KOKSILAH WATERSHED HYDROLOGICAL ANALYSIS

January 2021

Prepared for:

Cowichan Tribes – Lulumexun Land and Governance

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SUMMARY

The main findings of the Hatfield Consultants LLP (Hatfield) Koksilah Watershed study are summarized below. This is intended as a plain-language summary of the main findings of the technical report to create common understanding, to inform water management decisions and to identify additional studies that are needed to guide the water management solutions for the watershed.

Background

Xwulqw'selu Sto'lo, otherwise known as the Koksilah River is located within the territories of Cowichan Tribes and other First Nations south of Duncan on Vancouver Island. The watershed is important to Cowichan Tribes and other First Nations for cultural and spiritual reasons and the sustenance of livelihood practices. Residents and land users rely on the watershed as a source of drinking water, for irrigation on farms, and recreational opportunities.

Over time it has been noticed that water levels in the Koksilah River were getting lower in the summer than they used to be. To find out why these lower water levels are happening, Cowichan Tribes hired Hatfield to carry out a hydrological study of the Koksilah River. This report provides the findings of that study.

What were we trying to learn?

Hydrology is the science of how water moves through the environment. The way that water moves through a watershed is called the hydrological cycle, illustrated in Figure A. Rivers are an important part of the hydrological cycle. River levels go up and down with the seasons. Water levels are lowest in the summer. We call this *summertime low flow* or just *low flow*. Summertime low flow can be a problem for communities, fish, and wildlife especially if it is lower than normal or is going down over time as has been observed in the Koksilah watershed. Figure A also summarizes the main changes in water movement over time (red text).

Beginning in 2017, biologists for the Ministry of Forests, Lands, Natural Resource Operations & Rural Development (FLNRORD) noticed flows in the river were getting low enough to threaten the survival of fish. An order was issued that temporarily forced certain surface water and groundwater users to stop pumping water from the underlying aquifers or directly from the river to protect the fish. The order was initiated on August 16th, 2019 for approximately one month. The result was a noticeable increase in river flows, but it was clear that a better understanding of the potential reasons of declining summertime low flows was needed to help identify ways to manage the problem. The study Hatfield was asked to do by Cowichan Tribes had four goals:

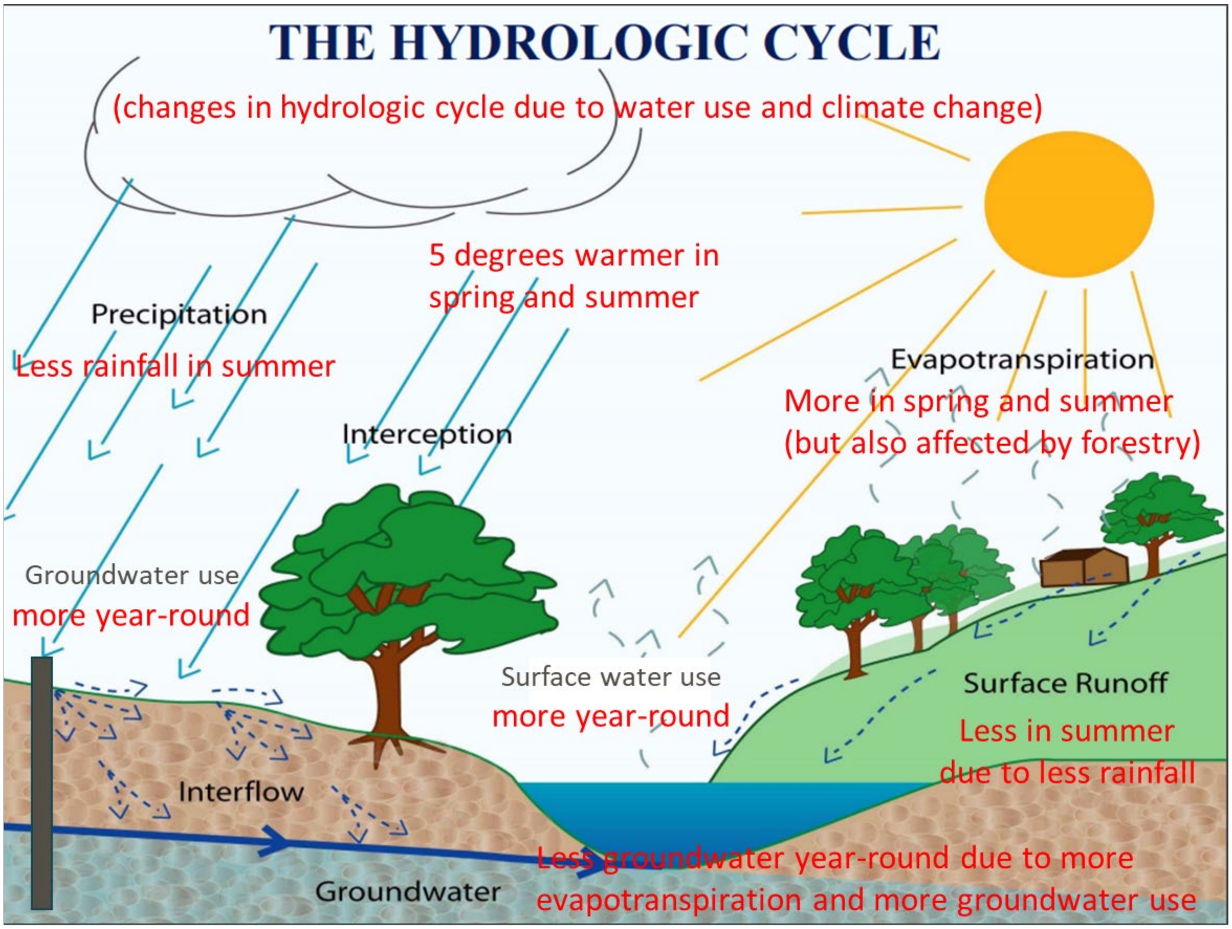
i) Identify the possible causes of low flows in the summer;

ii) Figure out which causes are most important and which causes were less important (that is, what is the relative importance of each of the potential causes);

iii) Identify what other sorts of information we need to understand the problem (that is, knowledge or data gaps); and

iv) Provide recommendations for different steps or actions that might be taken to manage summertime low flows, including recommendations for new or additional studies that might be needed.

Figure A The main causes of declining summertime flows in the Koksilah River.



https://www.epa.gov/sites/production/files/2015-07/documents/lecture-5-hydrologic-processes.pdf

What did we learn?

Cowichan Tribes and FLNRORD identified the following potential causes of declining summertime flows and asked Hatfield to investigate these causes:

- People using water for agriculture (irrigation), drinking water, industry, or other purposes.
- Changes in forest cover due to forestry practices.
- Climate change.
- Changes or impacts on the river channel (called *stream morphology*).
- Other factors.

The results of Hatfield's study tell us that there appear to be two main reasons for the decline in low flows:

- Increased use of both groundwater and surface water; and
- The effects of climate change.

These two main causes appear to be roughly equal in terms of their relative importance. In other words, increasing usage of water and climate change are both to blame for the decline in low flows. As indicated, Figure A also summarizes changes to the hydrological cycle which affect Koksilah River low flows, with these changes explained below.

Increased Water Use

Through our analysis we learned that:

- There has been a large increase in water use in the watershed. Water use now is almost three times as much as it was in the 1960s.
- Surface water use has not increased by much since about 1980, but groundwater use has continued to grow.

Most of the water use is happening in the lower portions of the watershed where most people live and where most agriculture is happening. This is discussed in Section 4.1.3 of the report and shown in Figure 4.12 to Figure 4.15. The large increase in water use over time is discussed in Section 4.2.3 of the report and shown in Figure 4.29. The effects of this growing water use on low flows in the Koksilah River can potentially be addressed through water management actions.

To figure out if increased water use was the only cause of declining low flows we ran a calculation called a *flow naturalization*. Flow naturalization is a calculation we used to estimate how much water flow there would be in a stream or river if people didn't use the water, in other words, how much water would flow in the Koksilah River if there was no human use of surface or groundwater in the watershed. The flow naturalization calculations are discussed in Section 4.2.6 of the report (Figure 4.33 and Figure 4.34).

Based on our flow naturalization calculations, we found that human use of water causes some but not all of the lower water levels in the river that have happened since the 1960s. What this means is that some of the decline is due other causes. We suspected that climate change or change in forest cover (due to forestry) could explain the rest of the lower summertime flows and looked at this further.

Climate Change

Looking at the historical weather records for nearby Shawnigan Lake, we learned that there are two climate change effects happening:

i) Spring and summer have been getting up to 5 degrees warmer since the 1960s. This is illustrated in Figure 4.17 of the report. Warmer temperatures cause trees and plants to use more water for growth and nutrition through a process called evapotranspiration. More evapotranspiration means more of the rainfall falling on the watershed is lost back to the atmosphere and less water arrives in the Koksilah River as runoff and groundwater flow (Figure A).

ii) It rains less in the summer (June, July and August) than it did in the 1960s. This is illustrated in Figure 4.18 of the report. The drier summers lead to less runoff and smaller low flows in the river (Figure A).

Of these two climate change effects, the effect of more evapotranspiration on groundwater is most important. Groundwater is very important for Koksilah River summertime flows. Runoff is not as important as groundwater for these summertime flows. The importance of groundwater for low flows is illustrated in Figure 4.22 of the report.

The challenge of these climate change impacts on Koksilah River water levels is that they cannot be directly controlled through local water management measures. These climate change effects are likely to get worse into the future. We also learned that understanding these effects from climate change since the 1960s is made more difficult because of forestry activities happening over the same time period.

Forest Cover Change (Forestry)

We found that forest cover changes related to historical forestry activity in the watershed were also important. We learned that:

- The lower water levels due to climate change that have happened in the past could likely have been even worse if there had been no forestry activities. This is illustrated in Figure 4.35 of the report and discussed in Section 4.2.7.
- The effects from historical forestry on Koksilah River flows may have been strongest in the 1980s and 1990s following a period of intense logging in the watershed when there were a lot of (former) clearcuts with only very young trees. These very young trees (less than 10-20 years old) and areas without trees use less water (less evapotranspiration) relative to the mature trees (100 years old or more) that were removed by logging. This lower water loss to the atmosphere (less evapotranspiration) in clearcuts may have partially offset the effect from increased water demand and climate change on summertime flows in the river during the 1980s and 1990s.
- The effects from historical forestry on summertime flows in the Koksilah River may have become less important in recent decades as trees in former clearcuts have grown and as logging activity is less intense and focused on second growth forests. Due to the current mix of younger and older trees in the watershed, the net effect of forestry activities on flows in the Koksilah River is estimated to be very small now.
- In the future, as trees in the watershed are in active growth, it is possible that moderate age trees (40-50 years old) become dominant in the watershed. Moderate aged trees use more water than mature trees (100 years old or more) and more water than very young trees (10-20 years old). If moderate trees become dominant, this could reduce water availability in the watershed and decrease the flows in the river. This evidence provided by scientific researchers on water use by trees of different ages is discussed in Section 3.3.7 of the report.

It has now been about 40-50 years since the period of intense logging, which indicates that there could be future risk of water shortage from forest management that happened in the past. Forest management has also been linked to other concerns such as greater winter runoff, channel aggradation (which is excess sediment deposition in the stream and can result in what was surface water instead flowing through gravels leading to less surface water depth), sediment erosion and turbidity in the river. How forests in the watershed are managed is therefore an important factor when considering how to manage low flows and maintain enough water for fish habitats in the river.

What do we not know yet?

We need to better understand how much water fish need to survive and to reproduce. To do this we need to understand how much water these fish need during different times of year and in different parts of the river. An *Environmental Flow Needs* (EFN) study would help to answer many of these questions.

We do not yet know what other physical changes may have occurred to the river channel (called *channel morphology*) in the past or how water quality may have been affected by sediment or pollutants. Stormwater outfalls, culverts, sedimentation from forestry activities and road building, use, and maintenance, and other potential factors such as water pollution can all affect the wellbeing of fish. These changes can be studied through a *habitat assessment* along different parts of the Koksilah River. A habitat assessment is often done together with an EFN study.

We do not yet know how climate change and forestry may affect summertime flows in the future. Potential effects from climate change and forestry scenarios (i.e., "what if" scenarios, discussed in more detail in Section 5.5 of report) could be studied through a *water balance model*. The water balance model could be used to look at what would happen if there was:

- No change in water use but climate change continues to get worse.
- Land use change (forestry) making the low flow problem either better or worse or having only a very small effect.
- A situation in which there is more water use in future than is happening now.
- A combined situation in which climate change continues to get worse, water use continues to increase and forest management also makes low flows worse.
- A best situation for low flows considering factors that can be controlled or mitigated by regulation or management practices.

We do not know exactly how much water different types of trees and trees of different ages use and how it compares to water use by other plants such as irrigated crops grown by farmers. To some degree a water balance model can help bring more certainty to these questions, but this is also something that the scientific community needs to work on by studying evapotranspiration (water use by trees and plants) for forest stands of different ages and characteristics (i.e., types of trees, height and size of trees, etc.).

We did learn that the effect of human water use in the lower portion of the watershed where most people live is more important that water use higher up in the watershed (Section 5.3 of report and Figure 5.1). But we do not yet know the relative importance of water use within smaller sub-areas (Kelvin Creek, Glenora Creek, Patrolas Creek and Koksilah River itself). This can be looked at further with a water balance model or *groundwater model* and by better flow monitoring of the different creeks and streams in the watershed. A water balance model may be better for looking at things like climate and evapotranspiration while a groundwater model may be better to look at things like how groundwater use affects low flows. Additional monitoring of different creeks will also help inform the water management plans and will help with building the models. The use of a water balance model would also be assisted with better knowledge of the amount of precipitation (rain and snow) that falls in the higher elevation portions of the watershed. Now this is only measured at nearby Shawnigan lake at lower elevation.

Recommendations

Based on our study, Hatfield recommends the following:

- Create plans to address key issues affecting water availability:
    - Water Sustainability Plan – to address challenges related to water use.
    - Forest Management Plan – to address risks related forest cover changes on water availability.
- Studies that can be done by the community (Cowichan Tribes and FLNRO):
    - Environmental Flow Needs study (how much water do fish need).
    - Determine changes or impacts on the river channel (habitat and stream morphology assessments).
    - Build a water balance model and/or groundwater model – to help predict/plan future conditions in the watershed. For example, “what if” scenarios to help with planning.
    - Additional monitoring of water levels in different parts of the watershed (Kelvin Creek, Glenora Creek, Patrolas Creek) – to help with planning and to help with building the models.
- Studies that could be done by the scientific community:
    - Studying evapotranspiration (water use by trees and plants) for forest stands of different ages and characteristics (i.e., types of trees, height and size of trees, etc.).
    - Measuring precipitation (rain and snow) at higher elevations in the watershed.

DISTRIBUTION LIST

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Jessica Doyle	Ministry of Forests, Lands, Natural Resource Operations & Rural Development	-	✓	✓
Tracy Fleming	Cowichan Tribes	-	✓	✓

AMENDMENT RECORD

This report has been issued and amended as follows:

Issue	Description	Date	Approved by	
1	First version of Koksilah Watershed Hydrological Analysis	20201120	Tim Bennett, PEng Project Director	Jos Beckers, PhD, PGeo Project Manager
2	Second version of Koksilah Watershed Hydrological Analysis	20210120		
			Tim Bennett, MSc, PEng Project Director	Jos Beckers, PhD, PGeo Project Manager

1.0 INTRODUCTION

The Koksilah River, Xwulqw'selu Sto'lo, watershed (the watershed) is located south of Duncan on Vancouver Island and is within the traditional territories of Cowichan Tribes and other First Nations in the area. In recent years, the river has been subject to extremely low summer flows that threaten to endanger several fish species including steelhead and anadromous salmonids (Pritchard et al. 2019). These fish populations are culturally and economically important for local First Nations. The watershed is valued by all residents, resource users and visitors to the watershed, as a primary drinking water source, for supporting agricultural lands and the spiritual connection and recreational opportunities that the area offers (MODUS 2020). Low summer flows are particularly concerning for farmers in the area that rely on surface and groundwater extraction for irrigation during the growing season (MODUS 2020).

The watershed has seen a significant increase in water demand over time. Water sustainability issues have been noted in the watershed dating back as far as the 1980s because of increased surface water demand through the 1970s and a shift towards groundwater use between the 1970s-1990s (Pritchard et al. 2019). However, there are several other factors in addition to water demand changes that may have played a role in the observed decline in summertime flows. These include land-use change, climate change and stream morphology changes and/or other factors. Land use changes in the watershed include historical and current forestry activities, increased residential (urban) development and agricultural land conversion in the downstream portions of the watershed. MODUS (2020), in seeking stakeholder input on long-term water sustainability, identified the following observed changes and key concerns in the watershed related to summertime flow and aquatic habitat:

- It was generally agreed that flow rates and water levels in the summer are lower than in years previous. Some describe swimming holes that are no longer there, and wells that are drying up.
- Some have noticed that ambient water temperatures have increased over the years.
- Rainfall incidences were observed to now happen more sporadically but with more rain. Furthermore, some have observed less snowfall than in the past.
- The more intense rainfall events are thought to have resulted in greater sediment build up in lower areas of the watershed.
- More wells are being drilled, likely a result of more, and larger farms, and more residences in the middle and lower areas of the watershed. Nowadays, agricultural operations in the watershed are much larger in scale and are engaged in farming activities that require much more intensive water use. There was also a general sense that increased residential and industrial development in the lower parts of the watershed has increased over the past decade.
- Forestry operations, and in particular the practice of clearcutting was a source of concern for many of the participants. Stakeholders indicated that surface water was flowing in abundance into waterways in the winter and evaporating quickly in the summer, leading to lack of groundwater recharge. The lack of tree cover is also believed to result in the snowpack melting quicker, contributing to greater runoff into the river.

- Several stakeholders noted that clear cutting activity is likely contributing to increased turbidity in the water as there was greater erosion due to lack of root systems and increased water flow down the mountainside.
- Interviewees were concerned with the water quality in the river. Several discussed coliform contamination in the river and expressed concern over issues with management of manure by farms. Algal blooms have also been an issue, a phenomenon attributed to the release of phosphorus.

Some of these concerns echo historical disturbances documented for the nearby Cowichan River (Pike et al. 2017) although there are key differences between the watersheds (e.g., lack of a large lake or weir control on flows in Koksilah watershed). Concerns around extremely low summertime flows for the Koksilah River were elevated in 2019 following a review by Ministry of Forests, Lands, Natural Resource Operations & Rural Development (FLNRORD) biologists. That review identified that flows in the watershed were low enough to threaten the survival of Coho and Steelhead fry in the river (Barroso and Wainwright, in press). As a result, a Ministerial Order to cease using water was issued to specific water users (both surface and groundwater licensees and unlicensed groundwater users) to protect fish populations. The order was issued on August 16th, 2019 and repealed on September 18th, 2019 when river flows increased. While this temporary water use curtailment was successful (Northwest Hydraulics Consultants; NHC 2020), it was considered a short-term solution that was implemented to address the imminent threat to fish populations.

A better understanding of all potential factors affecting summertime low flows is required to provide a common understanding of the water sustainability problem. As part of seeking a long-term solution, Cowichan Tribes and FLNRORD have entered a Government-to-Government agreement to work together in partnership to ensure long-term water sustainability in the watershed. This includes scoping a Water Sustainability Plan under the *Water Sustainability Act*. A Water Sustainability Plan may provide a new framework to improve the management of water and land use in the watershed.

1.1 STUDY OBJECTIVES AND SCOPE OF WORK

The purpose of this report is to investigate and document the potential environmental and anthropogenic factors that may be responsible for the observed decline in summertime flows. Cowichan Tribes, in partnership with FLNRORD, will use this information to identify which tools under the *Water Sustainability Act*, including a Water Sustainability Plan, could be appropriate to mitigate and or restore summertime flows in the watershed. The work also represents a critical component for scoping a Water Sustainability Plan for the watershed.

The specific objectives of this hydrological watershed assessment were to:

- Conduct a literature review of previous studies and work done in the watershed including but not limited: to the ecosystem review (Pritchard et al. 2019), the water use and curtailment preliminary analysis (Barroso and Wainwright, in press), the Koksilah regulatory response to low flows effectiveness analysis (Northwest Hydraulic Consultants 2020), a surface water and groundwater interaction study (Sivak and Wei 2019), and other relevant literature (e.g., forestry effects on watershed function).
- Compile and review available data for the watershed including but not limited to:

  - Historical surface flow and water elevations.
  - Groundwater level elevations.
  - Water consumption from surface and groundwater.
  - Climate data including historical climate change, precipitation, and temperature records.
  - Land-use changes.
  - Physical data including physiography, soil conditions, geology (including karst deposits), stream morphology (historic and change over time) and vegetation.
  - Available data and reports on fish populations, habitat, and critical ecosystems functions.
- Conduct hydrological analysis of the watershed (i.e., baseline hydrologic characterization).
- Review historical flow patterns and observed changes (i.e., hydrological change analysis).
- Assess natural and biological features of the basin that impact the hydrological response.
- Identify potential causes of summertime low flows in the watershed (e.g., surface water and groundwater use, change in successional forest growth due to forestry activities (i.e., forest cover change, climate change and stream morphology changes, others).
- Determine the relative magnitude and sensitivity of these factors impacting low flows.
- Identify key data gaps required to determine or improve the understanding and quantify magnitude of contributing factors affecting low flows.
- Provide recommendations of how to address data gaps (e.g., monitoring plan).

1.2 REPORT ORGANIZATION

This report is organized as follows:

- Section 2.0 provides a description of the existing watershed setting (i.e., topography and drainage, climate, geology, land use, etc.) based on the collated data and literature.
- Section 3.0 describes data and methods used for the baseline hydrologic characterization, hydrological change analysis and environmental flow needs (EFN) assessment.
- Section 4.0 describes results from the baseline hydrologic characterization and hydrological change analysis.
- Section 5.0 discusses potential causes of summertime low flows in the watershed and their relative importance.
- Section 6.0 identifies key data and knowledge gaps and provides recommendations to address these gaps.

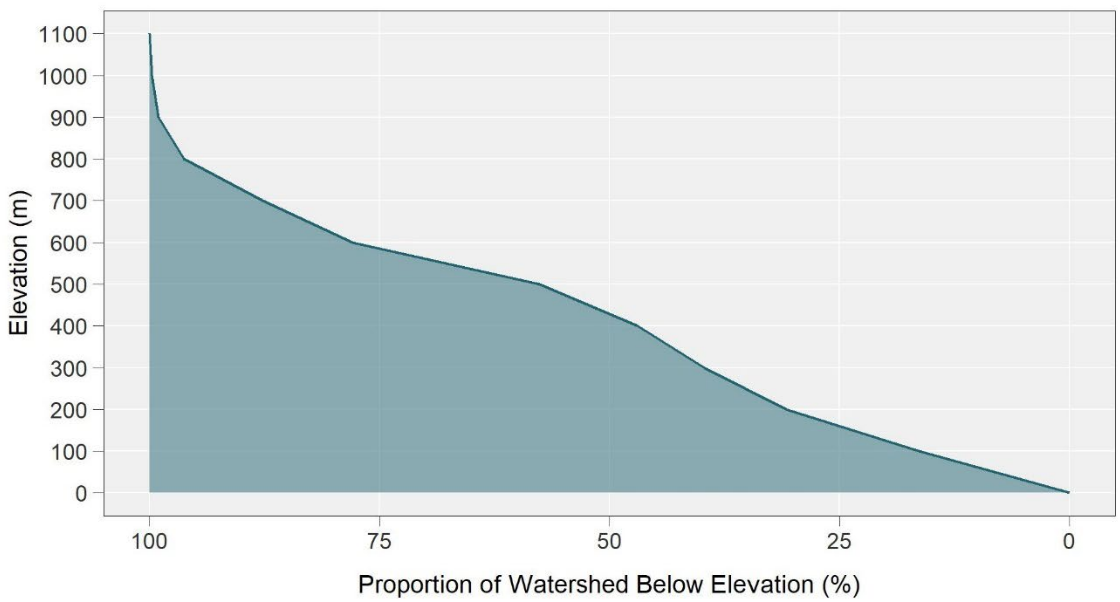
2.0 SETTING

2.1 TOPOGRAPHY AND DRAINAGE

The Koksilah River watershed is located on Vancouver Island south of the City of Duncan and falls within the traditional territory of the Cowichan Nation. The Koksilah watershed is located primarily in the Cowichan Valley Regional District (CVRD). The river connects to the tidal reach of the south arm of the Cowichan River before it drains into Cowichan Bay. The overall watershed drainage area is 311 km^2. Figure 2.1 shows the distribution of elevations within the watershed, with 95% of the watershed below 800 m in elevation and 50% below 450 m. The 500-600 m elevation band occupies a relatively large proportion of the watershed (20%). Elevations in the watershed range from sea level to the highest point, Waterloo Mountain, at 1070 metres above sea level (masl) in the headwaters of the watershed (Figure 2.2).

