan Basin (Carmichael et al., 2009)
(5) Geometric mean of pumping test results in the Regional District of Nanaimo (Carmichael et al., 2013)
(6) Median value of pumping test results in the Regional District of Nanaimo (Carmichael et al., 2013)
(7) Typical value for fractured sandstone on Salt Spring Island (Carmichael et al., 2013)

Table C2: Hydraulic conductivity (K) and specific storage (Ss) values used to calculate the hydraulic diffusivity values for aquifer types 1a, 1b, 1c, 2, 3, & 4a (Kuang et al. 2020). Full bibliographic information in Kuang et al. (2020).

Lithology	**Aquifer type**	**Thickness (m)**	**Method of Data Interpretation**	**K (m/s)**	**S_s (m^{-1})**	**Reference**
Sand	Unconfined	1	HYPARIDEN	1.67E-05	1.75E-04	Vandenboede and Lebbe (2003)
Sand	Unconfined	3.5	HYPARIDEN	2.31E-05	5.90E-05	Vandenboede and Lebbe (2003)
Sand	Unconfined	22.86	Boulton method (1963)	5.97E-05	2.41E-03	Prickett (1965)
Sand	Unconfined	4	Inverse numerical model	6.41E-05	1.90E-04	Lebbe et al. (1995)
Sand	Unconfined	6.25	Boulton method (1954, 1963) Neuman method (1972, 1974) Moench et al. method (2001) Mathias-Butler method (2006) Mishra-Neuman method (2011)	6.42E-05	5.17E-05	Mishra and Neuman (2011)
Sand	Unconfined	7.5	Inverse numerical model	6.60E-05	1.90E-04	Lebbe et al. (1995)
Sand	Unconfined	7	Neuman method (1972, 1974)	1.25E-04	4.21E-04	Heidari and Moench (1997)
Sand	Unconfined	7	Boulton method (1954, 1963) Neuman method (1972, 1974)	1.51E-04	5.71E-04	Nwankwor et al. (1992)
Sand	Unconfined	6.4	Boulton method (1963)	5.01E-04	5.78E-05	Prickett (1965)
Sand	Unconfined	11.28	Boulton method (1963)	5.76E-04	5.23E-05	Prickett (1965)
Sand	Unconfined	25.6	Boulton method (1963)	9.38E-04	2.07E-05	Prickett (1965)
Sand	Unconfined	18.29	Boulton method (1963)	2.55E-03	7.22E-05	Prickett (1965)
Sand and gravel	Unconfined	12.19	Boulton method (1963)	8.31E-05	7.79E-05	Prickett (1965)
Sand and gravel	Unconfined	22.5	Moench et al. method (2001)	4.95E-04	4.68E-04	Poulsen et al. (2011)
Sand and gravel	Unconfined	12.19	Boulton method (1963)	5.12E-04	5.17E-04	Prickett (1965)
Sand and gravel	Unconfined	210	Moench method (1993)	5.28E-04	2.86E-05	Appiah-Adjei et al. (2013)
Sand and gravel	Unconfined	5.49	Boulton method (1963)	5.71E-04	1.44E-04	Prickett (1965)
Sand and gravel	Unconfined	5	Inverse numerical optimization	6.00E-04	3.16E-03	Hvilshøj et al. (1999)
Sand and gravel	Unconfined	34.75	Boulton method (1963)	6.62E-04	9.41E-05	Prickett (1965)
Sand and gravel	Unconfined	42.67	Boulton method (1963)	8.42E-04	3.35E-05	Prickett (1965)
Sand and gravel	Unconfined	18.29	Boulton method (1963)	1.01E-03	2.24E-03	Prickett (1965)
Sand and gravel	Unconfined	18.29	Boulton method (1963)	1.02E-03	7.65E-06	Prickett (1965)
Sand and gravel	Unconfined	30.5	Neuman method (1974) Moench method (1995)	1.15E-03	6.48E-04	Chen and Ayers (1998)

Table C2 Continued.