Koksilah River is the main watercourse, with Glenora Creek, Kelvin Creek, Patrolas Creek, Wild Deer Creek and Fellows Creek being the main tributaries. There are four lakes in the watershed, Dougan, Keating, Wild Deer and Grant, that occur in the headwaters of the sub-watersheds. In addition, several wetland areas are found along Kelvin Creek and dotted throughout the mid and upper watershed (NHC 2020 and references therein).

Figure 2.1 Hypsometric curve for the Koksilah Watershed.



Note: Data from ClimateBC using a grid with a resolution of 250 m x 250 m.

2.2 LAND USE

Approximately 85% of the watershed is mapped as logged or forested land-use (Figure 2.3). The downstream 17 km river reach flows almost entirely through agricultural lands, which make up 14% of the land use in the watershed (Pritchard et al. 2019). Urban development also occurs primarily in the lower elevations of the watershed and equates to about 1% of the overall watershed area.

2.3 CLIMATE

Climate conditions of the watershed are typical of the Pacific Northwest. Mean annual temperature at the Shawnigan Lake Climate Station is approximately 10°C, with minimum temperatures typically occurring in late December and maximum temperatures in early August.

The watershed is rain-dominated with a wide range in annual precipitation over its area. The portion of the watershed above about 300 m is in the mixed rain-snow regime. The headwaters can receive more than twice the annual average amount of precipitation compared to the mouth (NHC 2020).

2.4 HYDROLOGY

As a mostly rain-dominated watershed, Koksilah River flows are highest during the winter wet season, start declining during the spring season and are lowest towards the end of summer (August) before rising again with increased precipitation in the fall. Because the Koksilah River does not have a large lake or any significant water storage, summer flows are very low, and the river is highly responsive to rainfall inputs. Groundwater flows are also important inputs to the Koksilah River (NHC 2020).

The Water Survey of Canada (WSC) monitors the Koksilah River at Cowichan Station (ID. 08HA003), immediately downstream of the confluence of Patrolas Creek (Figure 2.4). This station contains the longest record for the watershed, making it the primary data source for characterizing long term patterns in Koksilah River flows. Because the WSC gauge provides the point of reference for the hydrological baseline characterization and for the hydrological change analysis, the watershed was separated into two areas for the purposes of this study:

- Upstream watershed: that portion of the watershed upstream of WSC gauge 08HA003, totalling 228 km^2 in area. This portion of the watershed includes Patrolas Creek, Wild Deer Creek and Fellows Creek.
- Downstream watershed: that portion of the watershed downstream of WSC gauge 08HA003, totalling 83 km^2 in area. This portion of the watershed includes Glenora Creek and Kelvin Creek.

The 2019 water use curtailment (NHC 2020) was predominantly focused on a short section of the Koksilah River immediately upgradient of the long-term WSC gauge, the portion of Patrolas Creek to Dougan Lake, and the reach of Koksilah River between the WSC gauge and the FLNRORD gauge (08HA0022; Figure 2.4) that was installed to monitor low flows in the river. The 2019 temporary curtailment area therefore straddles the boundary of the upstream and downstream portions of the Koksilah watershed.

2.5 SURFICIAL AND BEDROCK GEOLOGY

Surficial mapping in the Koksilah watershed area shows fluvial and glaciofluvial sediments along Koksilah River, marine and glaciomarine sediments closer to the Cowichan Bay shoreline, and thin colluvial and till sediments at higher elevations (Figure 2.5). The surficial geology is described in detail by Blyth et al. (1993a and 1993b); Halstead (1965) and Hammond et al. (2019).

The bedrock geology can be grouped into sedimentary, volcanic and intrusive rocks (Figure 2.6). The lower watershed is primarily underlain by sedimentary rocks of the Upper Cretaceous Nanaimo Group. The upper watershed is primarily made up of volcanic rocks from the Wrangellian Terrace. The terrace is made up of the Sicker, Buttle Lake, Vancouver, and Bonanza Groups. The Mount Mark Formation of the Buttle Lake Group is found in several locations throughout the watershed and is comprised of limestone deposits. This limestone has the potential for karst formation, although detailed mapping of the karst has not been completed, and the relationship to the Koksilah River has not been assessed. These potential karst areas are shown on Figure 2.6. Finally, Island Plutonic Suite and Westcoast Crystalline Complex intrusive rocks are found in the lower and upper watersheds, respectively. The Island Plutonic Suite, comprising granodiorite, quartz, feldspar and feldspar porphyry, represent the youngest rocks in the watershed.

2.6 MAPPED AQUIFERS

As of 2019, there are a total of eight (8) aquifers which intersect the watershed. Six (6) are identified as sand and gravel aquifers, with remaining two (2) being bedrock aquifers (Figure 2.7 and Figure 2.8). There is limited groundwater use in the western portion of the watershed, and therefore, no mapped aquifers west of Wild Deer Creek. Table 2.1 provides a summary of the mapped aquifers in watershed describing their type, documented stratigraphic units and size.

Table 2.1 Mapped aquifers in the watershed.

Aquifer Number	Aquifer Type	Stratigraphic Unit	Size (km^2)
185	Confined sand and gravel	Vashon Drift	8
186	Unconfined sand and gravel	Salish Sediments	17
188	Confined sand and gravel	Vashon Drift	9
197	Confined sand and gravel	Quadra Sand/ Dashwood Drift	49
198	Bedrock	Nanaimo Series	105
199	Confined sand and gravel	Quadra Sand/ Dashwood Drift	28
201	Unconfined sand and gravel	Quadra Sand/ Dashwood Drift	2
202	Bedrock	Bonanza Group and Sicker Volcanics	40

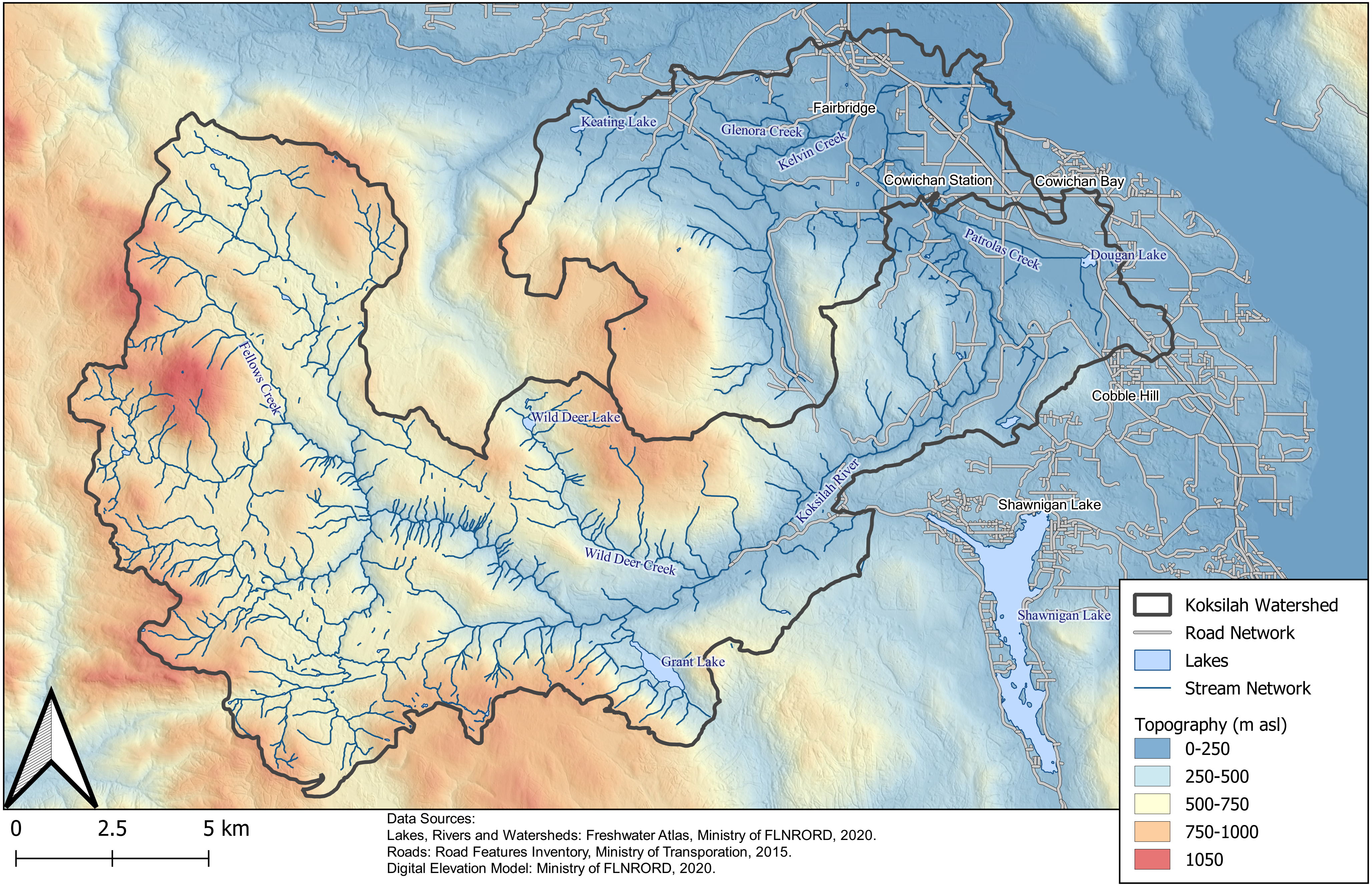
2.7 WATER USE

The Koksilah River runs through agricultural lands where many users extract surface and groundwater for irrigation and/or domestic purposes.

There are reportedly 129 surface water licenses in the Koksilah watershed of which 121 were used in this study (Figure 2.4), the remaining licenses could not be georeferenced and were not used.

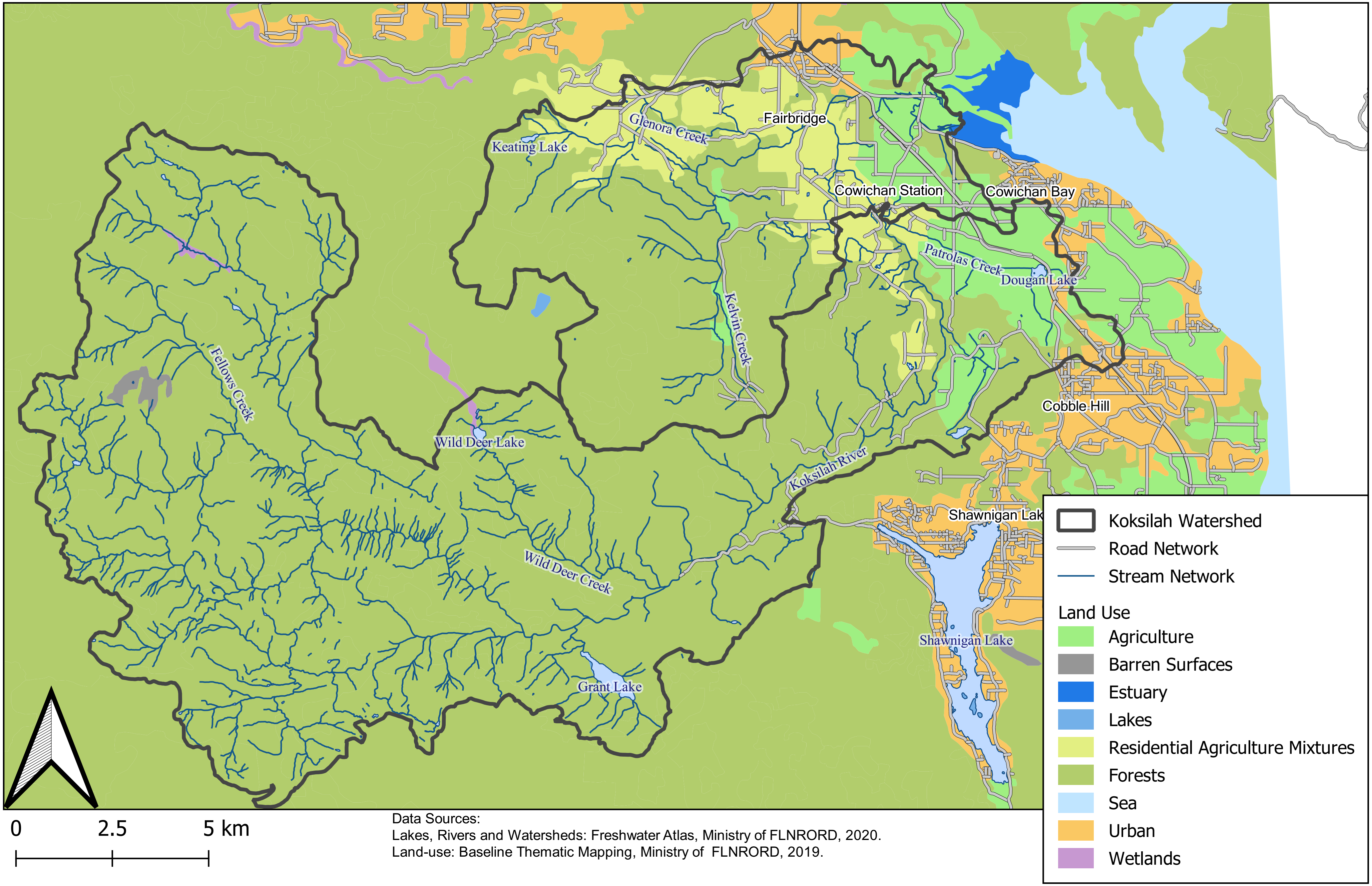
There are over 1,300 documented (registered) groundwater wells in the Koksilah watershed. A total of 1,187 wells had sufficient information to be classified into unconfined and confined unconsolidated sediments, and crystalline or fractured sedimentary bedrock by Sivak and Wei (2019). This dataset was used in this study to categorize the water use by aquifer type. The majority of the wells have been drilled in unconsolidated aquifer materials, making up 44% of the wells (shown in Figure 2.7), and 30% of all wells are drilled in bedrock, mostly screened in sedimentary bedrock (shown in Figure 2.8), the remaining wells are unclassified (no lithology information).

Figure 2.2 Topography and drainage.



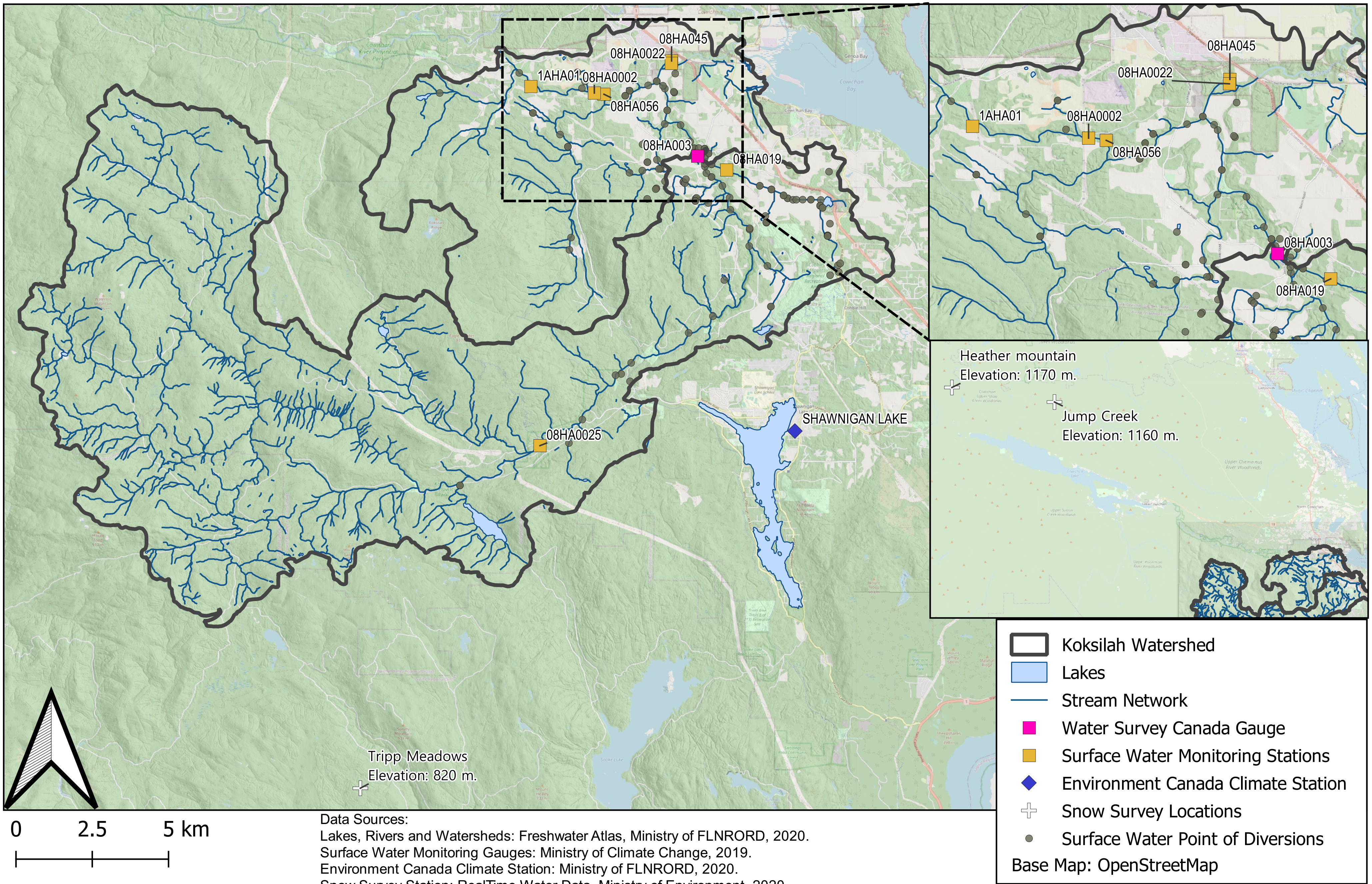
Data Sources:
Lakes, Rivers and Watersheds: Freshwater Atlas, Ministry of FLNRORD, 2020.
Roads: Road Features Inventory, Ministry of Transporation, 2015.
Digital Elevation Model: Ministry of FLNRORD, 2020.

Figure 2.3 **Existing land use.**



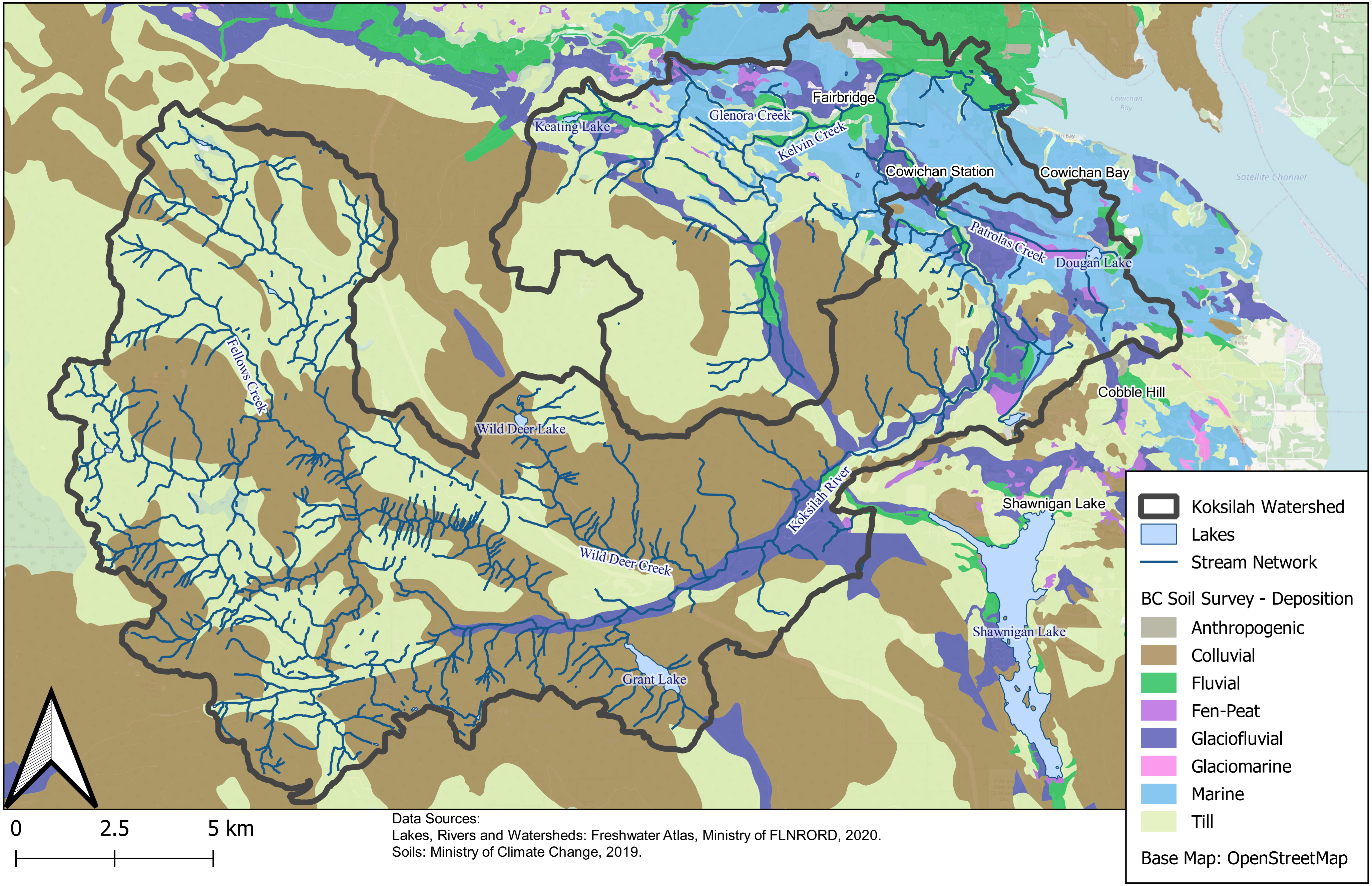
Data Sources:
Lakes, Rivers and Watersheds: Freshwater Atlas, Ministry of FLNRORD, 2020.
Land-use: Baseline Thematic Mapping, Ministry of FLNRORD, 2019.

Figure 2.4 Surface water licenses together with climate and hydrological monitoring locations.