Lithology	Aquifer type	Thickness (m)	Method of Data Interpretation	K (m/s)	S_s (m^{-1})	Reference
Sand and gravel	Unconfined	51.82	Neuman method (1974) Moench et al. method (2001) Tartakovsky-Neuman method (2007)	1.16E-03	7.54E-05	Tartakovsky and Neuman (2007), Yeh and Huang (2009)
Sand and gravel	Unconfined	30.48	Boulton method (1963)	1.18E-03	7.55E-05	Prickett (1965)
Sand and gravel	Unconfined	22.25	Boulton method (1963)	1.45E-03	4.72E-05	Prickett (1965)
Sand and gravel	Unconfined	10.97	Boulton method (1963)	2.06E-03	7.65E-05	Prickett (1965)
Sand and gravel	Unconfined	8.24	Neuman method (1972) Neuman method (1974) Neuman method (1975) Leng-Yeh method (2003)	2.10E-03	1.92E-04	Neuman (1975), Heidari and Moench (1997), Leng and Yeh (2003)
Gravel	Unconfined	36	Székely method (1992)	8.10E-04	1.50E-05	Székely (1995)

Table C3: Hydraulic conductivity (K) and specific storage (Ss) values used to calculate the hydraulic diffusivity values for aquifer type 4b (Kuang et al., 2020). Full bibliographic information in Kuang et al. (2020).

Lithology	Aquifer type	Thickness (m)	Method of Data Interpretation	K (m/s)	S_s (m^{-1})	Reference
Sand	Confined	4.6	Hemker method (1999)	1.13E-05	2.34E-05	Székely et al. (2015)
Sand	Confined	3	Theis method (1935) Cooper-Jacob method (1946)	1.80E-05	6.67E-05	Grisak and Cherry (1975)
Sand	Confined	60	Cooper-Jacob method (1946) Banton-Bangoy method (1996)	2.94E-05	1.67E-06	Banton and Bangoy (1996)
Sand	Confined	5	Hantush method (1960)	3.40E-05	3.10E-05	Alexander et al. (2011)
Sand	Confined	9.75	Halford-Healy method (1997)	5.64E-05	4.92E-06	Halford (1997)
Sand	Confined	10.5	Hantush-Jacob method (1955)	9.00E-05	1.50E-04	Shih (2018a)
Sand	Confined	7.2	Theis method (1935)	1.07E-04	3.22E-04	Trefry and Johnston (1998)
Sand	Confined	83	Theis method (1935) Black-Kipp method (1977)	1.11E-04	6.45E-06	Black and Kipp (1977)
Sand	Confined	6.1	Halford-Healy method (1997)	1.27E-04	5.58E-06	Halford (1997)
Sand	Confined	41.7	Theis method (1935) Hemker-Maas method (1987)	2.75E-04	2.12E-06	Sahoo and Jha (2017)

Table C3 Continued.