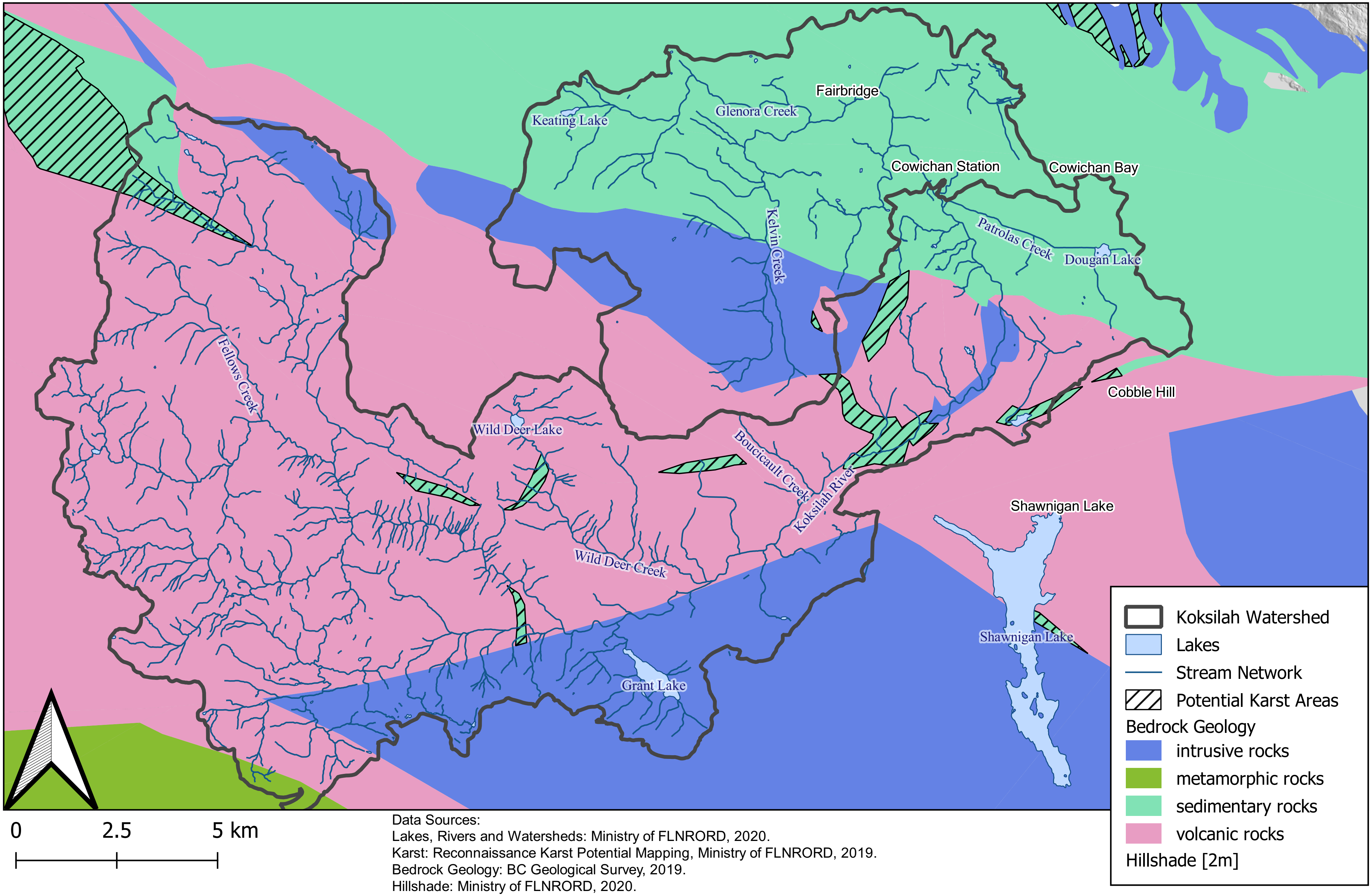
Data Sources:
Lakes, Rivers and Watersheds: Freshwater Atlas, Ministry of FLNRORD, 2020.
Surface Water Monitoring Gauges: Ministry of Climate Change, 2019.
Environment Canada Climate Station: Ministry of FLNRORD, 2020.
Snow Survey Station: RealTime Water Data, Ministry of Environment, 2020.
Surface Water PODs: Ministry of FLNRORD,

Figure 2.5 Soil and surficial geology mapping.



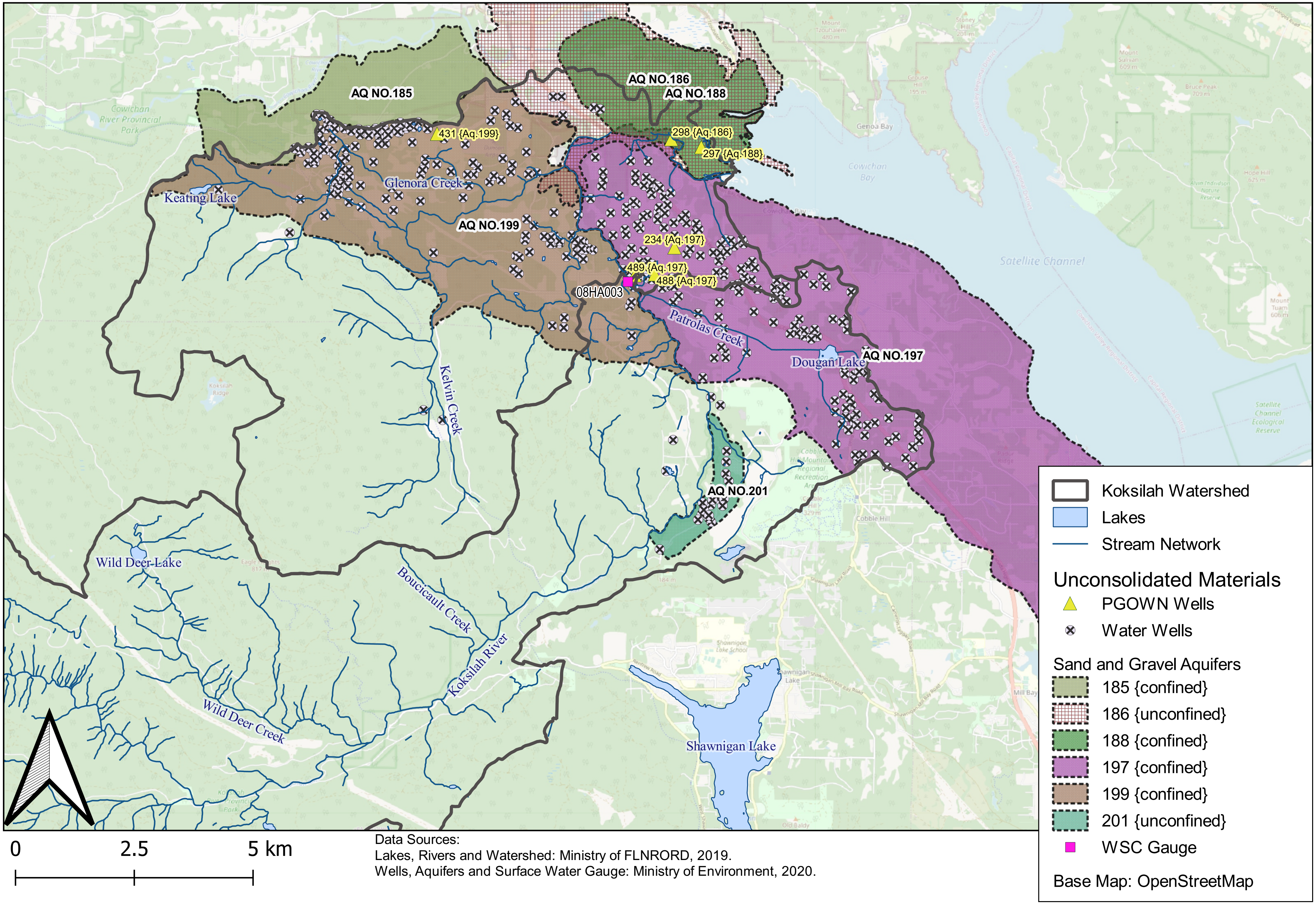
Data Sources:
Lakes, Rivers and Watersheds: Freshwater Atlas, Ministry of FLNRORD, 2020.
Soils: Ministry of Climate Change, 2019.

Figure 2.6 Bedrock geology and karst occurrence.



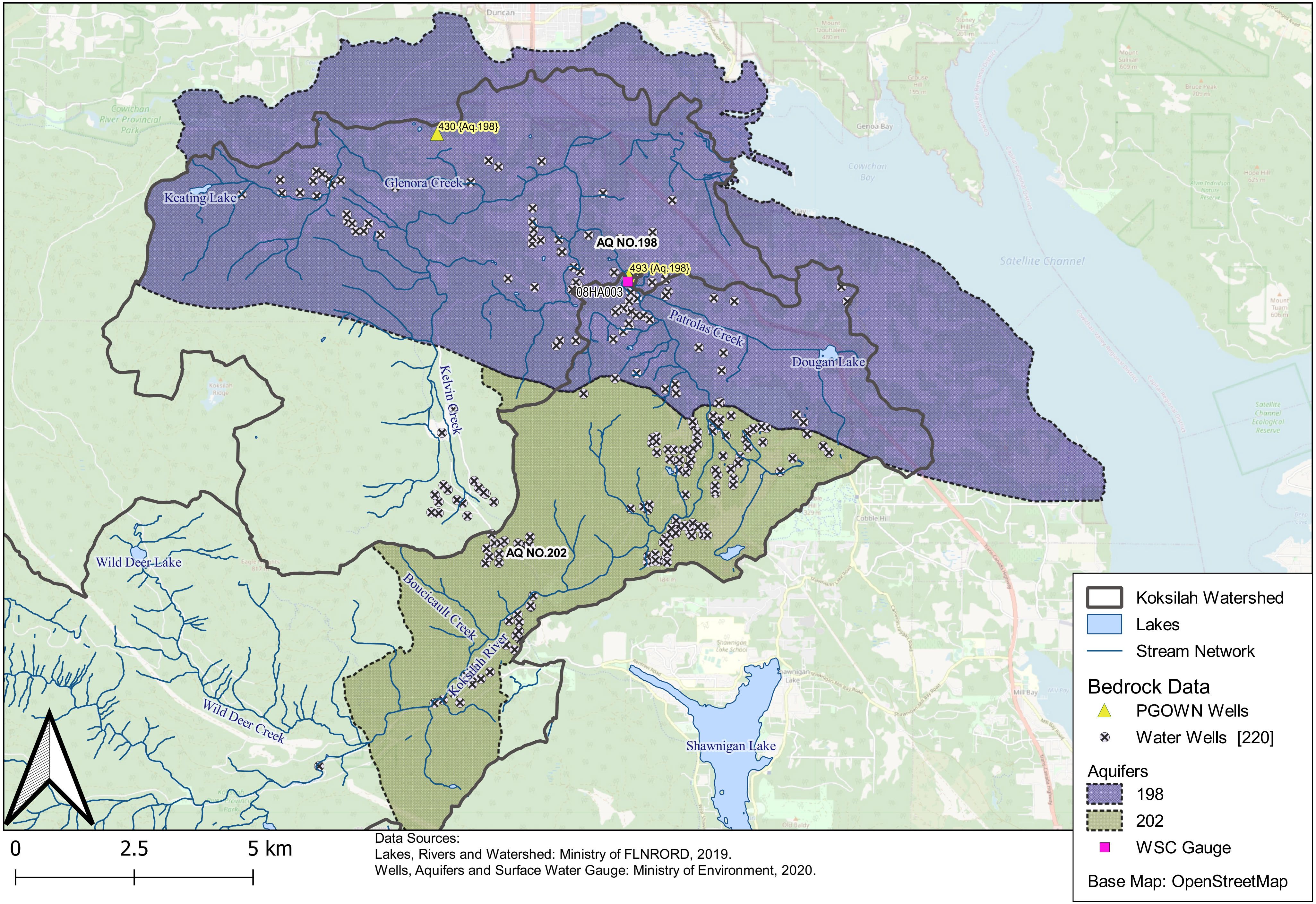
Data Sources:
Lakes, Rivers and Watersheds: Ministry of FLNRORD, 2020.
Karst: Reconnaissance Karst Potential Mapping, Ministry of FLNRORD, 2019.
Bedrock Geology: BC Geological Survey, 2019.
Hillshade: Ministry of FLNRORD, 2020.

Figure 2.7 Mapped sand and gravel aquifers, registered water wells and provincial groundwater observation wells.



Data Sources:
Lakes, Rivers and Watershed: Ministry of FLNRORD, 2019.
Wells, Aquifers and Surface Water Gauge: Ministry of Environment, 2020.

Figure 2.8 Mapped bedrock aquifers, registered water wells and provincial groundwater observation wells.



Data Sources:
Lakes, Rivers and Watershed: Ministry of FLNRORD, 2019.
Wells, Aquifers and Surface Water Gauge: Ministry of Environment, 2020.

3.0 DATA AND METHODS

3.1 SPATIAL AND TEMPORAL EXTENT OF THE ANALYSES

WSC station 08HA003, located immediately downgradient of the confluence with Patrolas Creek (Figure 2.4), contains the longest hydrological data record for the watershed, making it the primary data source for this study. Most of the analyses and interpretations (Sections 4.0 and 5.0) therefore focus on the upstream watershed except where noted. Section 5.3 does provide discussion of additional hydrological change in the downstream watershed as this is where greatest water demand occurs.

Generally, all annual climate and hydrological analyses were conducted using a water year (WY) time frame (i.e., between October to September of the following year), except where noted below. A water year is a term commonly used in hydrology to describe a period of 12 months for which precipitation totals are measured. Its beginning differs from the calendar year because part of the precipitation that falls in late autumn and winter accumulates as snow and does not drain until the following spring or summer's snowmelt.

While the WSC gauge has been active since 1914, flows were not consistently recorded at the station until 1960. Consistent and comprehensive climate data also only exists since 1961, but there is missing data for part of October 1961. Based on these considerations, the reference period for most analyses is WY 1962-2019 (specific analysis periods may vary slightly due to data considerations and are noted below).

3.2 BASELINE CHARACTERIZATION

3.2.1 Climate

Climate data were compiled from the following sources to capture the baseline variability in precipitation, snowpack, temperature and evapotranspiration across the Koksilah watershed:

- Environment and Climate Change Canada (ECCC) Shawinigan Lake weather station (1961-2019).
- ClimateBC gridded climate datasets (1961-2019).
- Tripp Meadows historic snow survey station (1957-1987).

The Shawnigan Lake weather station contains the longest direct record of precipitation and temperature just outside the Koksilah watershed (Figure 2.4). The station is located at an elevation of 159 masl, and it is assumed that observations from the station are representative of conditions in lower elevation areas of the watershed. However, data from the station may not provide an accurate representation of higher elevation areas in the watershed. To characterize climatic patterns across the entire watershed, high resolution gridded monthly climate datasets for the study area were downloaded from ClimateBC (Wang et al. 2016), which uses baseline data from the Pacific Climate Impact Consortium (PCIC), including data from the Shawnigan Lake weather station. ClimateBC gridded datasets for precipitation, snowfall, temperature, and Hargreaves evapotranspiration (ET) were used.

ClimateBC[1], is a standalone software application (Wang et al. 2016) that extracts and downscales gridded (800 x 800 m) monthly climate data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM; Daly et al. 2008), developed by the Pacific Climate Impacts Consortium (PCIC). The gridded climate data are derived from monthly data collected at regional climate stations throughout BC and surrounding provinces in Canada and the United States and can be downscaled in ClimateBC to point locations through a combination of bilinear interpolation and dynamic local elevational adjustment. This is considered more representative than the traditional approach of identifying and using regional climate station data directly.

It is noted that the reference crop (potential) evapotranspiration (PET) variable predicted by ClimateBC is the water quantity lost from an idealized grass crop with unlimited water supply, under ambient climate conditions, not actual evapotranspiration (AET) which is lower due to factors including limited soil moisture and plant stomata controls on transpiration.

As no snow survey stations are located directly in the watershed, data from nearby snow survey stations were used as surrogates for characterizing monthly patterns in snow water equivalence (SWE). These included Tripp Meadows (approximately 7 km SSW of Koksilah; 820 masl), Jump Creek (approximately 35 km NW of Koksilah; 1160 masl) and Heather Mountain (approximately 50 km NW of Koksilah; 1170 masl), as shown in Figure 2.4. Snow surveys were conducted at Tripp Meadows between 1957-1987 and at Heather Mountain between 1959-1991 and 2013-2016 on an approximately monthly basis between February and May. SWE has been recorded at Jump Creek daily since 2003. SWE is defined as the water content of a snowpack (i.e., the amount of water released if the snowpack melts).

Generally, all annual climate analyses were conducted using a WY time frame. The only exception to this is for the ClimateBC data, where variables were only available on a calendar year time frame.

3.2.2 Hydrology

Hydrological data was downloaded from all available stations and field sites across the watershed (locations shown in Figure 2.4) to characterize baseline conditions in the Koksilah watershed. WSC station 08HA003 (Koksilah River at Cowichan) is the only long-term station in the watershed that is currently active (nearly continuous record from January 1, 1960 to present) and was used for characterizing baseline conditions. The station 08HA0022 (Koksilah River at Trestle) has a recent continuous record (September 6, 2018 to October 19, 2020) and was used to contrast recent low flows in the downstream portions of Koksilah River.

Flows from the WSC station were separated into their baseflow and runoff. Baseflow is defined as the groundwater contribution to stream discharge while (shallow) runoff occurs along watershed hillslopes directly to the Koksilah River and its tributaries in direct response to precipitation or snowmelt events. To separate baseflows from total discharges, a baseflow recession analysis was performed on the 08HA003 synthetic hydrographs. The recession analysis approach developed by Lyne and Hollick (1979) was used through the ecohydrology R package. Runoff was then calculated as the difference between daily discharge and daily baseflow:

$$\text{Runoff} = \text{Total Discharge} - \text{Baseflow}$$

[1] http://climatebc.ca/

Work is currently being undertaken to develop a critical environmental flow threshold (CEFT) for the Koksilah River. Currently two thresholds have been proposed based on the habitat needs of Coho and Steelhead fish species: an upper threshold of 490 L/s (about 5% of the mean annual discharge; MAD), and a lower critical environmental flow threshold (CEFT) of 180 L/s (Barroso and Wainwright, in press). These thresholds were considered as reference points for analyses completed in this report.

3.2.3 Water Demand

Current (i.e., 2020) surface and groundwater demand estimates in the watershed were provided by FLNRORD (Barroso and Wainwright, in press) and processed further for the purpose of this study. There may be minor discrepancies between the two studies from differences in joining raw data sources, and in the end these differences do not materially influence the outcome of the analyses conducted herein.

The FLNRORD dataset contains water uses categorized into agricultural, commercial/industrial, municipal and domestic purposes. Groundwater and surface water licenses were divided into either a year-round or seasonal category depending on their license purpose:

- **Year-round** includes domestic, domestic & stock watering, commercial, industrial, institutional, waterworks, recreational, industrial – washing gravel, pond & aquaculture, livestock & animal, cooling (industrial), power: residential, stream storage: non-power, civic/institutional/recreational and undefined purposes.
- **Seasonal** was assumed to include irrigation and agriculture stock watering purposes. Stock watering could alternatively be classified as year-round, but water use numbers are small, and this assumption does not materially affect the analyses conducted.

Annual estimates of surface water and groundwater use were determined by FLNRORD summarizing the daily water demand rate for all existing licenses in a year over either a seasonal or annual window. Seasonal groundwater licenses were multiplied by an irrigation window of 153 days, and surface water licenses by an irrigation window of 183 days. Water licenses with daily volumes for water use were multiplied by a year-long window of 365.25 days.

Monthly estimates of water use were determined by applying a monthly weighting to each year's annual water demand, with weightings based on seasonal or year-round use and purposes. Monthly weightings for year-round water uses were based on the number of days in each month (see Table 3.1). Monthly weightings for seasonal water use (e.g., irrigation) were based on monthly distributions estimated using the BC Agriculture Water Calculator (v 2.1.0)[2]. The distribution was based on the average, monthly water demand values for ten randomly selected agricultural land parcels in the watershed. These seasonal monthly weightings are also shown in Table 3.1.

The provided surface water demand data (129 licenses) was associated with BC's Water Rights Licenses by License Point of Diversions (POD's) (BC Data Catalogue 2020). The final dataset had 121 licenses (the remaining licenses could not be georeferenced) which also provide the license date, purpose, and demand values (m^3/d).

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[2] http://bcwatercalculator.ca/agriculture/welcome

FLNRORD's groundwater use dataset was generated by compiling a variety of data sources, such as, water license, groundwater license applications, mapped wells and accompanying information, parcel data and water service area information. The full methodology is described in Barroso and Wainwright (in press). A subset of the provided dataset was used corresponding to locations also incorporated by Sivak and Wei (2019) for subsequent streamflow depletion analysis (Section 3.2.4). The provided dataset subset data was joined spatially to two datasets: i) BC's Integrated Cadastral Fabric through Parcel ID's (PID's) (BC Data Catalogue, 2020), and ii) aquifer classification provided by Sivak and Wei's (2019) through well tag numbers (to assess groundwater-surface water connectivity; Section 3.2.4). The processed and joined final dataset has 575 records with wells assigned to an aquifer type (unconsolidated or bedrock), usage purpose and estimated use. In addition, there are 42 parcels in the processed dataset that have been flagged as potential irrigation use, but these parcels are not considered in this analysis. Potential irrigation use includes those parcels cleared for agricultural purposes but inferred to currently not have an irrigation system in place.

Table 3.1 Weighted seasonal distribution of water use.

Month	Irrigation	Year-Round Purposes
January	0	0.085
February	0	0.077
March	0	0.085
April	0.002	0.082
May	0.089	0.085
June	0.238	0.082
July	0.313	0.085
August	0.240	0.085
September	0.117	0.082
October	0.002	0.085
November	0	0.082
December	0	0.085

Note: The weighting for year-round purposes is dependent on the number of days in each month.

3.2.4 Aquifer-Stream Connectivity and Streamflow Depletion Factor

Sivak and Wei (2019) investigated the hydraulic connection between streams and underlying aquifers in the watershed using well lithology data and surface water and groundwater level data. Their analysis considered areas where surface water (i.e., the Koksilah River and its tributaries) is perched above underlying groundwater systems (i.e., separated from groundwater table by a partially saturated zone that limits river leakage) versus those areas where groundwater and surface water are in direct connection (which may act as either areas where groundwater discharge occurs or where river leakage to groundwater is not inhibited). The concept of perched versus connected systems is illustrated in Barlow and Leak (2012) as well as Sivak and Wei (2019).

Sivak and Wei, (2019) defined perched reaches as those locations where stream elevation was greater than 3 m above estimated groundwater elevation (determined from contouring of water level data). Along these perched reaches, groundwater and surface water are not in direct connection. In areas where groundwater and surface water are in potential connection, Sivak and Wei (2019) also considered the presence of confining materials as potentially limiting hydraulic connectivity. Blocked reaches were defined as those areas where confining sediments were contiguous below the stream with a minimum thickness of 3 m. For the purposes of this study, those reaches which were not considered blocked and not characterized by perched conditions were caried forward for map visualization purposes. These reaches are identified herein as “areas of potential hydraulic connectivity” (i.e., between surface water and groundwater).

Any groundwater use in a watershed will ultimately lead to streamflow depletion in hydraulically connected streams (e.g., deep groundwater use could hypothetically affect discharge to marine environment instead). Stream depletion factors (SDFs) are a relative measure of how quickly streamflow depletion (i.e., the loss of flow from a stream due to groundwater use) in hydraulically connected streams can occur from well pumping. While SDF is strictly not needed to calculate streamflow depletion (Section 0), the two concepts are related and SDF is useful for illustrative purposes to understand streamflow responses to groundwater pumping. Streamflow depletion from well pumping and recovery from streamflow depletion after pumping stops are expected to occur more quickly where the SDF is smaller. The SDF will depend both on distance of the well to the stream and properties of the aquifer from which the well draws water, as expressed in the equation developed by Jenkins (1968):

$$SDF = {d^2S}/{T}$$

Where, d is the nearest distance to a stream reach with inferred hydraulic connectivity to groundwater, S is aquifer storativity and T is aquifer transmissivity. Jenkins (1968) defines SDF as the time required for the ratio between the rate of streamflow depletion and the rate of well pumping to reach 28% (Barlow and Leake 2012). Time scales for this to happen can range from hours (for wells in immediate proximity to streams) to decades (for wells located a large distance away). At time scales that are much longer than the SDF, streamflow depletion will ultimately become equal to the well pumping rate (i.e., after a long time of pumping, the loss of water from the connected stream will be the same as the pumping rate). To calculate SDFs for wells in the watershed, Sivak and Wei (2019) determined distances from each well to their corresponding point of hydraulic connection (PoHC) (i.e., distance to the closest stream segment with potential hydraulic connectivity). The aquifer parameters used in the SDF calculation are provided in Table 3.2 and align with those used by Barroso and Wainwright (in press). Aquifer types were determined by Sivak and Wei (2019) for each well considered in the analysis based on the recorded well lithologies.