Lithology	Aquifer type	Thickness (m)	Method of Data Interpretation	K (m/s)	S_s (m^{-1})	Reference
Sand	Confined	15.55	Fujinawa method (1977)	6.09E-04	5.72E-06	Chen and Jiao (2005) (note publication date inconsistent with in Kuang et al. (2020)
Sand	Confined	25.91	Theis method (1935)	6.10E-04	1.50E-05	Jacob (1940)
Sand	Confined	21.3	Parr et al. method (1983)	6.18E-04	2.85E-05	Parr et al. (1983)
Sand and gravel	Confined	36	Hantush-Jacob method (1955)	1.20E-05	4.92E-05	Shih (2018a)
Sand and gravel	Confined	6	Cooper-Jacob method (1946) Numerical modeling	4.00E-05	1.60E-04	Miyake et al. (2008)
Sand and gravel	Confined	9	Cooper-Jacob method (1946) Numerical modeling	4.20E-05	2.30E-05	Miyake et al. (2008)
Sand and gravel	Confined	20	Cooper-Jacob method (1946) Numerical modeling	5.00E-05	6.00E-05	Miyake et al. (2008)
Sand and gravel	Confined	8	Cooper-Jacob method (1946) Numerical modeling	7.80E-05	5.60E-05	Miyake et al. (2008)
Sand and gravel	Confined	24.95	Fujinawa method (1977)	1.85E-04	4.09E-06	Chen and Jiao (2005) (note publication date inconsistent with in Kuang et al. (2020)
Sand and gravel	Confined	15.55	Fujinawa method (1977)	3.48E-04	4.05E-06	Chen and Jiao (2005)
Sand and gravel	Confined	15.55	Numerical modeling	4.35E-04	4.05E-06	Chen and Jiao (2005)
Sand and gravel	Confined	24.95	Numerical modeling	6.00E-04	1.73E-05	Chen and Jiao (2005)
Sand and gravel	Confined	3.05	Cooper-Jacob method (1946) Banton-Bangoy method (1996)	6.53E-04	1.11E-03	Banton and Bangoy (1996)
Sand and gravel	Confined	28.35	Jacob method (1950)	6.62E-04	3.95E-06	Neuman and Witherspoon (1972)
Sand and gravel	Confined	68	Hantush method (1961a, b)	8.58E-04	1.40E-05	Ni et al. (2011)
Sand and gravel	Confined	20	Harp-Vesselinov method (2011)	1.21E-03	4.04E-03	Luo and Illman (2016)
Sand and gravel	Confined	10.7	Moench method (1985) Butler-Zhan method (2004)	1.34E-03	2.72E-05	Butler and Zhan (2004)
Sand and gravel	Confined	10.5	Inverse numerical model	1.50E-03	7.40E-05	Bohling and Butler (2001)
Sand and gravel	Confined	19.8	Theis method (1935)	6.20E-03	1.98E-04	Pinder and Bredehoeft (1968)
Gravel	Confined	15.55	Fujinawa method (1977)	7.83E-04	9.26E-06	Chen and Jiao (2005)

Table C4: Hydraulic conductivity (K) and specific storage (Ss) values used to calculate the hydraulic diffusivity values for aquifer type 6a (Kuang et al. 2020). Full bibliographic information in Kuang et al. (2020).

Lithology	Aquifer type	Thickness (m)	Method of Data Interpretation	K (m/s)	S_s (m^{-1})	Reference
Granite	Unconfined		Hsieh and Neuman (1985)	2.12E-10	5.06E-07	Illman and Tartakovsky (2006)
Granite	Confined	30	Theis method (1935) Cooper-Jacob method (1946)	2.66E-06	3.19E-05	Lee and Lee (1999)
Granite	Unconfined	18.48	Barker method (1988)	4.00E-05	8.30E-05	Maréchal et al. (2004)
Granite	Confined	24	Rathod-Rushton method (1991)	4.63E-05	1.67E-04	Rathod and Rushton (1991)
Granite	Unconfined	7	Rushton-Holt method (1981)	1.21E-03	1.00E-03	Rushton and Holt (1981)

Table C5: Hydraulic conductivity (K) and specific storage (Ss) values used to calculate the hydraulic diffusivity values for aquifer type 6b (Kuang et al. 2020). Full bibliographic information in Kuang et al. (2020).

Lithology	Aquifer type	Thickness (m)	Method of Data Interpretation	K (m/s)	S_s (m^{-1})	Reference
Fractured igneous and metamorphic	Confined	9	Hemker method (1999)	7.52E-09	3.63E-05	Székely et al. (2015)
Fractured igneous and metamorphic	Confined	168	Cooper-Jacob method (1946)	8.05E-09	1.28E-08	Stober (2011)
Fractured igneous and metamorphic	Confined	150	Cooper-Jacob method (1946)	4.07E-08	3.33E-08	Stober and Bucher (2005)
Fractured igneous and metamorphic	Confined	374	Cooper-Jacob method (1946)	1.06E-07	2.67E-08	Stober and Bucher (2007)
Fractured igneous and metamorphic	Unconfined	20	Maréchal et al. method (2010)	3.10E-06	1.00E-05	Maréchal et al. (2010)
Fractured igneous and metamorphic	Confined	400	Moench method (1984)	1.00E-05	1.50E-06	Moench (1984)