Table 3.2 Aquifer input parameters (Barroso and Wainwright, in press).

Aquifer Type	Transmissivity (m^2/d)	Storativity (unitless)
Unconsolidated and unconfined	300	0.20
Unconsolidated and confined	200	0.05
Bedrock (sedimentary and crystalline)	1.5	0.005

The FLNRORD aquifer parameters are a slight modification of the parameters used by Sivak and Wei (2019). FLNRORD's aquifer parameters were based on compiled aquifer properties from Carmichael (2014) for a simplified grouping of three aquifer types and modified using sensitivity analysis and review of model results (Barroso and Wainwright, in press). A higher T (300 m^2/d) was considered appropriate for other unconsolidated-unconfined aquifers. For the unconsolidated-confined aquifers, the same T value as and lower S values than Sivak and Wei (2019) were used. A median value between values for sedimentary and crystalline bedrock wells was chosen for bedrock wells in the model for simplification purposes and based on limited sensitivity of summertime streamflow depletion to bedrock groundwater use (Sylvia Barroso, FLNRORD, personal communication).

3.2.5 Water Balance

A high level long-term average (1963-2019) annual water balance was constructed from the climatic, hydrological and water demand baseline characterization to assess the relative importance of different water balance components in the upstream watershed. The ClimateBC gridded precipitation and PET data (Section 3.2.1) together with long-term gauging data for the WSC station (Section 3.2.2) were used for this purpose.

3.3 HISTORICAL CHANGE ANALYSIS

3.3.1 Climate

Long-term changes in annual, seasonal, and monthly temperature and precipitation were analyzed using both the ClimateBC gridded datasets, spatially averaged over the upstream watershed, and observations directly from the Shawinigan Lake weather station. Long-term patterns in snow accumulation (SWE) across the watershed were estimated using direct observations from the Tripp Meadows, Heather Mountain and Jump Creek snow survey stations that are located nearby the watershed. Long-term trends in these climate variables were analyzed over the 1962-2019 analysis period.

3.3.1.1 Evapotranspiration

Reference ET (PET) calculations are subject to uncertainty as different calculation methods may yield considerably different outcomes, and evapotranspiration data are not available as an independent check on the calculations. To address this uncertainty, evapotranspiration was calculated and compared using three methods. These included:

- PET extracted directly from the ClimateBC Hargreaves monthly ET raster for the Shawnigan Lake climate station location.

- PET calculated using the Hamon equation for the latitude of Shawnigan Lake from the USGS Thornthwaite Monthly Water-Balance Program (McCabe and Markstrom 2007).

- PET manually calculated using the Hargraeves method (Hargreaves & Samani 1985) to daily climate data from the Shawnigan Lake weather station using the R package 'Evapotranspiration'.

The Hargreaves evapotranspiration method used by ClimateBC requires knowledge of two variables: an estimate of solar radiation above the atmosphere and range in temperatures for the latitude of a site on a given day of the year. It is calculated using the following equation, where nd = number of days in the month, S_0 = water equivalent of radiation above the atmosphere (mm/d), T_m is the mean monthly temperature and T_r is the difference between the monthly mean maximum and minimum temperatures:

$$E_{har} = 0.0023 * nd * \; S_0(T_m + 17.8) * T_r^{0.5}$$

The evapotranspiration method used by the USGS Thornthwaite Water Balance Program uses the Hamon equation (Hamon 1961):

$$PET_{Harnon} \; = 13.97 * d * D^2 * W_r$$

where d = number of days in a month, D is the mean monthly hours of daylight, and W_t is the saturated water vapour density. The saturated water vapour density term is calculated by the following:

$$W_t = \frac{4.95 * \; e^{0.062 * T}}{100}$$

where T is the mean monthly temperature.

3.3.2 Hydrology

Long term hydrological trends were analyzed on a monthly and annual scale for WSC station 08HA003 using raw daily flow data for WY 1963 – 2019. Monthly changes in flows over the WY 1963-2019 period were investigated concurrently with changes in climate variables and water use to identify causal factors that may have a relationship with recently observed declines in low summer flows. Monthly and annual changes in baseflow (groundwater discharge) and runoff were also assessed individually to investigate changes in each of these flow components contributing to total discharge recorded at the WSC station. The recession analysis approach developed by Lyne and Hollick (1979) was used through the ecohydrology R package to separate baseflow and runoff, as outlined in Section 3.2.2.

3.3.3 Water Demand

FLNRORD estimated current (i.e., 2020) surface and groundwater demand in the watershed (Barroso and Wainwright, in press). Historical changes in water demand were conceptualized as follows:

- Individual surface water use at a POD was assumed to start at the license date and continue until the end of the analysis period (2019).

- Individual groundwater use was assumed to start at the date a well was drilled and continue until the end of the analysis period (2019). This approach therefore does not account for potentially abandoned wells that may no longer be in use, or wells where use has varied (i.e., increased or decreased over time) or began later than the drill date.

Within each year of record, monthly groundwater and surface water demand was distributed using the approach outlined in Section 3.2.3, and weights provided in Table 3.1. The overall record spans the period from the early 1900s to 2020 but for hydrologic change analysis, the emphasis was on WY 1963-2019.

The historical water demand trends were separately analyzed for the upstream watershed (i.e., upstream of the WSC gauge) and the entire Koksilah watershed.

3.3.4 Groundwater Levels

BC has a Provincial Groundwater Observation Well Network (PGOWN) to monitor groundwater levels within many aquifers. There is a total of eight (8) active and inactive PGOW wells located within the watershed (Figure 2.7 and Figure 2.8). Water level data for these observation wells was downloaded and a trend analysis was conducted.

The groundwater level data review used the water level trend analysis script that was previously developed for BC State of Environment[3] reporting. This script was downloaded from GITHub[4] and adapted for the purposes of the project to include analysis of observation wells with a minimum 5-year data record, where all other criterion remained as default (less than 25% of missing data and time series ending after 2009). This methodology is identical to that applied in the 2019 PGOWN review (Hatfield 2020).

Using the State of Environment methodology and criteria for establishing groundwater level trends and their significance, each groundwater level time series was analyzed using the Theil-Sen approach (Sen 1968) to determine slope. Results are tested for significance ($p < 0.05$) using the Mann-Kendall trend test. The results are interpreted as (Hatfield 2020):

- Stable or Increasing: the slope is not significantly different from zero, the slope is significantly different from zero with an increasing trend, or the slope is significantly different from zero with a declining trend of less than 3 cm per year.
- Moderate Rate of Decline: the slope is significantly different from zero with a declining trend of between 3 and 10 cm per year.
- Large Rate of Decline: the slope is significantly different from zero with a declining trend of more than 10 cm per year.

3.3.5 Streamflow Depletion

While surface water demand (Section 3.2.3) will have a direct impact on streamflow, the impact of groundwater use on surface water flows (i.e., streamflow depletion) is delayed in time, as explained through the SDF concept in Section 3.2.4. The Glover solution developed by Glover and Balmer (1954) was used for determining the effects of pumping on streamflow and incorporates the SDF concept:

[3] http://www.env.gov.bc.ca/soe/indicators/water/groundwater-levels.html

[4] https://github.com/bcgov/groundwater-levels-indicator

$$Q_s = Q_w erfc\left(\sqrt{(d^2S)/(4Tt)}\right)$$

In which Q_W is the pumping rate of a well and Q_s is the associated streamflow depletion, which is calculated from a complementary error function, that depends on the time (t) since pumping started, and which incorporates the SDF concept based on the distance (d) of the well to point of hydraulic connection (PoHC) of the nearest stream, and aquifer transmissivity and storativity (Table 3.2). The distance of wells to the nearest stream was calculated by Sivak and Wei (2019) in a GIS analysis as outlined in Section 3.2.4.

While the above Glover equation is for a time invariant Qw, application of this equation to calculate streamflow depletion was expanded to allow for the monthly varying pumping rates utilized in this study (Section 3.2.4). The Glover solution was calculated at a monthly time step for every well in the dataset. A cumulative streamflow depletion sum for each month and year was calculated for both the upstream watershed and for the entire watershed. The calculated monthly streamflow depletion time series for the upstream watershed was then used in the flow naturalization for the WSC gauge data (Section 3.3.6).

3.3.6 Flow Naturalization

Naturalized flows are the flows that would be present in the absence of anthropogenic water use. Naturalized flows at WSC station 08HA003 were calculated by adding monthly surface water use and streamflow depletion time series for the upstream watershed to the daily gauged flows for the station.

The impact of flow naturalization on low flows recorded at the WSC gauge was subsequently assessed. The NHC (2020) 7-day low flow analysis was reproduced using recorded flows for the WY 1963-2019 reference period and subsequently repeated for the naturalized daily flow time series. This allowed for direct assessment of the effect of historical water demand in the upstream portion of the watershed on the documented declining trend in 7-day low flows at the long-term WSC gauge.

3.3.7 Historical Forest Cover Changes

The ecosystem review (Pritchard et al. 2019) documented significant historical changes in forest condition (forest age classes) in the watershed since 1955 through geospatial analysis. Geospatial data for select time snapshots (1954, 1972, 1985, 1996, 2007 and 2018) was kindly provided by the Cowichan Station Area Association for the specific purpose of the hydrological change analysis. The resultant geospatial data summary is provided in Table 3.3. Age ranges for each forest age class were estimated (assumed) by Hatfield based on limited guidance. It is noted that there does not appear to be a consistent definition of forest age classes. The provided data suggests the following trends:

- A large decrease in old growth forest upstream of WSC gauge from 50% upstream watershed area in 1954 to 5% in 2018. For the entire watershed, the decrease is from 43% to 4% over this period.
- A peak in total logged (clear cut) areas around the 1970s with an emphasis on old growth logging (about 20% of watershed area).
- A peak in very young recovering forests (assumed less than 20 years old) around the mid-1980s corresponding to the previously logged old growth areas.
- A transition to logging immature-mature stands (assumed 80-100 years old) in recent years.

- A watershed area of about 10% in a clear-cut state, which is half that of the 1970s situation and closer to the amount of clear-cut area in 1954 (6-9%).
- An increase in mature forest stands (assumed 100-120 years old) in the most recent assessment year (2018).

it is noted that these forest age classes are not necessarily a good predictor of stand level evapotranspiration, which is better assessed through tree physiological characteristics (stand height, crown closure, leaf area index) and through vegetation types present (which may differ in factors such as leaf stomatal resistance, rooting depth, etc.). These physiological factors are captured in the physically based Penman-Monteith equation for calculating ET (e.g., Beven 1979), which is based on an energy balance approach rather than the simplified temperature driven algorithms used herein. The Penman-Monteith equation is the United Nations Food and Agriculture Organization (FAO) and American Society of Civil Engineers standard method for modeling evapotranspiration. Due to the complexity of parameterizing the Penman-Monteith equation it was not used for the hydrological change analysis. Its use is better reserved for more detailed water balance modelling, which could also incorporate more detailed physical data (stand height, crown closure) owned by Mosaic Forests (David Beleznay, personal communication), as discussed further in Section 6.

The effects of forestry on streamflow have been investigated for at least a century (Moore et al., 2020). In most studies, emphasis has been on water yield and peak flows, with less attention paid to low flows. Over the last decade, however, there has been increasing concern about forestry effects on low flows, particularly in the context of climatic change, which is projected to result in more frequent and severe droughts in many regions, including the Pacific Northwest (Pike et al. 2010). Several research papers were provided by Cowichan Tribes that discuss forestry effects on low flows. Only those research papers applicable to rain-dominated watershed conditions of coastal BC (i.e., applicable to the Koksilah situation) were retained and are discussed below. The provided research papers were supplemented by additional pertinent literature, to support the historical change assessment.

Table 3.3 Estimated Percentage of Koksilah watershed area (A_{FC}) occupied by forest age classes over time.

Forest Age Class	Age Range	1954		1972		1985		1996		2007		2018	
		Km²	%	Km²	%	Km²	%	Km²	%	Km²	%	Km²	%
Upstream of WSC gauge													
Old Growth	250	116	50%	67	29%	36	16%	23	10%	14	6%	11	5%
Logged - Old Growth	0	20	9%	49	21%	31	13%	13	6%	10	4%	4	2%
Logged - Immature	0	-	-	3	1%	-	-	-	-	-	-	-	-
Logged - Immature-Mature	0	-	-	-	-	6	2%	6	2%	11	5%	25	11%
Very Young	0-20	-	-	-	-	50	21%	33	14%	18	8%	21	9%
Young	20-40	-	-	20	9%	20	9%	50	21%	33	14%	18	8%
Young (Burn)	20-40	12	5%	-	-	-	-	-	-	-	-	-	-
Young-Immature	40-60	69	30%	78	33%	-	-	19	8%	49	21%	33	14%
Immature	60-80	-	-	-	-	-	-	-	-	19	8%	42	18%
Immature-Mature	80-100	-	-	-	-	72	31%	67	29%	56	24%	11	5%
Mature	100-120	-	-	-	-	-	-	-	-	-	-	46	20%
Non-Forest	-	15	7%	15	7%	17	8%	21	9%	22	9%	22	9%
Entire Koksilah Watershed													
Old Growth	250	136	43%	80	25%	46	15%	31	10%	17	5%	12	4%
Logged - Old Growth	0	20	6%	56	18%	34	11%	16	5%	15	5%	4	1%
Logged - Immature	0	-	-	9	3%	-	-	-	-	-	-	-	-
Logged - Immature-Mature	0	-	-	-	-	8	3%	10	3%	17	5%	31	10%
Very Young	0-20	-	-	-	-	58	18%	37	12%	24	8%	31	10%
Young	20-40	-	-	20	6%	20	6%	58	18%	37	12%	24	8%
Young (Burn)	20-40	12	4%	-	-	-	-	-	-	-	-	-	-
Young-Immature	40-60	118	37%	121	38%	-	-	20	6%	57	18%	37	12%
Immature	60-80	-	-	-	-	-	-	-	-	19	6%	49	16%
Immature-Mature	80-100	-	-	-	-	113	36%	104	33%	88	28%	11	4%
Mature	100-120	-	-	-	-	-	-	-	-	-	-	73	23%
Non-Forest	-	29	12%	29	12%	36	15%	39	17%	41	18%	42	18%

Note: (1) Data provided by Cowichan Station Area Association for the purpose of this hydrological change analysis.

(2) Forest age classes are from Pritchard et al. (2019). Age ranges were determined on basis of review of forest management literature.

(3) '-' = no data for particular forest age class.

Forest management (logging and subsequent regrowth and recovery) will affect the water balance of a watershed (i.e., water availability) predominantly through ET processes. The forest cover (and its removal) will also interact with snow accumulation and melt processes (i.e., shading affecting the snowpack energy balance), but this is expected to be of secondary importance in the rainfall dominated Koksilah watershed) and has not been evaluated below.

Evapotranspiration in the forest is a complicated physical process. It includes transpiration by the green mass of the tree crowns (i.e., the stomata) which also depends on root water uptake (soil water availability), evaporation from the soil and by understory vegetation, and evaporation of intercepted precipitation (i.e., rainfall intercepted by the forest canopy which may subsequently evaporate back into the atmosphere or snow interception at higher elevations). These processes depend in different ways on forest types (e.g., different conifer types, different deciduous species) and forest age. The trajectory of hydrologic recovery will therefore depend on the types of vegetation and their rates of growth and successional processes (Moore et al. 2020). For the hydrologic change assessment, the separate processes contributing to forest ET were lumped into a single evaluation.

Limited stand level forest evapotranspiration data exists. There are not a lot of publications with good chrono sequences of evaporation (i.e., data for forest stands of different ages). Most of these studies usually consider a maximum stand age of 60 to 80 years where stand evaporation is still more or less at maximum. Furthermore, many of the evaporation papers are based on direct measurements on the trees using sap flow (e.g., Moore et al. 2004), but this technique does not provide evaporation from the understory and evaporation of intercepted precipitation stands (D. Spittlehouse, personal communication), which can be up to 30% of the precipitation annually in old stands (Spittlehouse 1998). A relatively systematic and holistic analysis on evapotranspiration from forest stands of various types and ages in comparison to evaporation from treeless areas was done in the 1960s and 1970s in the southern and central taiga subzones of Russia. The studies are representative of BC forest types in that deciduous species were found to dominate in young and middle-aged stands (as can be seen in recovering clear-cuts in coastal BC), while conifers dominate in mature forests. The ET data was collated in Reynolds and Thompson (1988) (their Figure 1 in the chapter on evapotranspiration in forest and fields) and was transcribed for use herein. The transcribed data in Table 3.4 expresses ET for different forest age classes (i.e., those shown in Table 3.3) as a percent of evapotranspiration for an old growth forest (based on the top panel in the abovementioned Figure 1).

The Reynolds and Thompson (1988) data suggest that evapotranspiration in logged areas (clear cuts) and very young recovering forests (less than 20 years old) is below ET values for an old growth forest. These reduced relative ET values would lead to *greater* water availability in the watershed. This matches review findings by Moore et al. (2020) who indicate that "paired-catchment studies conducted on small (<10 km^2) rain-dominated catchments revealed that forest harvesting resulted in a period of *increased* warm-season low flows ranging from less than five years to more than two decades, consistent with the results of stand-level studies and process considerations".

Quantitatively, it has been assumed that ET in logged areas (i.e., clear-cuts) is about 60% of that in a mature forest (Table 3.4). This assessment using Reynolds and Thompson (1988) data appears to be reasonably matched by Spittlehouse (2006) who used a physically based stand water balance model and found that summer evaporation from a high elevation clear-cut in the BC's southern interior was about 30% less than that from the forest (also see Figure 7.3 in Pike et al. 2010). Similarly, Jassal et al. (2009) indicate that, after clear -cut harvesting, evapotranspiration in a chrono sequence of three coastal Douglas-fir stands dropped to about 70% of that for a 58-year-old stand.

The Reynolds and Thompson (1988) data further suggest that evapotranspiration in young to immature recovering forests (20 to 80 years old) is above ET values for an old growth forest. This may be largely related to the lower stomatal resistance of grasses and deciduous plants that existing in recovering clear-cuts leading to higher transpiration rates than conifers under identical climatic conditions (Pike et al. 2010) These increased relative ET values would lead to *lesser* water availability in the watershed. Again, this matches review findings by Moore et al. (2020) who indicate that "two studies, one of rain-dominated catchments and one of snow-dominated catchments, found that summer low flows became more severe (i.*e., lower*) about two decades or so following harvest. Perry and Jones (2016) also note average daily streamflow in summer (July through September) in basins with 34- to 43-year-old plantations of Douglas-fir being 50% lower than streamflow from reference basins with 150- to 500-year-old forests dominated by Douglas-fir.

The above analysis suggests that the transition from greater to reduced water availability occurs for forest stands of around 20 years. This inference is reasonably matched by Ziemer (1964) who estimate that soil moisture increases because of logging (i.e., due to lesser ET) will become negligible about 16 years after cutting in the subalpine forest zone of the Sierra Nevada. Coble et al. (2020) suggest that this transition may occur sooner around 10 years after harvesting. They further indicate that "long-term streamflow records extending 38 to 50 years postharvest from paired catchment experiments in the Cascade Range of Oregon demonstrate persistent summer low flow decreases resulting from the replacement of native mature and old-growth forest with regenerating Douglas-fir plantations". The 38 to 50-year time frame would appear to match the period of increased ET in Table 3.4.

Table 3.4 Relative evapotranspiration for different forest age classes.

Forest Class	Age Range	Relative Evapotranspiration (RET_{FC})
Logged	0	60%
Very Young	0 to 20	75%
Young	20 to 40	120%
Young-Immature	40 to 60	130%
Immature	60 to 80	120%
Immature-Mature	80 to 100	110%
Mature	100 to 120	105%
Old growth	250	100%

Note: Data compiled from Reynolds and Thompson (1988) - Figure 1 in the chapter on evapotranspiration in forest and fields.

Therefore, while overall considerable uncertainty exists in the magnitude and time scales of the hydrologic response to forest harvesting and recovery, at a high level the relative evapotranspiration data shown in Table 3.4 data appear to match available literature relevant to the Pacific Northwest climatic and forest conditions. For the watershed-scale hydrological change assessment, the relative evapotranspiration for each forest class (RET_{FC}) in Table 3.4 was multiplied by the percent watershed area occupied by the forest age class (A_{FC}) shown in Table 3.3. Relative evapotranspiration in the watershed (RET_W) for each of the snapshot periods (1954, 1972, 1985, 1996, 2007 and 2018) was therefore calculated as:

$$RET_{watershed} = \sum_{FC} RET_{FC} * A_{FC}$$

Where FC represents the different forest age classes. Subsequently the annual watershed relative evapotranspiration values ($RET_{watershed}$) were compared against the 1954 calculation to evaluate the change in evapotranspiration on a watershed scale relative to this reference.

3.3.8 Urbanization

Urban development leads to loss of vegetative cover and an increase in impervious surfaces that may comprise anywhere from 10% of low-density residential areas to 90% of high-density business districts. Traditional stormwater systems serve a single purpose to convey runoff away from these impervious surfaces and into the receiving body (stream) as quickly as possible, thus reducing the potential for groundwater recharge over the developed area. Modern stormwater systems may include retention ponds, artificial wetlands, and means to facilitate infiltration of rooftop runoff. Modern stormwater systems have the potential to increase recharge compared to natural conditions as the potential for evapotranspiration is decreased.

The effect of urban development in the watershed on groundwater recharge was assessed by hypothetical examples whereby recharge over residential (urban) areas (Figure 2.3) was reduced by 10% (low density development) and 50% (medium density). This range of recharge reductions is deemed characteristic for low- to medium-density development combined with a traditional stormwater system (Beckers and Frind 2001).

4.0 RESULTS

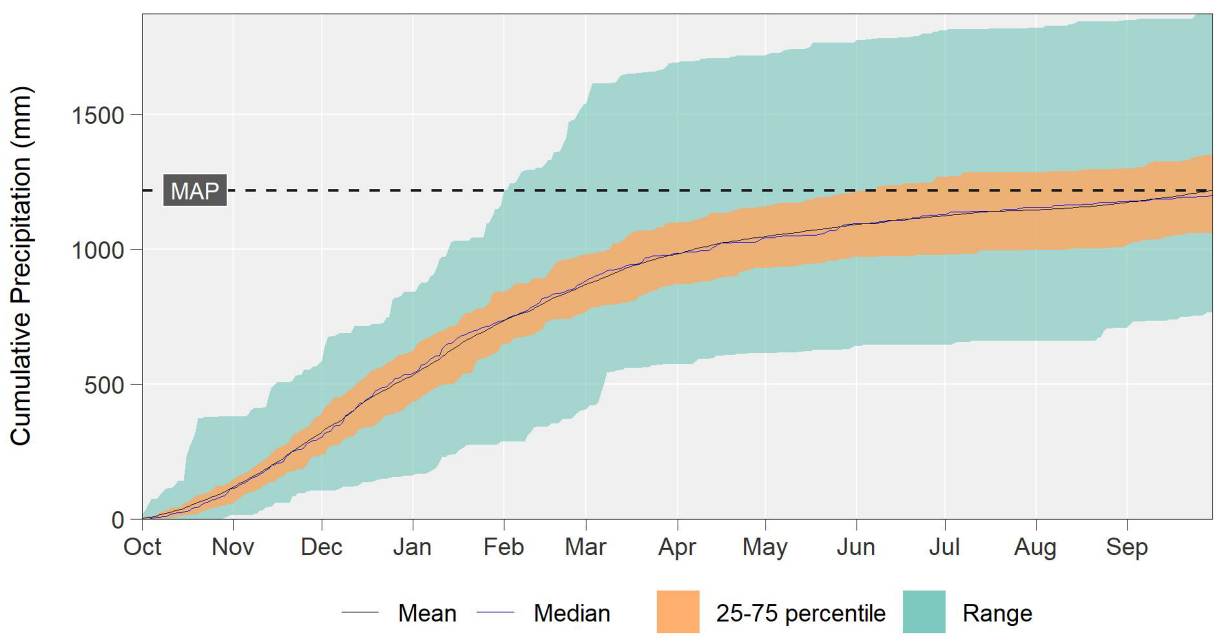
4.1 BASELINE CHARACTERIZATION

4.1.1 Climate

Precipitation

The long-term Mean Annual Precipitation (MAP) at the Shawnigan Lake ECCC Station is estimated to be 1237 mm, with a range of 767 to 1875 mm and standard deviation of 235 mm. The annual precipitation regime, shown in terms of daily cumulative sums in Figure 4.1, indicates that over 80% of annual precipitation occurs during the 6-month period from October to March, and less than 20% during the remaining months from April to September.

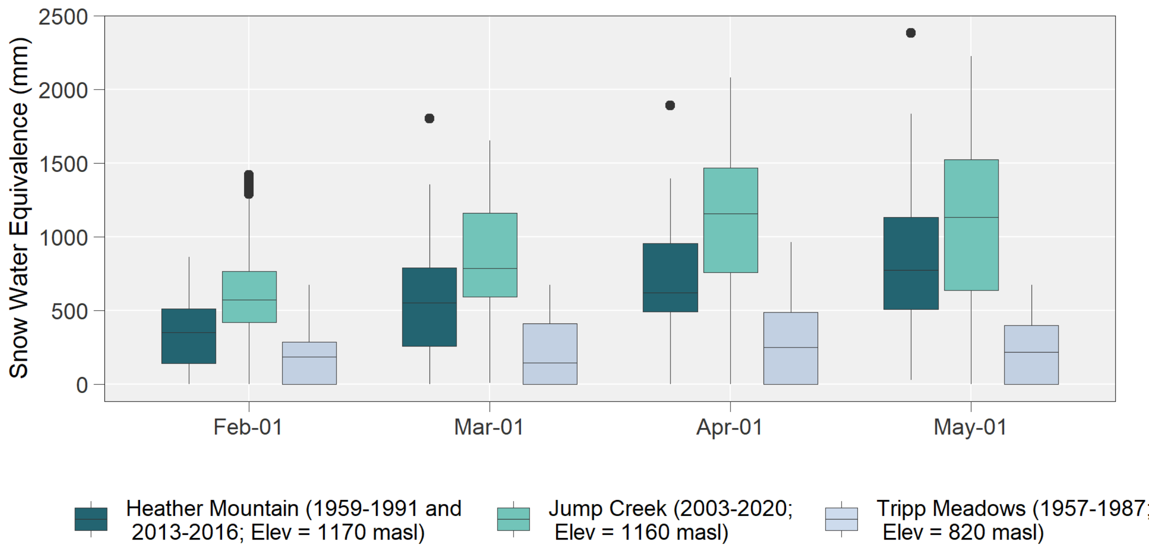
Figure 4.1 Cumulative annual precipitation at Shawnigan Lake.



Note: Figure generated using data from the Shawinigan Lake Environment Canada weather station (Climate ID = 1017230) for the 1962 – 2019 water years.

Figure 4.2 shows accumulated Snow Water Equivalent (SWE) values at the regional snow courses (Tripp Meadows, Station 3B06, 820 masl; Jump Creek, Station 3B23P, 1160 masl; and Heather Mountain, Station 3B13, 1170 masl) as an analog for snowpack conditions in the Koksilah watershed. The data indicate that snowfall accumulation occurs during most winters. The median SWE for Tripp Meadows is well below the monthly median SWE observed at Heather Mountain and Jump Creek, which are at about 350 m higher elevation. Patterns in snow accumulation at Tripp Meadows are likely more representative of Koksilah because the Tripp Meadows snow course elevation more closely corresponds to Koksilah while the other two snow courses are at or above the maximum watershed elevation (Figure 2.1). Table 4.1 shows limited available recent field observations of the snow line near the Jump Creek snow survey station between 2016-2019. While the available record is short, it shows the snowline elevation at Jump Creek has varied between 400-900 masl in recent years. In two of the years, the recorded mid-winter snowline elevation was equivalent to the highest elevation range in the Koksilah watershed. However, it should be noted that Tripp Meadows contains the least recent record.

Figure 4.2 Snow water equivalence from Tripp Meadows, Jump Creek and Heather Mountain



Note: The upper/lower whiskers extend from the third/first quartile to the largest/smallest value no further than 1.5 times the inter-quartile range. Data were collected monthly (typically less than 1-week before the stated dates) at the Tripp Meadows snowcourse (820 masl, 7 km south of Koksilah watershed southern boundary), between 1957-1987 and the Heather Mountain snow course (1170 masl, 50 km northwest of Koksilah watershed northern boundary) between 1959-1991 and 2013-2016. Data from Jump Creek were collected on a daily timestep (1160 masl, 35 km northwest of Koksilah watershed northern boundary) between 2003 – 2020.

Table 4.1 Snowline elevations from Jump Creek.

Date	Snowline Elevation (m)
2016-02-07	900
2018-02-20	400
2019-01-15	900

The spatial distribution of long-term MAP across the watershed is displayed in Figure 4.3. The data indicate that MAP rises from approximately 1200 mm around the mouth (as referenced by the Shawnigan Lake weather station data) to approximately double this amount (2858 mm) in the highest headwater areas. The majority of annual precipitation in the watershed comes from the mid-elevation bands which account for large portion of the watersheds overall area, with elevations between 400-700 m contributing to approximately 50% of the annual MAP total and approximately 41% of the total watershed area (Figure 4.3).

The watershed average MAP is estimated to be 1874 mm for the entire watershed, and 2027 mm for the watershed area upstream of the WSC hydrometric gauge.

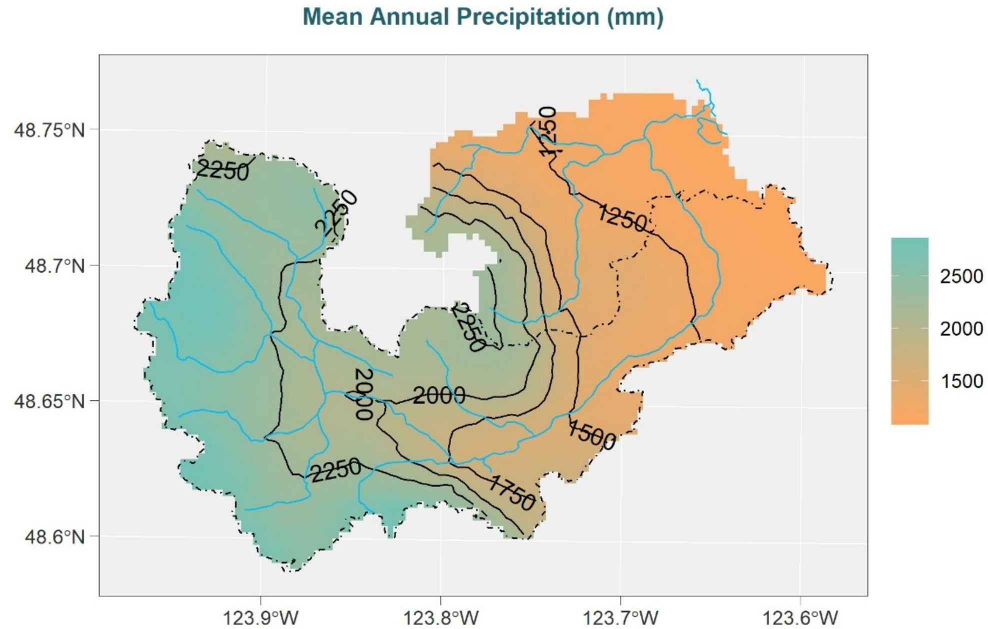
The long-term averaged annual proportion of precipitation that falls as snow for the entire watershed is estimated to be 17%. The proportion of precipitation as snow (PAS) is lowest near sea-level at approximately 5% and highest at approximately 32% for the 1000-1070 masl band (Table 4.2). The long-term averaged PAS for the 800-899 masl elevation band is estimated to be approximately 561 mm from the ClimateBC data. This elevation band is like the elevation of the nearby Tripp Meadows snow course (820 masl), where median SWE has varied between 145-250 mm over the 1967-1987 operational period (Figure 4.2). The PAS estimate of 561 mm for the 800-899 masl elevation band is presumed to be substantially higher than SWE recorded at Tripp Meadows due to intermittent snowmelt that is likely happening during warmer periods in winter at this elevation range (i.e., ignoring other potential factors such as local slope, aspect or forest cover that could also influence melt rates). PAS at the highest elevations in Koksilah (896 mm; Table 4.2) is expected to be close to the SWE recorded at Heather Mountain and Jump Creek (Figure 4.2) as the influence of intermittent wintertime snowmelt would likely be less at these higher elevations with cooler temperatures (and presuming that the regional, more distant, snow courses are in fact representative of conditions in the highest elevation range at Koksilah).

Temperature

The long-term Mean Annual Temperature (MAT) at Shawnigan Lake is estimated to be 9.8°C, with a range of 8.8 to 11.6°C and standard deviation of 0.7°C. The annual temperature regime, shown in terms of daily statistics in Figure 4.4, indicates that daily mean temperatures rarely drop below 0°C (reaching mean minimums of 2°C during January) and increase steadily thereafter to mean maximums of 19°C during August.

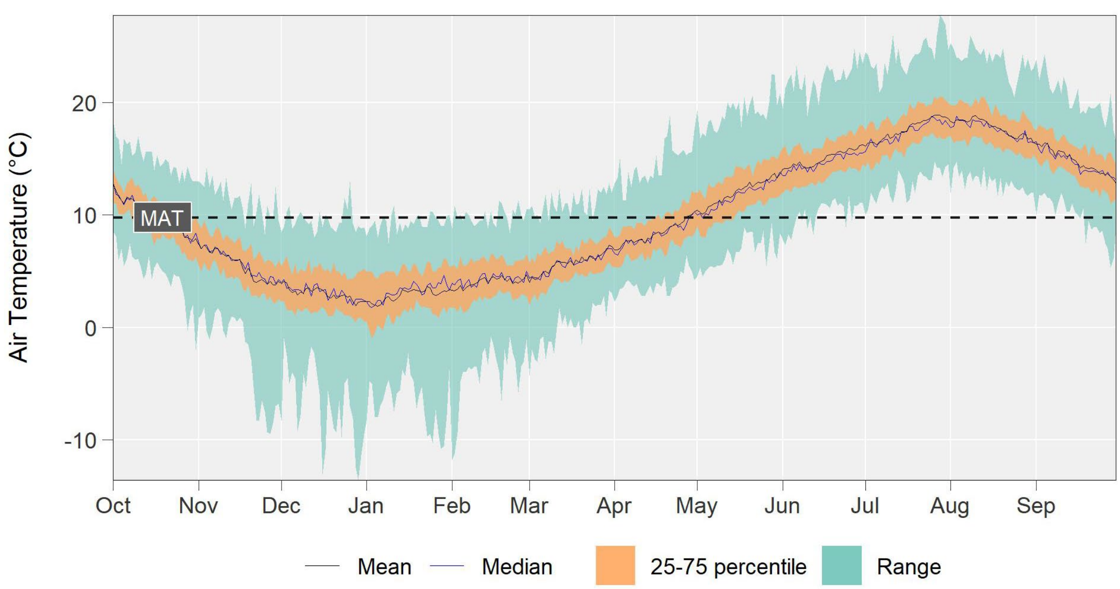
Spatially, the PCIC data predicts that MAT decreases from around 10°C near the mouth (similar to Shawnigan Lake results) to 5°C at the highest elevations (Figure 4.5; Table 4.2). Average winter temperatures at the higher elevations likely remain below freezing for extended periods, which promotes snowfall accumulation and the presence of snowpack until spring.

Figure 4.3 Long-term mean annual precipitation across the watershed.



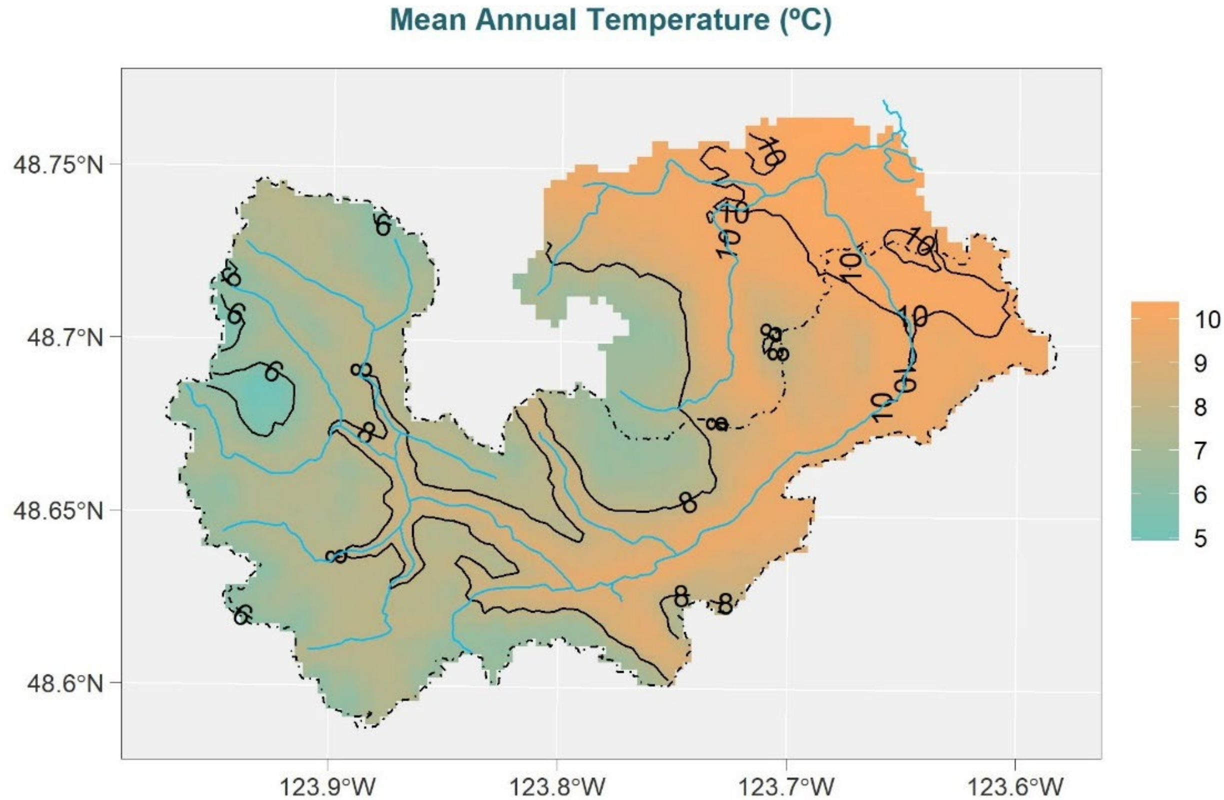
Note: Data generated by averaging gridded annual precipitation rasters from ClimateBC for the 1962 – 2019 calendar years.

Figure 4.4 Daily temperature statistics at Shawnigan Lake.



Note: Figure generated using data from the Shawinigan Lake ECCC Climate Station (Climate ID = 1017230) for the 1962 – 2019 water years.

Figure 4.5 Long-term mean annual temperature across the watershed.

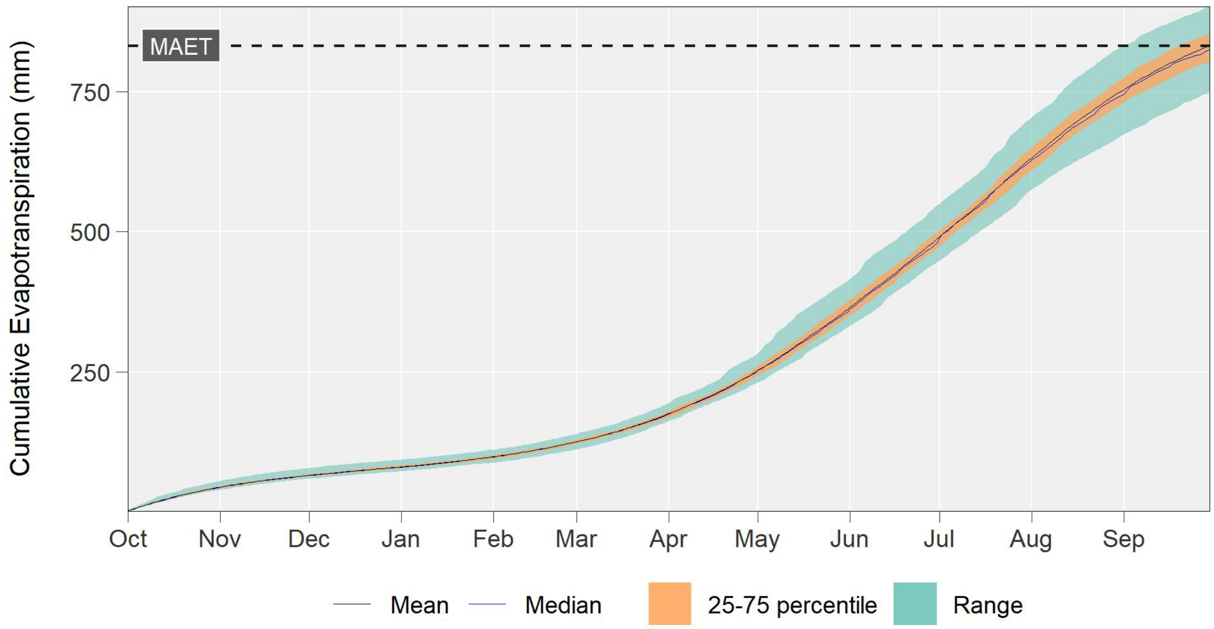


Note: Data generated by averaging gridded mean annual temperature rasters from ClimateBC for the 1962 – 2019 calendar years.

Evapotranspiration

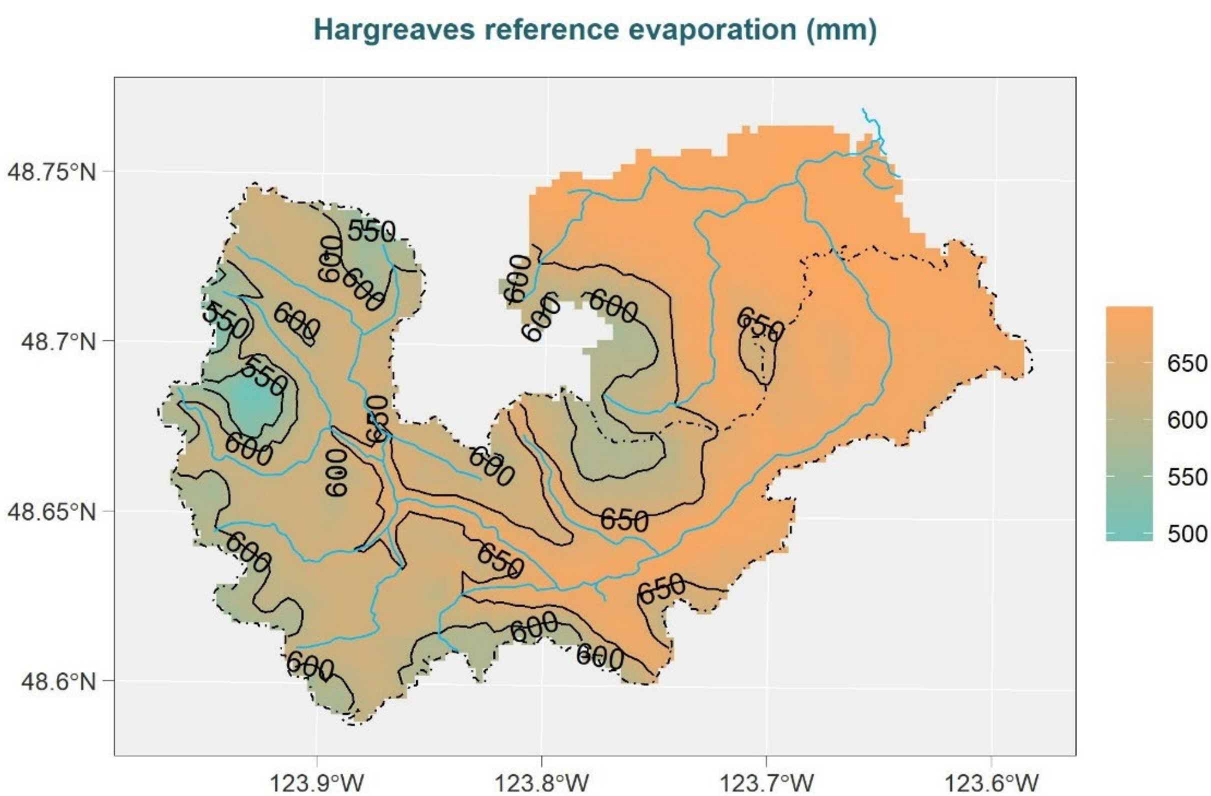
The long-term Mean Annual Evapotranspiration (MAET) at Shawnigan Lake is estimated to be 830 mm, with a range of 750 to 902 mm and standard deviation of 35 mm (Figure 4.6). The majority of annual evapotranspiration occurs during the 6-month period from April to September, and approximately 22% during the remaining months from October to April. Evapotranspiration is estimated to be greatest in the lower areas of the watershed, with the elevation bands below 600 masl each contributing up to 20% of the annual ET (and cumulatively up to 80%), and the higher elevation bands having a much smaller effect on overall ET (Figure 4.7 and Table 4.2). This gradient of declining PET with increasing elevation reflects the cooler temperatures in the upper portions of the watershed. There is a relatively large discrepancy (close to 200 mm) between the PET estimate for Shawnigan Lake and the ClimateBC generated gridded PET estimates at lower elevation, which is explained by differences in calculation methods (Section 3.3.1).

Figure 4.6 Cumulative evapotranspiration at Shawnigan Lake.



Note: Figure generated using data from the Shawinigan Lake ECCC Climate Station (Climate ID = 1017230) for the 1962 – 2019 water years.

Figure 4.7 Long-term Mean Annual Evaporation across the watershed.



Note: Data generated by averaging gridded annual evapotranspiration rasters from ClimateBC for the 1962 – 2019 calendar years.

Table 4.2 Summary of long-term annual climate variables by elevation band in the watershed.

Elevation Band (masl)	Area of Watershed		Temp	Mean Annual Precipitation		Precipitation as Snow			Evapotranspiration	
	(m^2)	% of total	(^0C)	mm	% of total	mm	% of total	% of MAP	mm	% of total
0-99	50,750,000	16	10.1	1172	10	50	4	4	691	18
100-199	44,812,500	14	9.6	1349	10	73	5	5	683	15
200-299	27,562,500	9	9.1	1570	7	112	4	7	671	9
300-399	22,625,000	7	8.6	1810	7	164	5	9	658	7
400-499	33,187,500	11	8.0	2031	12	233	11	11	640	11
500-599	62,937,500	20	7.5	2290	25	310	27	14	625	20
600-699	30,437,500	10	7.0	2367	12	384	16	16	606	9
700-799	26,625,000	9	6.6	2460	11	464	17	19	586	8
800-899	8,500,000	3	6.2	2591	4	561	7	22	567	2
900-999	2,312,500	1	5.4	2816	1	775	3	28	523	1
1000-1070	687,500	<1	5.0	2843	<1	896	1	32	496	<1
Total	310,437,500	100	-		100	-	100	-	-	100

Note: Table generated using long-term averages of climatic variables from ClimateBC rasters for the calendar years between the 1962 – 2019. The grid resolution of the dataset was 250 m x 250 m.[1] PAS refers to precipitation as snow.