APPENDIX D: SGI HISTOGRAMS FOR THE OKANAGAN BASIN

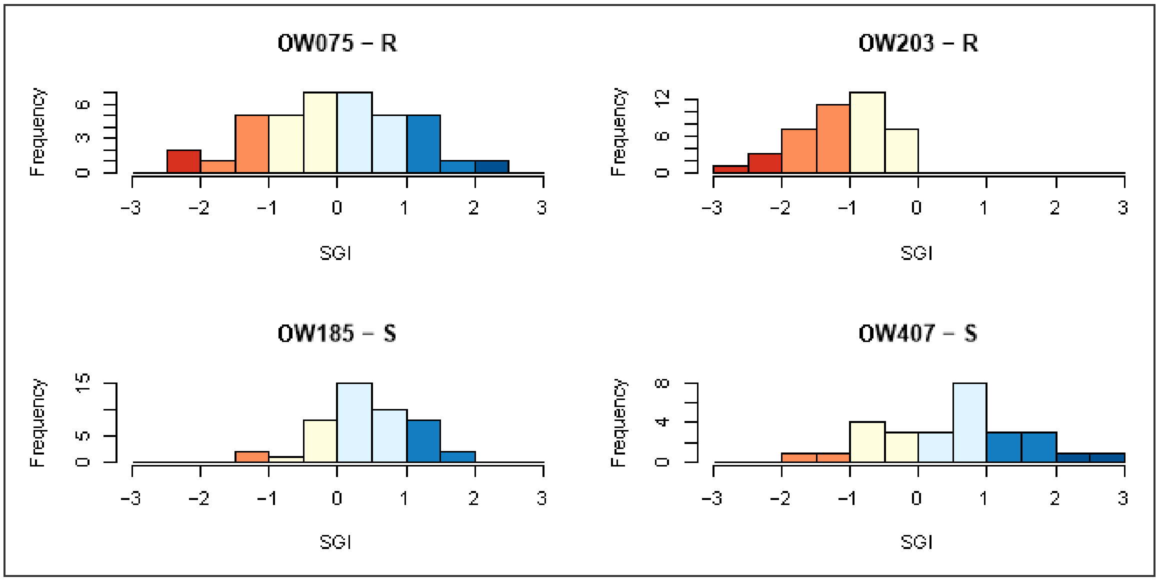


Figure D1: Histogram of SGI values for type 1a aquifers in the Okanagan Basin. The response mechanism is denoted in the plot titles by R (recharge driven), and S (streamflow-driven).

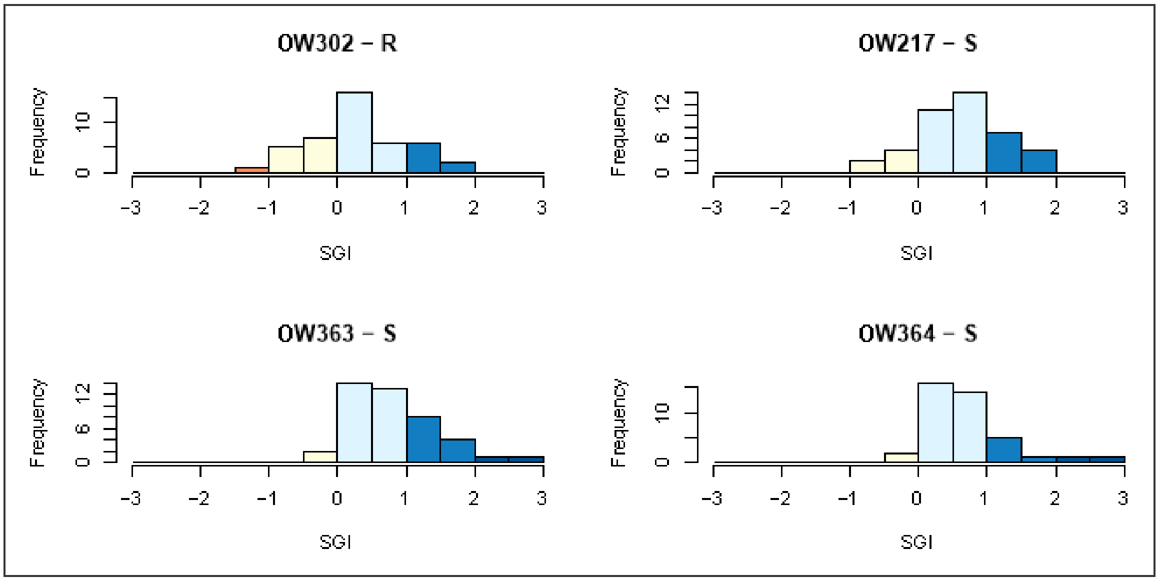


Figure D2: Histogram of SGI values for type 1b aquifers in the Okanagan Basin. The response mechanism is denoted in the plot titles by R (recharge driven), and S (streamflow-driven).