4.1.2 Hydrology

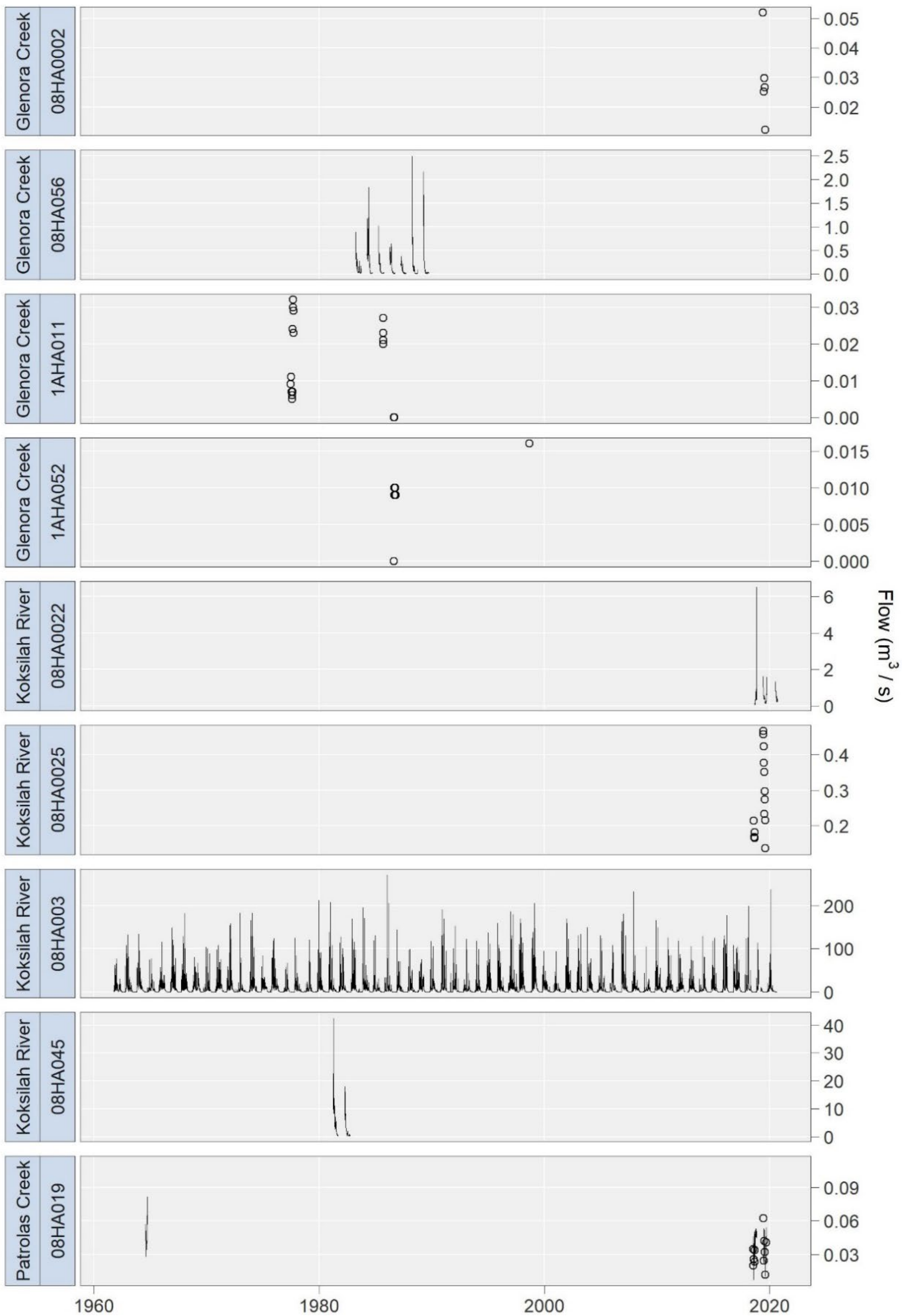
Figure 4.8 shows an overview of all flow data monitored in the Koksilah watershed from the 1962 WY to present. This includes the two active gauges on the Koksilah River mainstem (WSC gauge 08HA003 and FLNRORD gauge 08HA022), flume data from Patrolas Creek (08HA0027 and 08HA0019) and other decommissioned gauges which operated elsewhere in the watershed for short periods of time historically. The active long-term WSC gauge 08HA003 was used for most of the hydrological analyses as it is the only WSC gauge in the watershed with a long data record.

Figure 4.9 displays year-round daily flow statistics calculated from the WSC gauge 08HA003. Flows are consistently high between November – March, before declining through the spring to the lowest flows in July or August prior to rising again through fall. The absence of sustained high flows through April and May suggests that spring snowmelt from higher elevations is a minor component of the annual runoff budget, although the high flows during winter may either be rain-dominated or a mixture of rain and snowmelt from different elevations. The long-term mean annual discharge for WSC station 08HA003 is 9.65 m^3/s.

The interannual variability in discharge at the WSC gauge and the groundwater contribution (baseflow) to this discharge as determined from recession analysis is illustrated in Figure 4.11. The analysis suggests that on an annual basis, total discharge is comprised of approximately 69% runoff and 31% baseflow. Baseflow generally makes up that greatest proportion of flow during the driest summer months (July-August), with smaller contributions to overall flow observed between October-February when surface runoff from rain is highest. The groundwater discharge contribution to Koksilah River flows is typically up to about 80% in August.

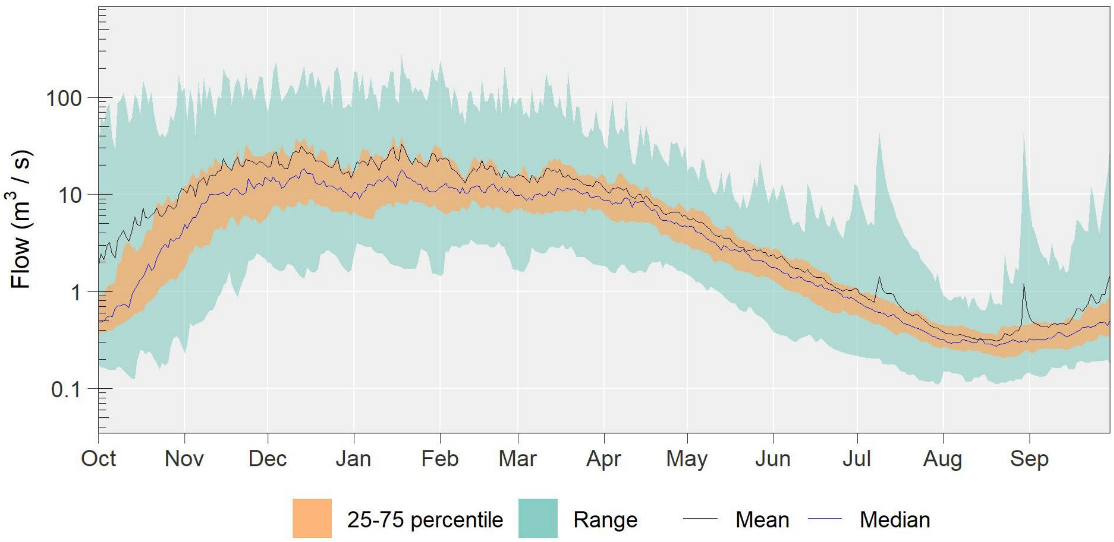
Figure 4.10 and Table 4.3 present the results of a frequency distribution curve of the 7-day low flows recorded at WSC gauge 08HA003 between the 1962 – 2019 water years. The analysis shows that the lower CEFT for Koksilah River of 180 L/s is predicted to have a return period of 4.35 years. The upper threshold of 490 L/s (5% of MAD) has a return period of about one year.

Figure 4.8 Gauged flow data on Koksilah River and tributaries.



Note: Data excluded from Koksilah River (08HA003) between 1914-1918 to improve visual clarity of record. Observations from Glenora Creek station 08HA002 include nine manual measurements in 1986 and 1998 from station 1AHA052, which is located approximately 300 m east of 08HA002.

Figure 4.9 Daily streamflow statistics for Koksilah River (08HA003 gauge).



Note: Daily statistics calculated from the analysis period for WSC station 08HA003 (1962-2019 water year)

Table 4.3 7-day low flow frequency analysis results for 08HA003.

Probability	Return Period (years)	7-day Low Flow (m^3/s)
0.01	100	0.104
0.02	50	0.114
0.04	25	0.127
0.05	20	0.131
0.10	10	0.149
0.20	5	0.173
0.23	**4.35**	**0.180**
0.50	2	0.232
0.80	1.25	0.308
0.98	1.02	0.464
0.99	1.01	0.509

Figure 4.10 Frequency distribution plot for 7-day low flows at 08HA003.

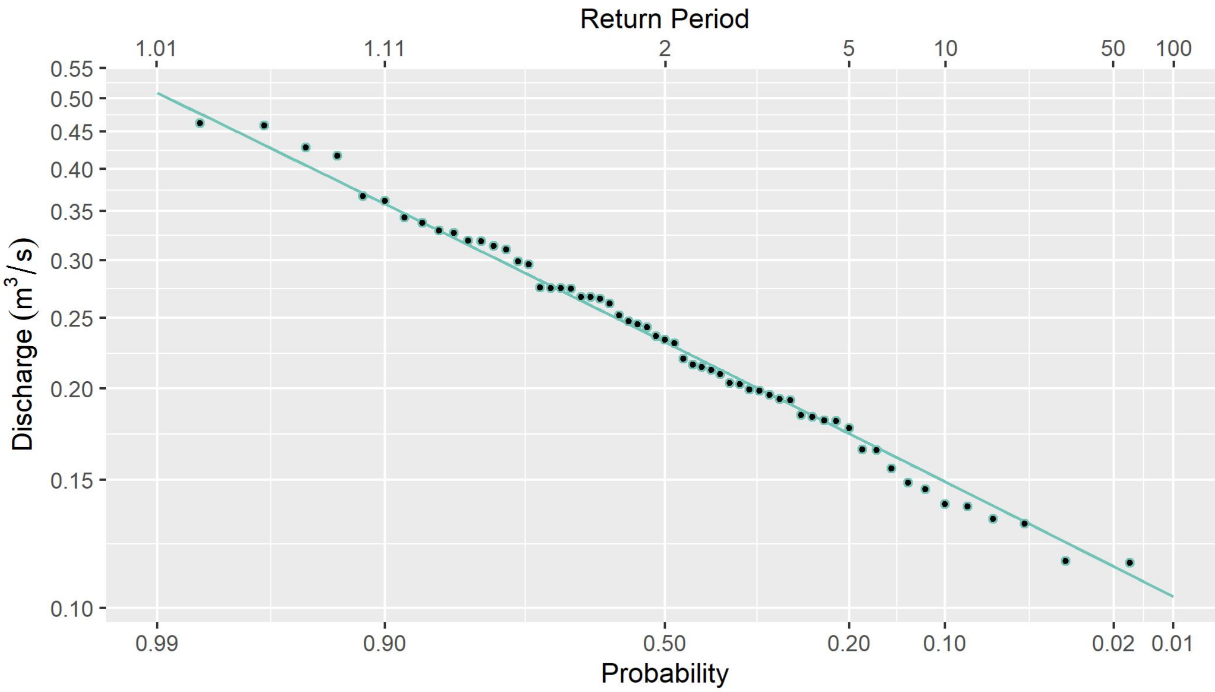


Figure 4.11 Mean monthly and annual flows and baseflow contributions at WSC gauge.

Note: In the mean monthly flow panel, the boxes represent median flow values (horizontal line) and 25th/75th percentile of monthly flows (lower and upper ends of boxes) while upper/lower whiskers of the boxes extend from the third/first quartile to the largest/smallest value no further than 1.5 times the inter-quartile range. Data beyond the end of the whiskers are outliers and are plotted individually as symbols.

4.1.3 Water Demand

There are 121 surface water licenses for various purposes ranging from domestic to irrigation for agricultural purposes, with POD's shown in Figure 4.12. Total licensed surface water volume in the watershed is 16,749 m^3/d, with 57% of this demand occurring downstream of the WSC gauge (Table 4.4). The 16,749 m^3/d estimate is approximately 10% lower than the surface water demand (consumptive use only) of 18,549 m^3/day provided in Barroso and Wainwright (in press), with this difference being attributed to the lower number of georeferenced licenses included in this study (121 versus 129 total licenses; Section 3.2.3).

A quarter of the surface water licenses are associated with large users (100 m^3/d or greater), and they are found along Koksilah River and its main tributaries (Glenora, Kelvin, Patrolas Creek). In addition, there are two very large (>1000 m^3/d) water use license near the confluence of Kelvin Creek (Figure 4.12), which is a quarry operation. The quarry has reported lower water usage relative to their license according to their operational records (Barroso and Wainwright, in press) but actual use is not incorporated in the analysis. Non-consumptive uses are shown in Table 4.4 (i.e., power generation and water storage) but they were excluded from consideration.

Table 4.4 Summary of licensed surface water use.

Licensed Purpose	Downstream of WSC 08HA003 (m^3/d)	Upstream of WSC 08HA003 (m^3/d)	Koksilah Watershed (m^3/d)
Domestic	81	127	208
Industrial	4,900	28	4,928
Irrigation[1]	4,347	5,522	9,869
Livestock	73	7	80
Pond & Aquaculture	136	0	136
Power: Residential[2]	0	1,210	1,210
Stream Storage: Non-Power[2]	27	266	293
Waterworks	23	0	23
Total (m^3/d)	**9,590**	**7,159**	**16,749**

Note: 1 Daily irrigation demand values represent average use over an assumed summer irrigation season of 183-days.
2 Licenses associated with these non-consumptive purposes are not shown in Figure 4.12.

The total groundwater demand incorporated in the current study is 13,190 m^3/day (Table 4.5), which is comparable to the groundwater demand estimate of 13,728 m^3/day in Barroso and Wainwright (in press). The 4% difference is attributed to the need to use of a subset of the provided dataset corresponding to locations also incorporated by Sivak and Wei (2019) for subsequent streamflow depletion analysis (Section 3.2.3). The overall processed groundwater and surface water demand for use in current study may therefore be downward biased by about 7% (29,939 m^3/day versus 32,277 m^3/day) relative to Barroso and Wainwright (in press).

The distribution (i.e., locations and relative volumes) of estimated groundwater use in unconsolidated deposits and bedrock is shown in Figure 4.13, Figure 4.14 and Figure 4.15, respectively, for the three aquifer types distinguished in the SDF and streamflow depletion analyses (Table 3.2). The lower volume cutoff of 2 m^3/day estimated water use, shown on these figures, corresponds to domestic water users. There is a total of 617 groundwater wells across these maps. There are relatively few groundwater users in unconsolidated unconfined aquifers, as most water wells are installed in unconsolidated confined aquifers and bedrock aquifers. Groundwater use in sand and gravel aquifers is predominantly located in the downstream portions of the watershed while bedrock groundwater use also occurs further upstream along the Koksilah River, where surficial aquifers are absent. Most of the estimated overall water demand occurs in sand and gravel aquifers (larger users) with small domestic use being dominant in bedrock aquifers.

While most groundwater wells in the watershed are for domestic users, domestic wells only account for 7% of the total water use volume across the entire Koksilah watershed (Table 4.5). Over half of the water demand by volume in is for agricultural purposes (56%), followed by waterworks (16%) and industrial (10%). About 65% of the overall groundwater demand occurs downstream of the WSC gauge and 35% is in the upstream watershed. The greatest groundwater demand in the upstream watershed is for agricultural (77%) purposes, whereas in the downstream watershed it is industrial (51%) and agricultural (47%) water use.

Table 4.5 Summary of estimated groundwater use.

Licensed Purpose	Downstream of WSC 08HA003 (m^3/d)	Upstream of WSC 08HA003 (m^3/d)	Koksilah Watershed (m^3/d)
Agriculture (irrigation) [1]	5,649	1,776	7,425
Agriculture (stock-watering) [1]	119	94	213
Domestic	484	420	904
Civic/Institutional/Recreational	644	26	670
Commercial	33	509	542
Industrial	1,273	4	1,277
Storage	0	12	12
Waterworks	412	1,734	2,147
Total (m^3/d)	**8,615**	**4,575**	**13,190**

1 Daily irrigation demand values represent average use over an assumed summer irrigation season of 153-days.

4.1.4 Groundwater-Surface Water Hydraulic Connectivity

Areas of inferred groundwater and surface water hydraulic connectivity are shown in Figure 4.13, Figure 4.14 and Figure 4.15 for the three different aquifer types and based on the work of Sivak and Wei (2019). For the overburden aquifers, predominant hydraulic connectivity is inferred to exist along the downstream to mid-watershed portions of the Koksilah River. Hydraulic connectivity is also inferred in the Patrolas Creek watershed (near Dougan Lake) and along Glenora Creek. For bedrock aquifers, the area of inferred hydraulic connectivity along the Koksilah River mainstem extends considerably further upstream than for the overburden aquifers.

4.1.5 Streamflow Depletion Factor Analysis

Most groundwater use in the watershed will ultimately have an influence on Koksilah River streamflow (i.e., groundwater use accessing deep bedrock aquifers that may be connected to the marine environment was assumed to be negligible). The distance to the nearest stream, aquifer material type, and degree of groundwater and surface water hydraulic connectivity will affect when the influence of pumping is observed in the river or its tributary streams. Generally, there is a time delay between the start of pumping and streamflow loss, which is expressed in by the streamflow depletion factor (SDF). The streamflow depletion factor is illustrated for the three aquifer types found in Koksilah, against the distance to the nearest stream (Figure 4.16a). The fastest response to pumping is seen for unconsolidated confined aquifers and the slowest response for bedrock aquifers. The streamflow response time to pumping in the watershed may range from less than a day (for those wells immediately adjacent to a surface water body) to over 10,000 days (i.e., more than 27 years) for more distant wells.

Figure 4.16b shows the cumulative percentage of groundwater demand in the watershed against the length of time until significant streamflow depletion (i.e., more than 28% of pumping rate; Section 3.2.4) is estimated to occur. Approximately 30% of groundwater use has SDF values of less than 100 days. Approximately 70% of groundwater use may impact nearby streams at more than 28% of the pumping rate within 1 year of pumping while less than 1% of groundwater demand is associated with SDF values greater than 10 years. This analysis suggests that streamflow depletion in the watershed in response to groundwater use is expected to be a relatively rapid response, for the most part on time scales of up to one year. While the SDF distribution for year-round and seasonal (irrigation) uses is somewhat different, they follow an overall similar pattern. The steps observed in the year-round water demand curve are attributed to large water users, such as industrial or waterworks operators.

Figure 4.12 Distribution of surface water use in the watershed.

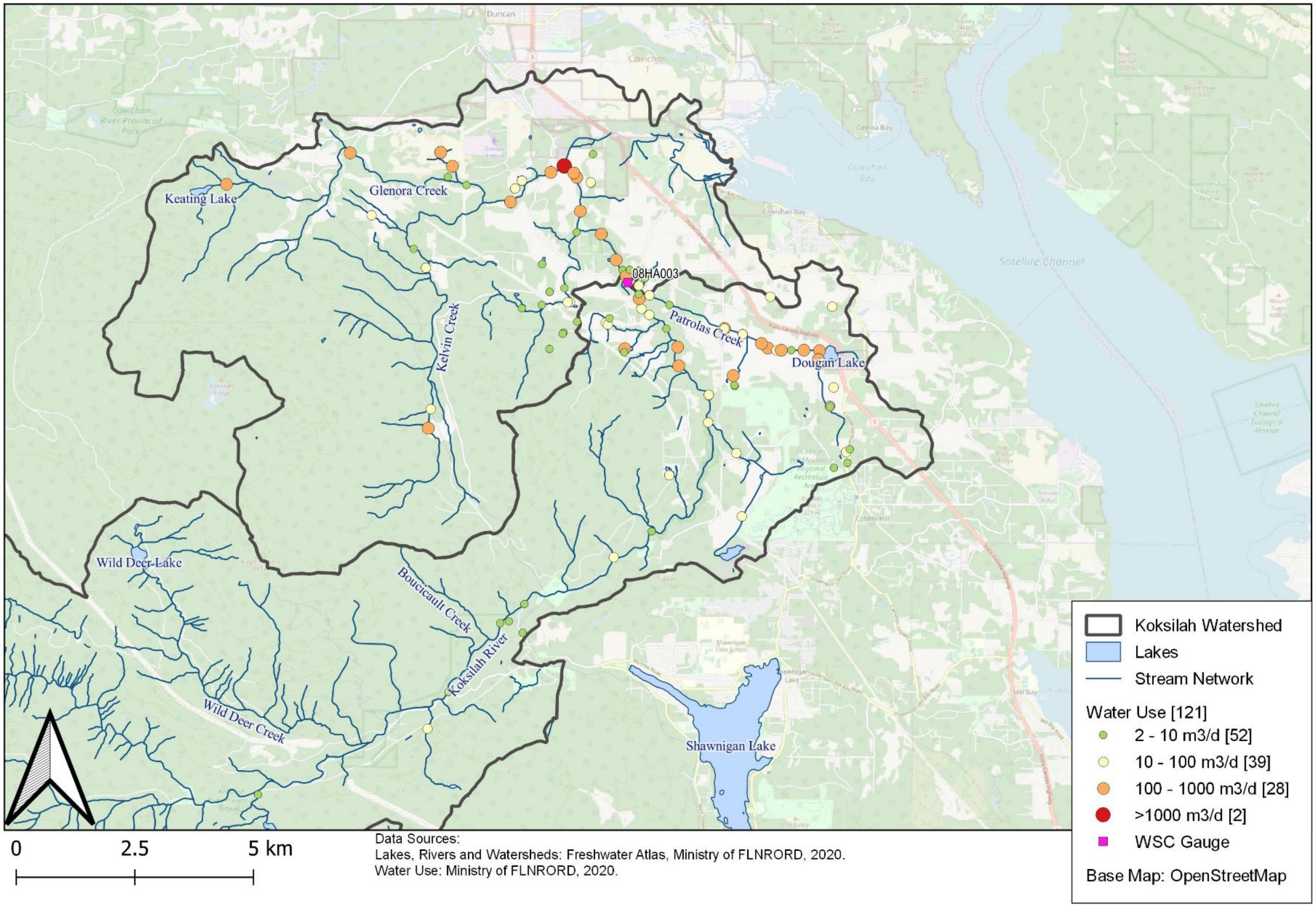
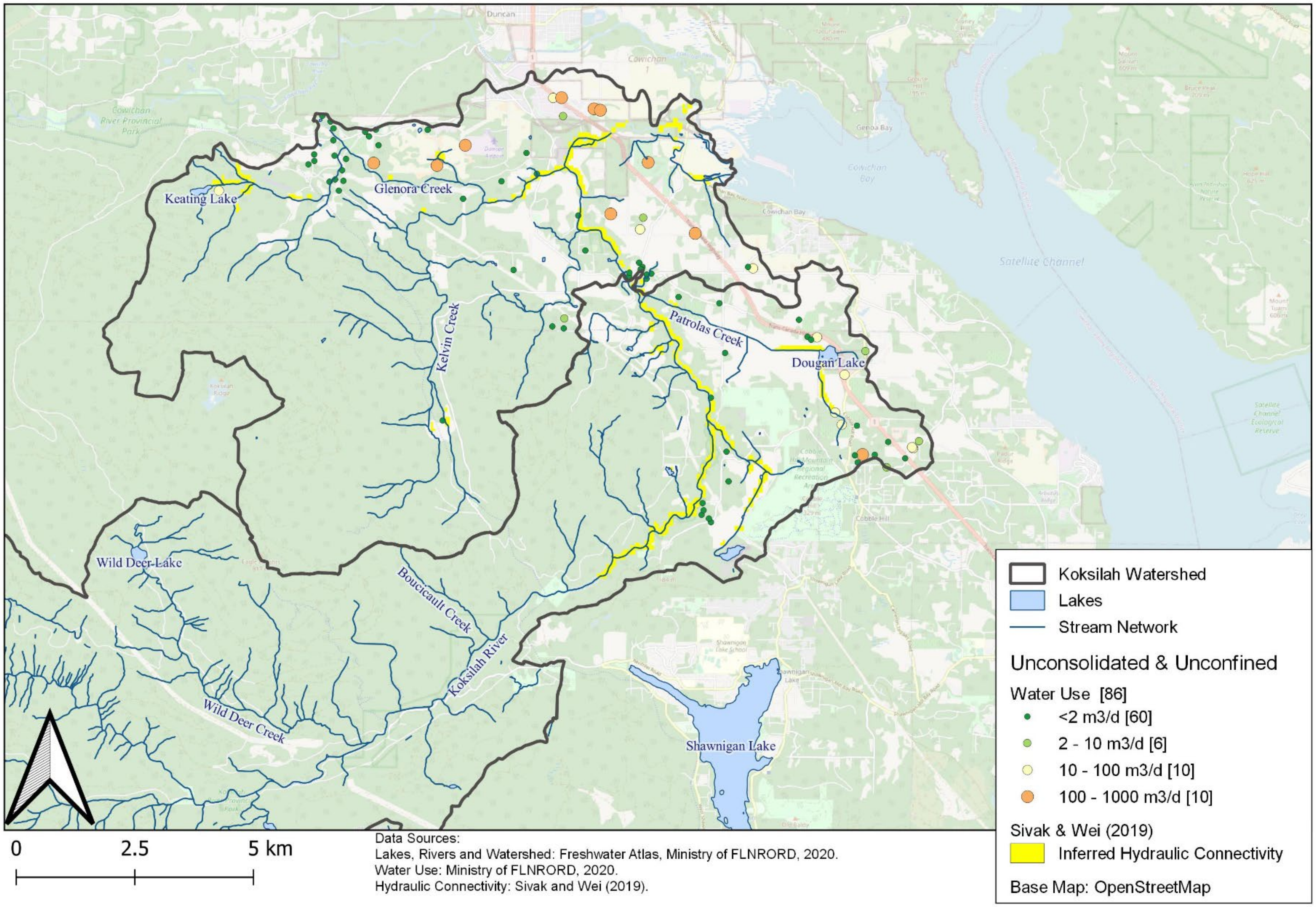


Figure 4.13 Groundwater use in unconsolidated unconfined aquifers.