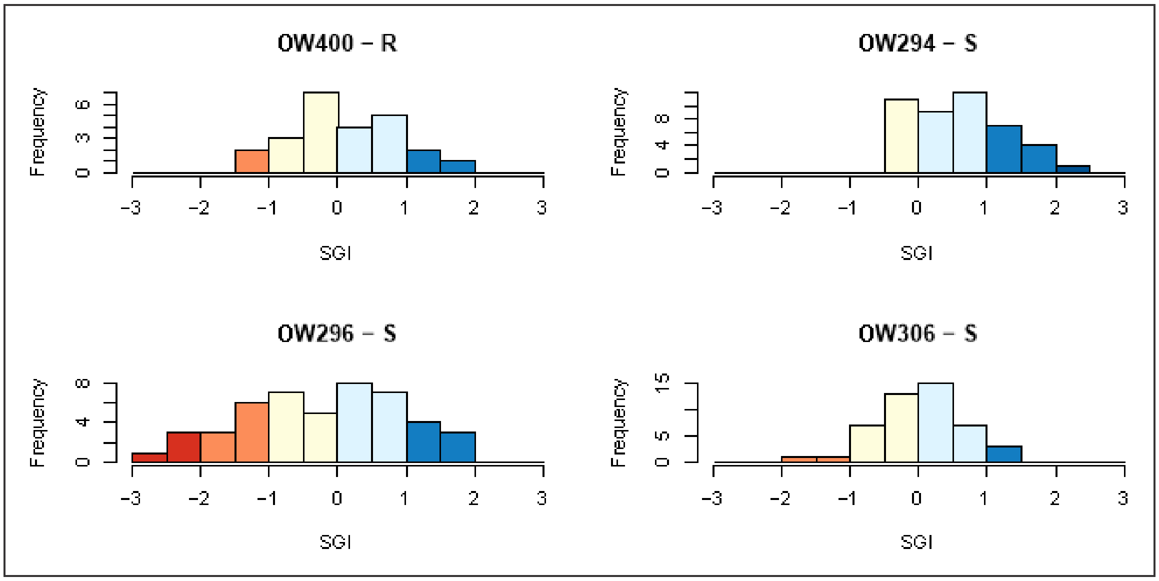


Figure D3: Histogram of SGI values for type 1c aquifers in the Okanagan Basin. The response mechanism is denoted in the plot titles by R (recharge driven), and S (streamflow-driven).

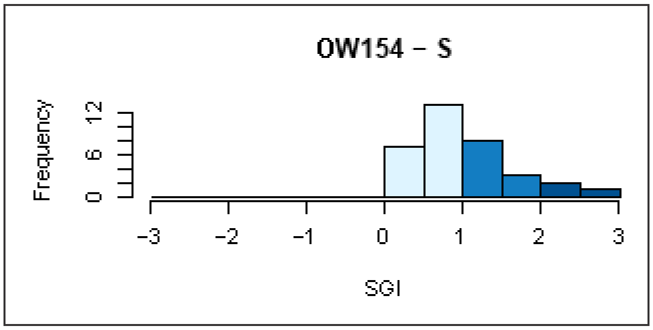


Figure D4: Histogram of SGI values for type 2 aquifers in the Okanagan Basin. The response mechanism is denoted in the plot titles by R (recharge driven), and S (streamflow-driven).

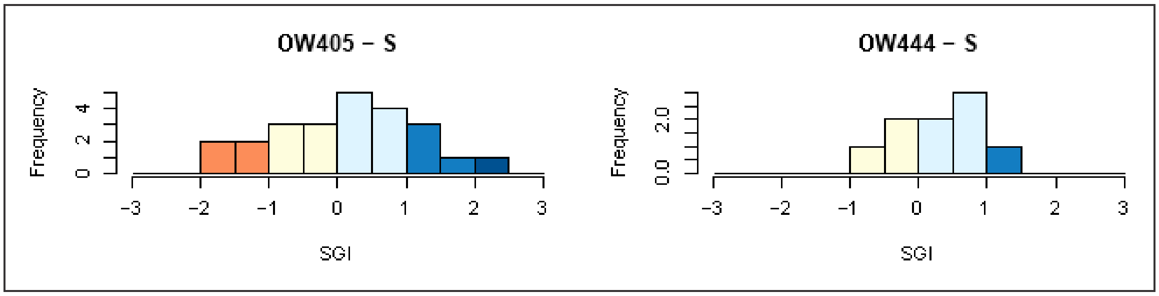


Figure D5: Histogram of SGI values for type 3 aquifers in the Okanagan Basin. The response mechanism is denoted in the plot titles by R (recharge driven), and S (streamflow-driven).

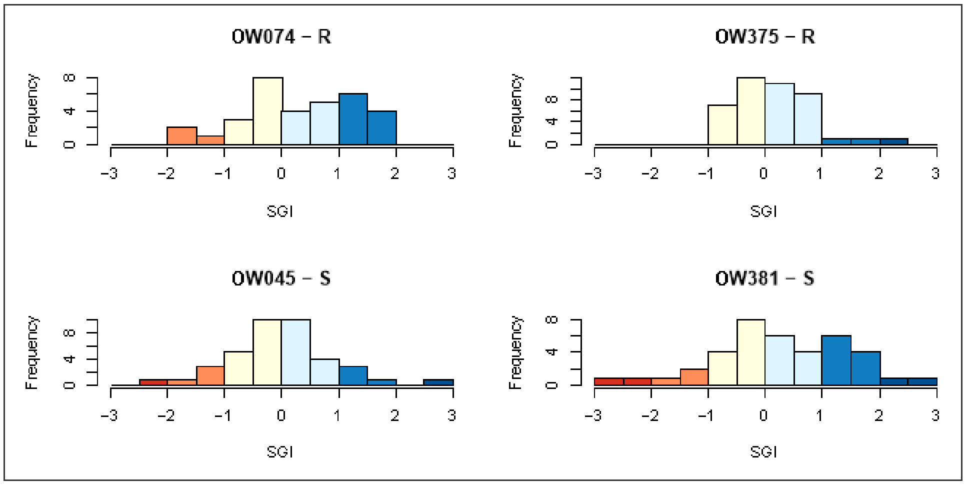


Figure D6: Histogram of SGI values for type 4a aquifers in the Okanagan Basin. The response mechanism is denoted in the plot titles by R (recharge driven), and S (streamflow-driven).