Data Sources:
Lakes, Rivers and Watershed: Freshwater Atlas, Ministry of FLNRORD, 2020.
Water Use: Ministry of FLNRORD, 2020.
Hydraulic Connectivity: Sivak and Wei (2019).

Figure 4.14 Groundwater use in unconsolidated confined aquifers.

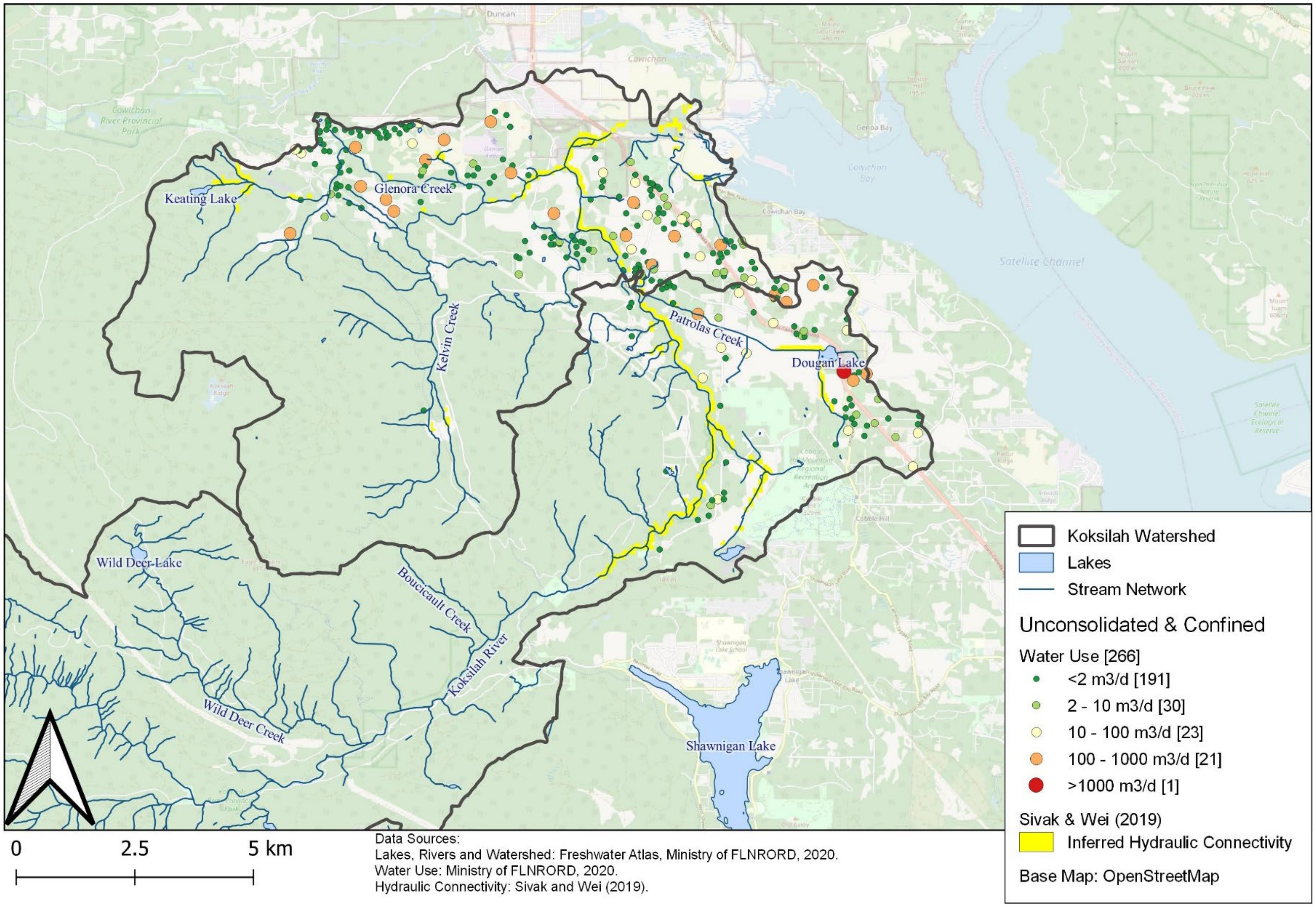


Figure 4.15 Groundwater use in bedrock aquifers.

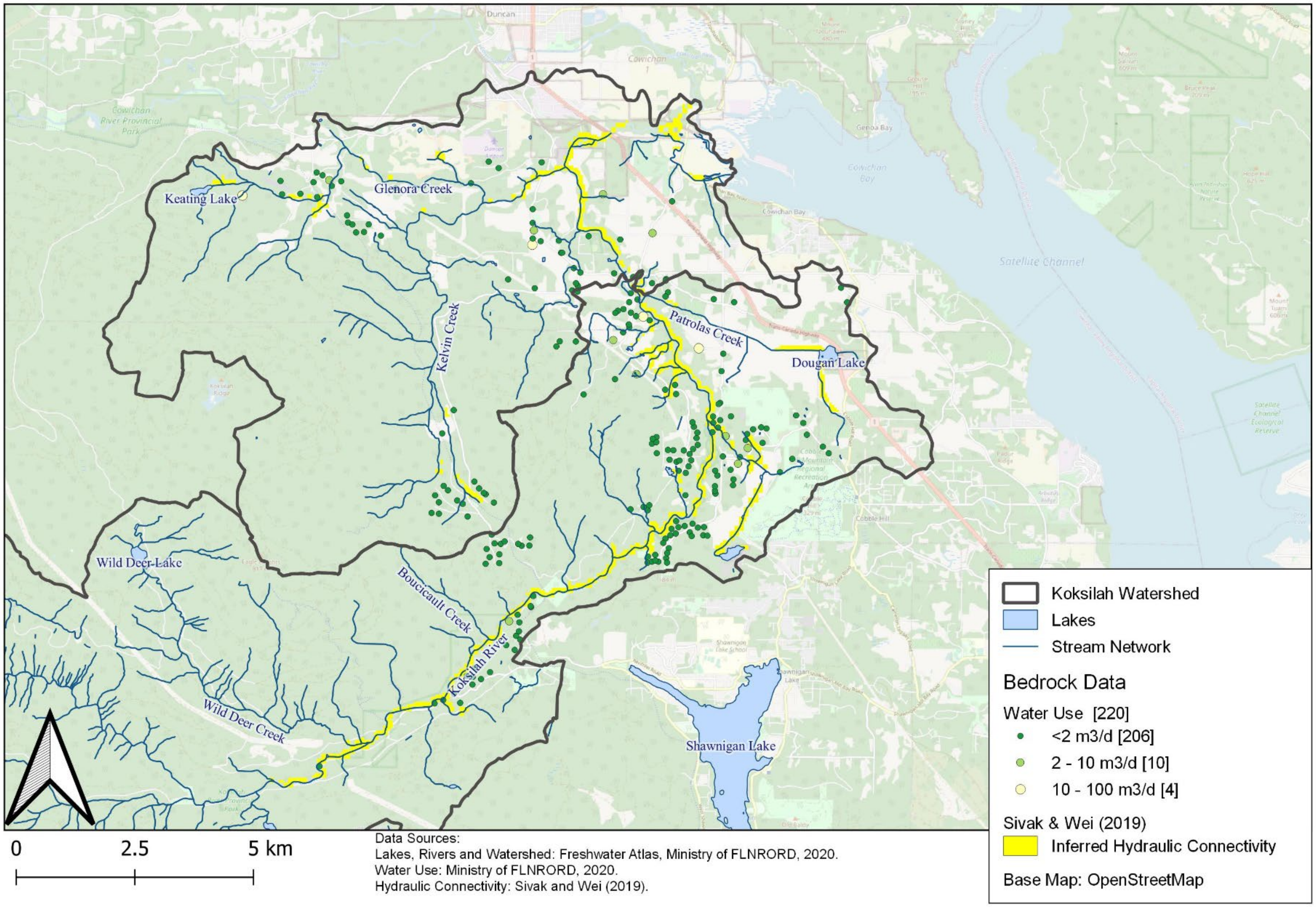
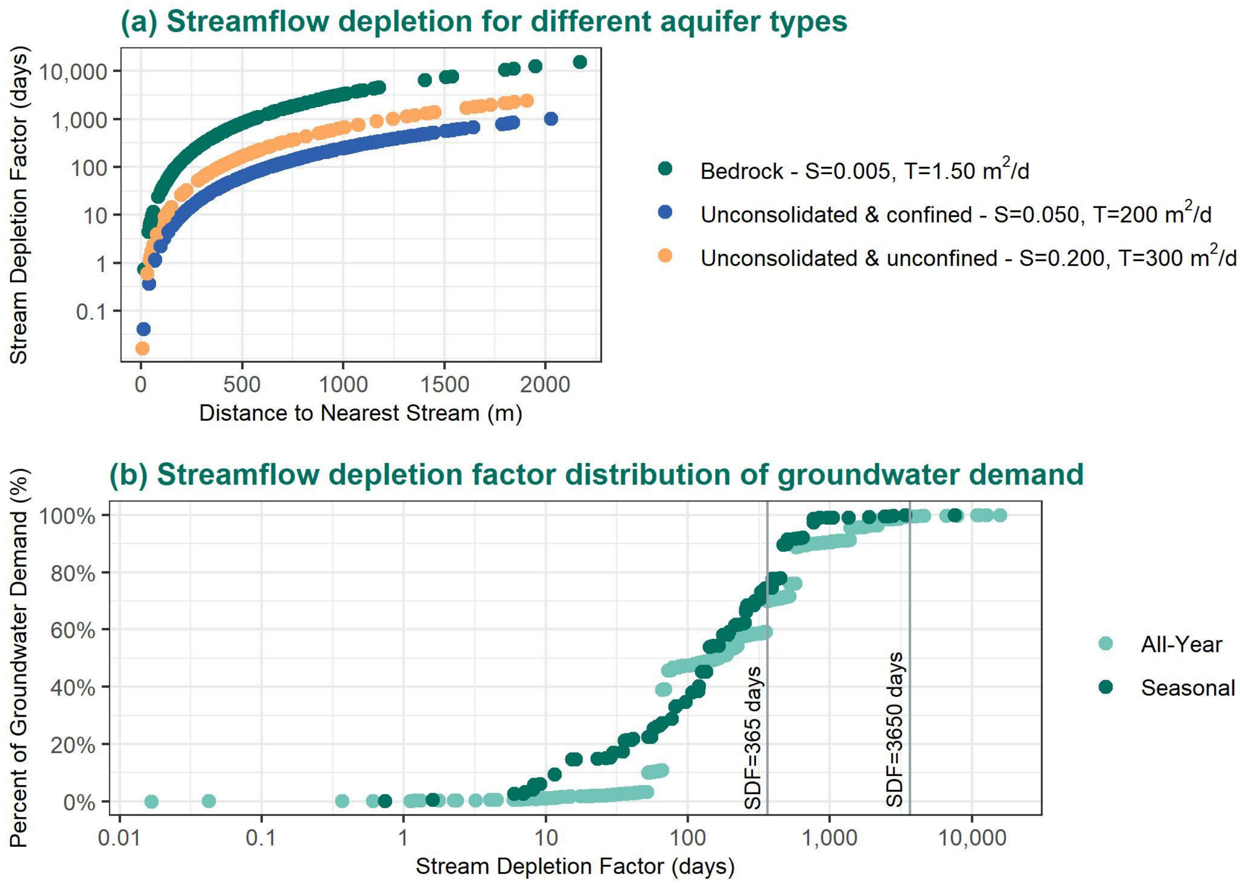


Figure 4.16 Streamflow depletion factor analysis.



4.1.6 Water Balance

A high-level long-term average (i.e., 1962 to 2019) water balance for the upstream portion of the watershed was developed from the preceding analyses (Table 4.6). It should be noted that there is relatively large uncertainty in precipitation inputs associated with the need to use gridded data, the presence of only a single nearby lower elevation climate station just outside the watershed (i.e., Shawnigan Lake), and no direct precipitation data (rain or snow) for higher elevations. ET was also based on gridded data and is not measured directly. However, there is only a 122 mm (7% of precipitation) discrepancy between watershed inputs (i.e., mean annual precipitation) and the total estimated outflows (surface water discharge, ET, water demand). This discrepancy may be impacted by uncertainty and/or bias in gridded precipitation but may also be attributable to ET. The value provided represents potential evapotranspiration, not actual evapotranspiration (AET), which is reduced relative to PET by factors such as soil water availability for plant root water uptake and vegetation physiological properties (stomata). In support of this assessment, Wang et al (2013) suggest AET for the east Vancouver Island region to be on the order of up to 600 mm for lower elevations and less than 500 mm for lower elevations in a Canadian wide study of the 1979-2008 period using a combination of remote sensing, climate, and land cover data. Despite the uncertainties in this preliminary analysis, the overall upstream watershed water balance appears reasonable and is useful to assess the relative importance of individual water balance components.

Table 4.6 Average annual water balance for upstream portion of the watershed.

	Component	Component Value (mm/yr)	Subcomponent Value (mm/yr)	Fraction of Precipitation (%)	Fraction of Discharge (%)
Input	Precipitation – PCIC Gridded Average	1874	N/A	N/A	
Outputs	Evapotranspiration – PCIC Gridded Average	646	N/A	34	
	Mean annual discharge (WSC gauge)	1334	N/A	71	
	Runoff	N/A	919		69
	Baseflow	N/A	415		31
	Mean annual water demand	16	N/A	1	
Error/Residual		122		16	14

The high-level water balance for the upstream watershed suggests that 71% of the water input to the watershed leaves via discharge at the WSC gauge and approximately 34% may leave via evapotranspiration (subject to the above-noted limitations of PET versus AET).

On an annual basis, current water demand only comprises 1% of the upstream watershed water balance. For water balance purposes, current (i.e., 2020) estimated groundwater and surface water demand (Table 4.4 and Table 4.5) excluding non-consumptive uses were used. The water balance ignores potential long-term declines in groundwater storage. Groundwater level trend analysis is discussed in Section 4.2.4 and provides no evidence for long-term declines in aquifer storage although data coverage is lacking.

Groundwater (415 mm) may comprise about 22% of the water balance. For bedrock aquifers on Gulf Islands, a recharge rate of 16% of precipitation was estimated, while limited previous recharge modelling in Lower Mainland BC (surficial aquifers) has obtained ranges from 32% to 65%. A Cobble Hill water balance study (Harris and Usher 2017) found that recharge may comprise anywhere from recharge the 12% to 55% of precipitation (spatially dependent), Therefore, the assessed importance of groundwater recharge in the Koksilah water balance appears reasonable.

4.2 HISTORICAL CHANGE ANALYSIS

The following sections analyze long-term trends in key climatic, hydrologic and other variables since the 1960s to the present period.

4.2.1 Climate

4.2.1.1 Temperature and Precipitation

Monthly mean precipitation and mean temperature during the 1962-2019 WY period show varying seasonal trends as illustrated in Figure 4.17. During the wet season, between October to March, variable positive (October, November, March) or negative (December, February) trends in precipitation are observed with no strong net effect over this period. Over the summer low flow season, Figure 4.17 shows a consistent potential decline in precipitation, although these trends are weak. In contrast, monthly mean temperature shows strong increasing trends from the 1960s to present, particularly during the warmer part of the year between April to September, with monthly temperature increases of up to 5^0C during the summer months.

Precipitation and snow data from spatially averaged ClimateBC output (PCIC analysis) and for the Shawnigan Lake climate station are shown in Figure 4.18. The top panels show the mean annual snow and precipitation values over the 1962-2019 analysis period, and the remaining rows show seasonal trends over 3-month periods (i.e., DJF represents December, January, February, etc.). The outputs suggest that annual precipitation has remained relatively constant over the 1962-2019 period (Shawnigan Lake station) or may have slightly increased (PCIC analysis) while annual snowfall amounts may have declined from about 300 mm in the early 1960s to 200 mm at present, with this latter trend possibly related to increasing temperatures (Figure 4.17). On a seasonal basis, precipitation from both Shawnigan Lake station and PCIC outputs shows a possible increase during spring (March to May; MAM) and fall (September to November; SON), and a decrease during the summer period (June to August; JJA), though none of these trends are significant. Shifts in rainfall patterns (frequency and intensity) were also noted as a community concern (Section 1; Modus 2020).

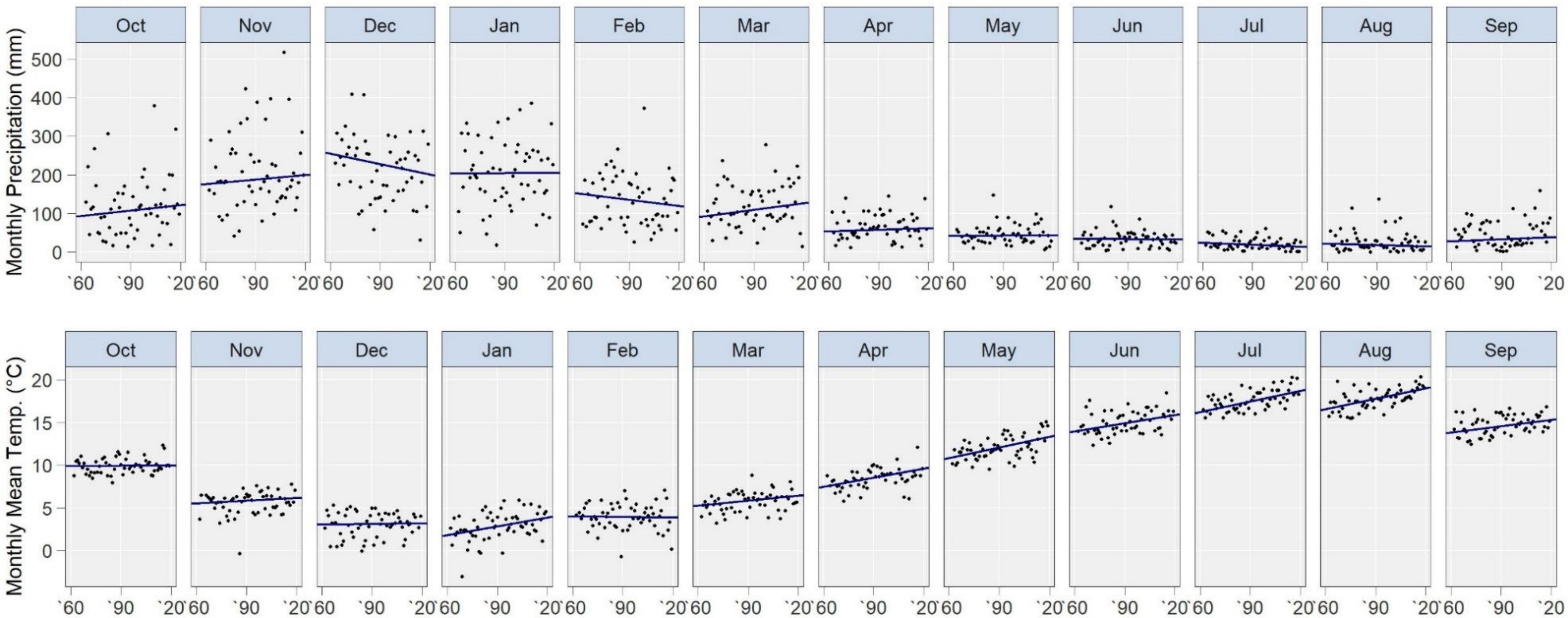
Temporal patterns in daily SWE at Jump Meadows (2003-2020), located approximately 35 km northwest of the north watershed boundary, are shown in Figure 4.19. In the most recent period since 2012 (B panel of Figure), there appears to be a trend towards declining maximum SWE and a shift to earlier snow melt compared to the previous period until 2011 (A panel). These trends are expected to be even stronger for the Koksilah watershed due to its lower elevation.

4.2.1.2 Evapotranspiration

The increasing trend in temperature, and changes in seasonal precipitation may have an influence on evapotranspiration in the Koksilah watershed, which in turn is expected to impact seasonal flows in streams. Figure 4.20 illustrates reference evapotranspiration (PET) results over the 1962-2019 WY period for the latitude of the Shawnigan Lake climate station that were obtained using three different methods.