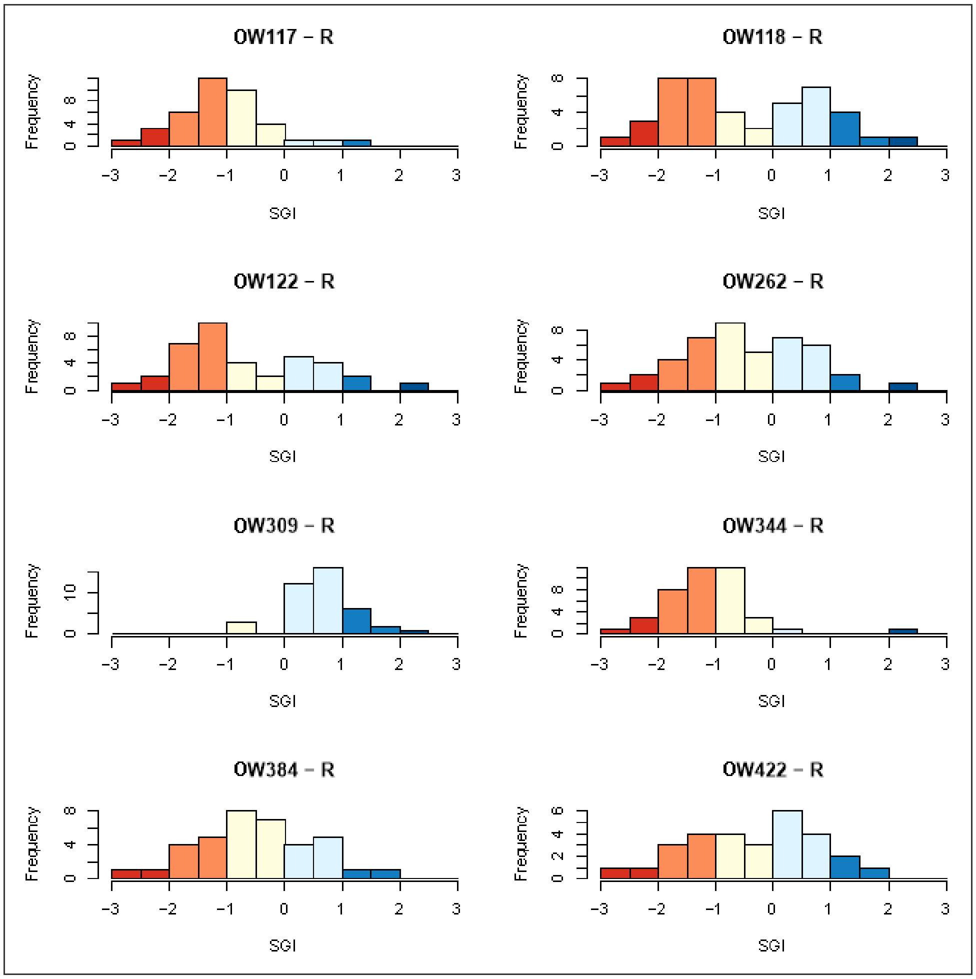


Figure D7: Histogram of SGI values for type 4b aquifers in the Okanagan Basin. The response mechanism is denoted in the plot titles by R (recharge driven), and S (streamflow-driven).

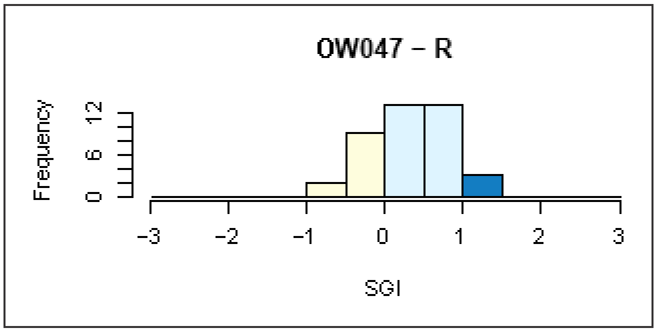


Figure D8: Histogram of SGI values for type 5a aquifers in the Okanagan Basin. The response mechanism is denoted in the plot titles by R (recharge driven), and S (streamflow-driven).

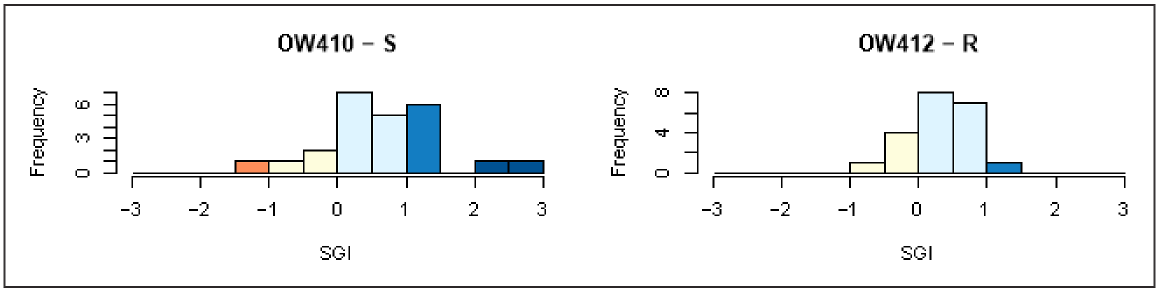


Figure D9: Histogram of SGI values for type 6b aquifers in the Okanagan Basin. The response mechanism is denoted in the plot titles by R (recharge driven), and S (streamflow-driven).