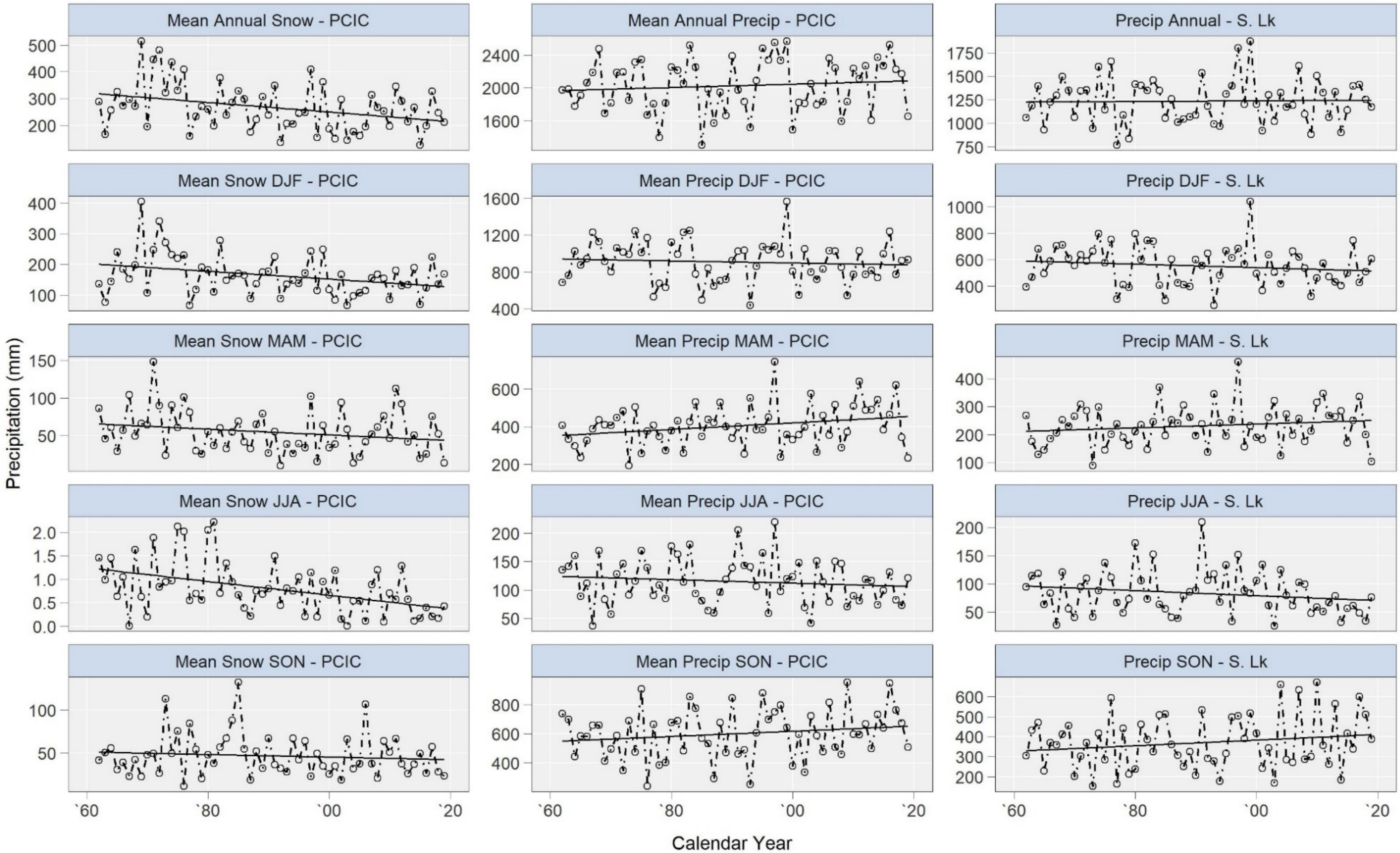
The Hargreaves evapotranspiration results extracted from the ClimateBC dataset show a muted increase in evapotranspiration since the 1960s (Figure 4.20), which does not correspond well with the strong increasing temperature trends observed in the watershed (Figure 4.17). For comparison, Hamon’s PET extracted using the USGS Water-Balance Model shows a significant increase in PET. Lastly, Hargreaves PET was manually calculated through the R package ‘Evapotranspiration’ using daily Shawnigan Lake weather station data. This manual calculation provides PET results that are intermediate between the ClimateBC and USGS extremes and was the dataset used for most subsequent hydrologic change analyses. The PET changes calculated by this method are compatible with the available literature, which suggests that a 3-5% increase in PET for each degree change in temperature may be expected (e.g., Yates and Strzepek 1994).

Figure 4.17 Long-term changes in monthly precipitation sums and monthly mean temperature at Shawingan Lake.



Note: Temperature and precipitation observations are directly from the Environment Canada weather station at Shawnigan Lake. Observations are summed over the Water Year, which runs from October 1 – September 30.

Figure 4.18 Annual and seasonal patterns in precipitation across watershed (PCIC analysis) and for Shawnigan Lake station.



Note: Seasonal precipitation from the PCIC ClimateBC datasets were averaged over seasonal precipitation rasters of the upper watershed for each year. Precipitation for the right panel (S. Lk) were summarized directly from the Environment Canada weather station at Shawnigan Lake.

Figure 4.19 Daily snow water equivalent at Jump Creek (2003-2020).

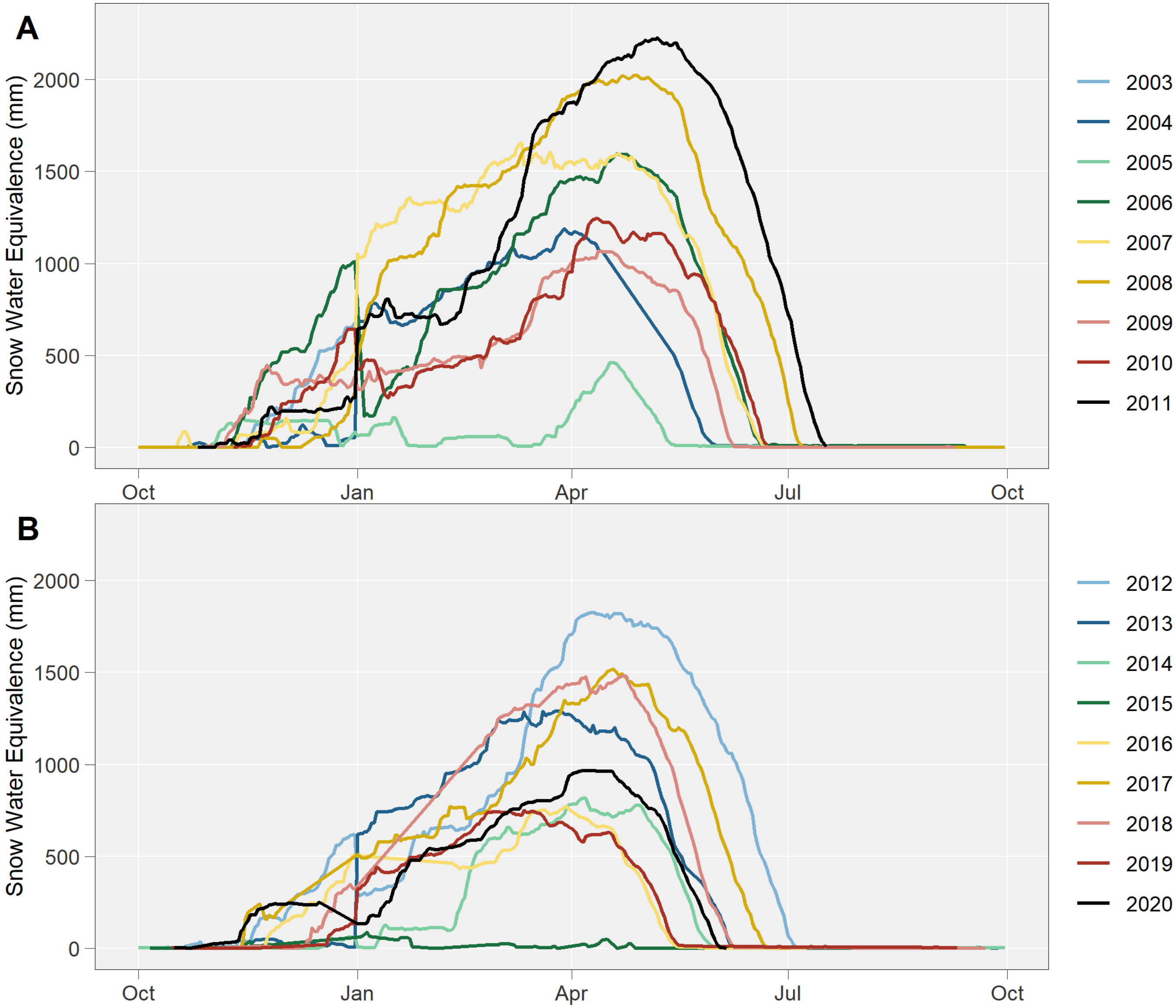
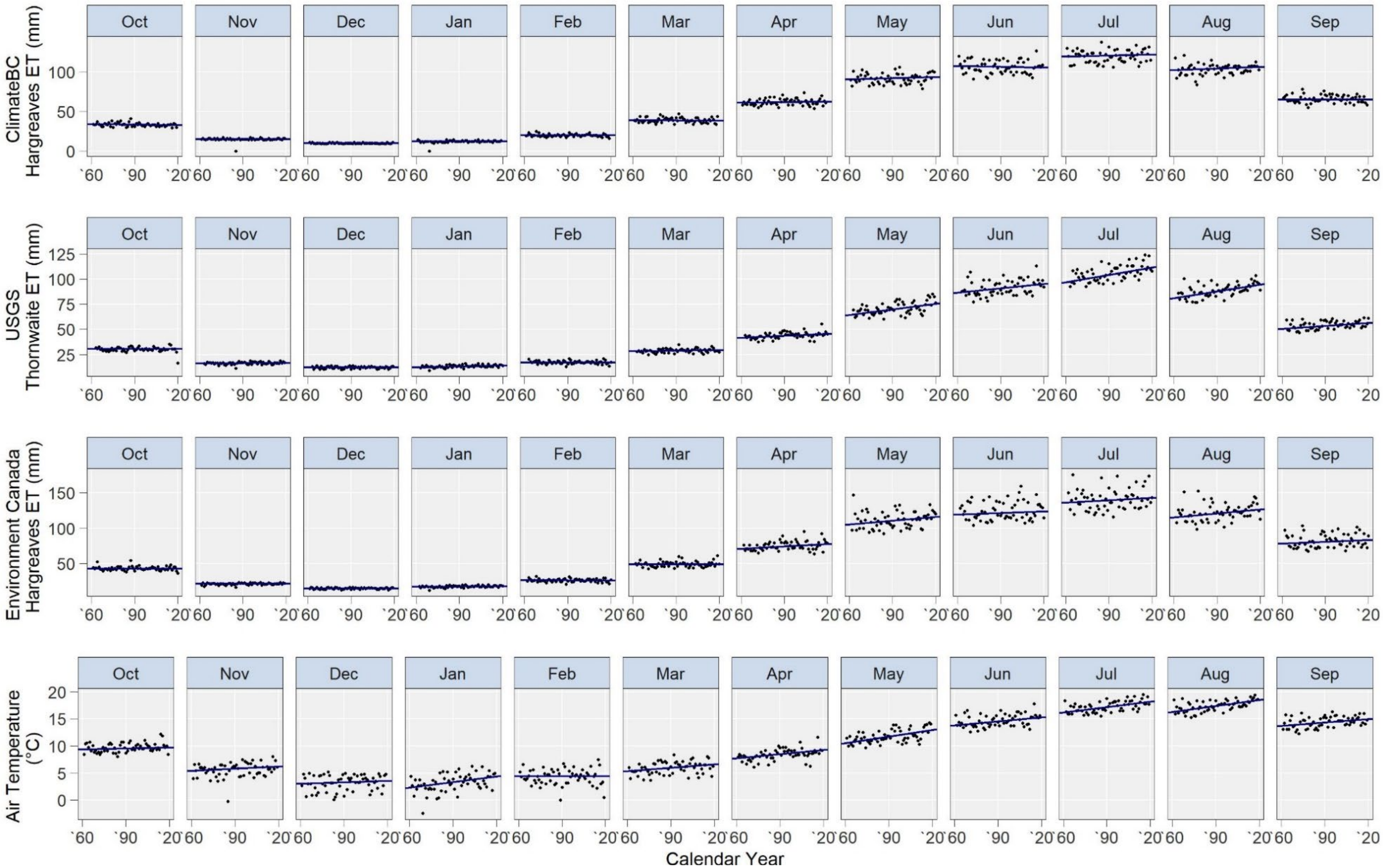


Figure 4.20 Long-term changes in evapotranspiration at Shawnigan Lake derived using three algorithms.



Note: ET was calculated using one of three methods: the first panel shows ET extracted directly from the ClimateBC Hargreaves monthly ET raster for a pixel located at Shawnigan Lake, the second panel shows ET extracted using the USGS monthly water balance model for the latitude of Shawnigan Lake, and the third shows ET manually calculated using the Hargreaves equation and daily observations from the Shawnigan Lake Environment Canada weather station.

4.2.2 Hydrology

4.2.2.1 Monthly and Seasonal Flow Changes

Long term trends in monthly mean flows at the WSC gauge are compared against long-term monthly precipitation and temperature trends (from preceding analyses) in Figure 4.21. Mean flows are shown on a log scale axis to accentuate the low flows occurring during summertime. This highlights the strong decreasing trend in summertime low flows over the 1962 to 2019 WY period, as previously documented (e.g., NHC 2019). During the wet season, between October to March, no strong positive or negative trends in streamflows are observed, like what was noted for monthly precipitation.

Long-term changes in the groundwater contribution (baseflow) to the Koksilah River were also evaluated (Figure 4.22). The baseflow contribution to stream discharge is lowest during the wet season (20-30%). In August, when annual flows are typically lowest, groundwater contributes up to approximately 80% of overall streamflow. A decline in the August and September groundwater contributions is noted over the 1962 to 2019 period. It is therefore evident that groundwater is a significant factor in declining summertime flows in Koksilah River, a finding that is in line with the increase in water temperatures noted as a stakeholder concern (Section 1.0) given that groundwater inflows act to cool stream temperatures in summer. This is illustrated further in Figure 4.23, which compares long-term mean monthly flow, baseflow and runoff. Declining trends in flows over the summer season are evident in both the baseflow and runoff components of overall discharge, though the declining trends are greater for baseflow. The declining trend in runoff over the summertime period is possibly directly correlated to declining summertime precipitation as runoff generation occurs over short time frames.

4.2.2.2 Annual Flow Changes and Shifts in Timing of Flows

Long-term trends in annual baseflow and overall discharge for the upper watershed are illustrated in Figure 4.24. While baseflow shows a slight non-significant declining trend, there is no notable long-term trend in mean annual discharge. Given the strong trends that are evident in the monthly flow data, this annual analysis suggests that changes in the timing of flows may be an important consideration for understanding possible causes of the declining summertime flows.

Possible changes in the timing of flows are investigated further in Figure 4.25 which shows mean monthly baseflows (logarithmic scale to emphasize changes) averaged for different decades from the 1960s to 2020. There are modest shifts evident in the timing of the onset of the decline in baseflow at the end of the wet season:

- In the 1960s and 1970s, the decline in baseflow appears to begin approximately mid-April;
- in the 1980s and 90s this decline in flows occurred in early April; and
- During the most recent decades, the onset of the decline in flows appears to occur later again.

Snowmelt and/or shifts in seasonal precipitation could be causal factors in these flow decline timing shifts. However, in the last decade, snowmelt at Jump Creek has started occurring earlier (Figure 4.19), while the snowpack also appears to have become smaller. This earlier snowmelt in the last decade is an opposite shift to the later onset of flows declines in recent decades. Alternatively, it is possible that the timing shifts reflect interaction of the forest canopy with snow processes with the earlier onset of the decline in flows in the 1980s and 90s coinciding with the period of industrial logging (i.e., accelerated snowmelt in clear-cuts) and the shift to a later onset of the decline in flows in recent decades corresponding to forest regrowth in former clear-cuts (i.e., more shading leading to slower melt rates). However, the timing shifts in onset of flow decline may also be related to shifts in seasonal precipitation, with a long-term increase in spring (March-May) precipitation noted (Figure 4.18). Overall this analysis is therefore inconclusive.

Figure 4.25 further suggests decadal changes in the rate of baseflow decline over the springtime period:

- The rate of this decline (slope of curve) was most gradual in the 1980s and 90s.
- The rate of the decline was steeper in the 1960s and 70s and is also relatively steep in the most recent two decades.

These changes in the rate of baseflow decline may be related to changes in evapotranspiration due to forest cover change (historical forest management) and climate change, affecting groundwater recharge (Section 5.0).

Finally, a drop in lowest summertime baseflows is evident in Figure 4.25, which may be related to rising water demand.

4.2.2.3 Low Flows and Climatic Variability

A complicating factor in relating long-term trends in summertime low flows to long-term climatic trends is the potential effect of climatic oscillations (i.e., climate variability), such as El Nino/warm and La Nina/cold Pacific Decadal Oscillation (PDO) phases. These oscillations operate on a decadal time scale, and their fluctuations can be greater than changes in mean climatic variables on a century scale (Rodenhuis et al. 2009). Figure 4.26 illustrates departures of the annual 7-day low flow magnitude from the lower CEFT (180 L/s), as defined by Barroso and Wainwright (in press) and the PDO index. Between the 1960s and early 1980s, the 7-day low flows were consistently well above the CEFT. These early years correspond to a cool phase of the PDO although the 1980s were characterized by a warm phase. The 2000s are characterized by having frequent flows close to or below the CEFT, and coincide with a strong cool phase of the PDO followed by a weaker warm phase. Visual comparison of PDO vs CEFT departure does not suggest any strong correlation between PDO and departure. To better assess the potential impact of PDO cycles on summertime flows, the 5-year running average of the PDO index was plotted against the 7-day low flow magnitude (Figure 4.27). The scatterplot also shows that while there is a weak trend towards warmer PDO years having lower flows, the trend is not significant.

4.2.2.4 Frequency Duration Curve Analysis

The trend to lower summertime flow magnitudes and more prevalent low flow periods in the last decades is illustrated by Figure 4.28 and Table 4.7, which are based on a frequency duration curve analysis of daily flows classified by decade. The magnitude of the 2nd percentile low flow has dropped by about 40% between the 1960s and 2010s (0.28 m^3/s to 0.17 m^3/s). The largest drop in the 2nd percentile daily flows appears to have occurred in the 1970s and 1980s. The largest drop in the 20th percentile daily flows also occurred in the 1970s, a period characterized by a large growth in water demand (Section 4.2.3). Figure 4.28 further illustrates the increase in frequency (duration) with which daily flows drop below the upper and lower CEFT in recent decades. In the last decade, daily flows were below the upper CEFT about 20% of the time while in the 1960s this only occurred about 13% annually.

The 2nd percentile low flow rose briefly in the 1990s (Table 4.7) before declining again in recent decades. The 1990s were also characterized by relatively frequent high flows (Figure 4.28). Both effects are possibly correlated with the period of intense logging in the watershed (i.e., reduced ET leading to higher summertime flows and lack of rainfall interception increasing peak flows) although this possible relationship cannot be determined with certainty.

4.2.2.5 End-Member Low Flow Analysis

The years with the 15 highest and 15 lowest 7-day low flows were selected to further investigate potential causal climate factors affecting low flows (i.e., potential for correlation with particularly hot or dry summers). As shown in Table 4.8, the lowest flows are overall characterized by 43% less summer precipitation and summer temperatures that are approximately 2ºC higher on average, as well as longer summertime drought periods (i.e., duration of periods without any precipitation). Temperature appears to be the main correlating factor. All 15 years with lowest 7-day low flows are characterized by summertime temperatures that are above the average summertime temperature of the 15 years with highest 7-day low flows. Conversely, summertime precipitation for the 15 years with lowest 7-day low flows is both above and below the average summertime precipitation of the 15 years with highest 7-day low flows. The lowest recorded 7-day low flow in 2015 is also the hottest summer on record (19.3 ^{0}C). It is noted that a hot summer could correlate with an increase in plant evapotranspiration and an increase in human water consumption. Conversely the second lowest recorded 7-day low flow in 1985 does not correspond to conditions that were particularly hot (17.0 ^{0}C is below average for the 15 years with smallest 7-day low flows). There are also two relatively wet summers among the 15 lowest 7-day low flows (1995 and 2007). Lack of unambiguous correlations reflects that one-on-one comparisons of low flows with possible causal factors are difficult because these comparisons ignore the compounding role of antecedent watershed conditions. Long-term trends in causal factors may be more important than conditions in any particular year.

Figure 4.21 Comparison of long-term trends in monthly flows at WSC gauge with climate variables at Shawnigan Lake.

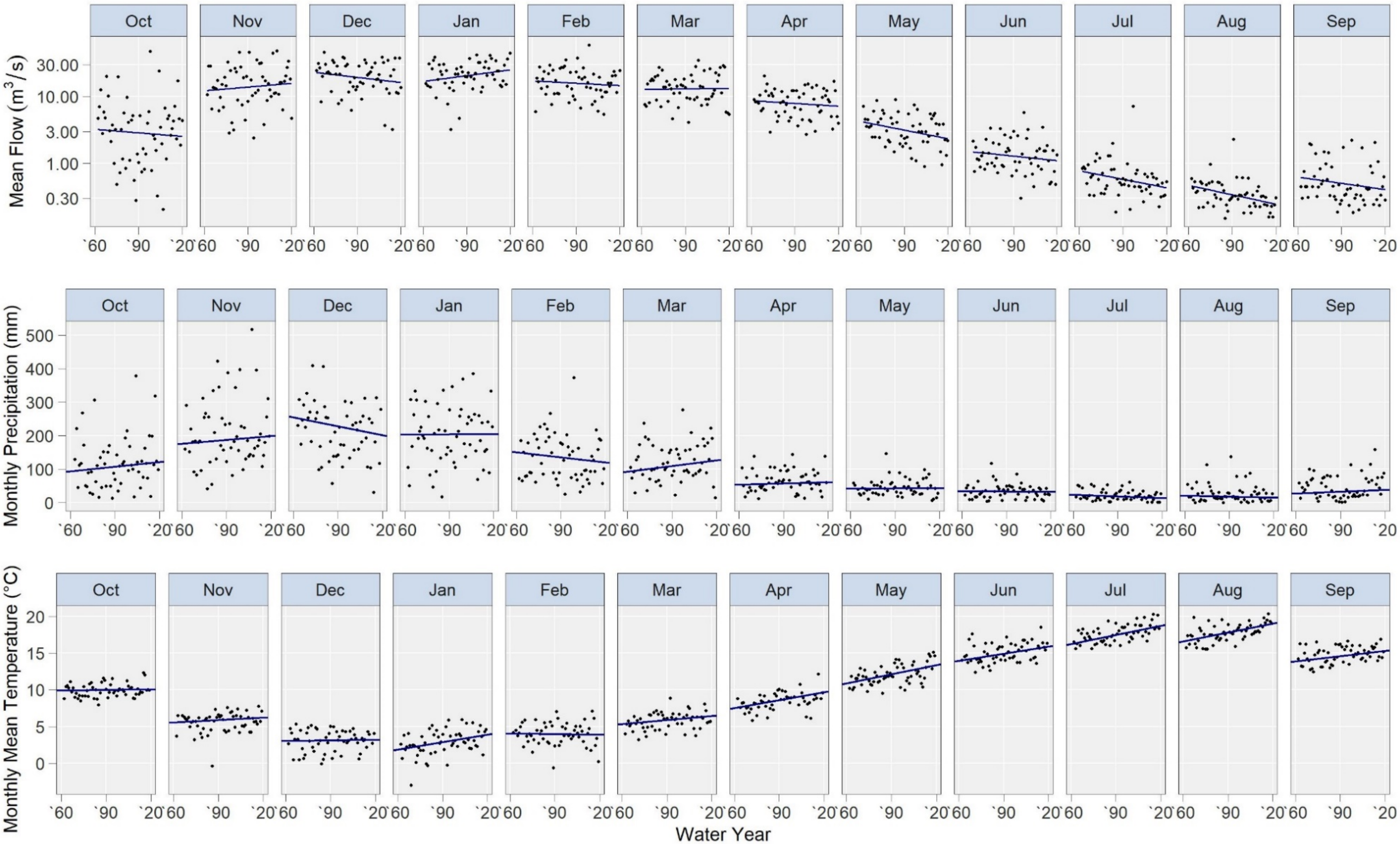


Figure 4.22 Long-term trends in contribution of groundwater to monthly flows at WSC gauge.

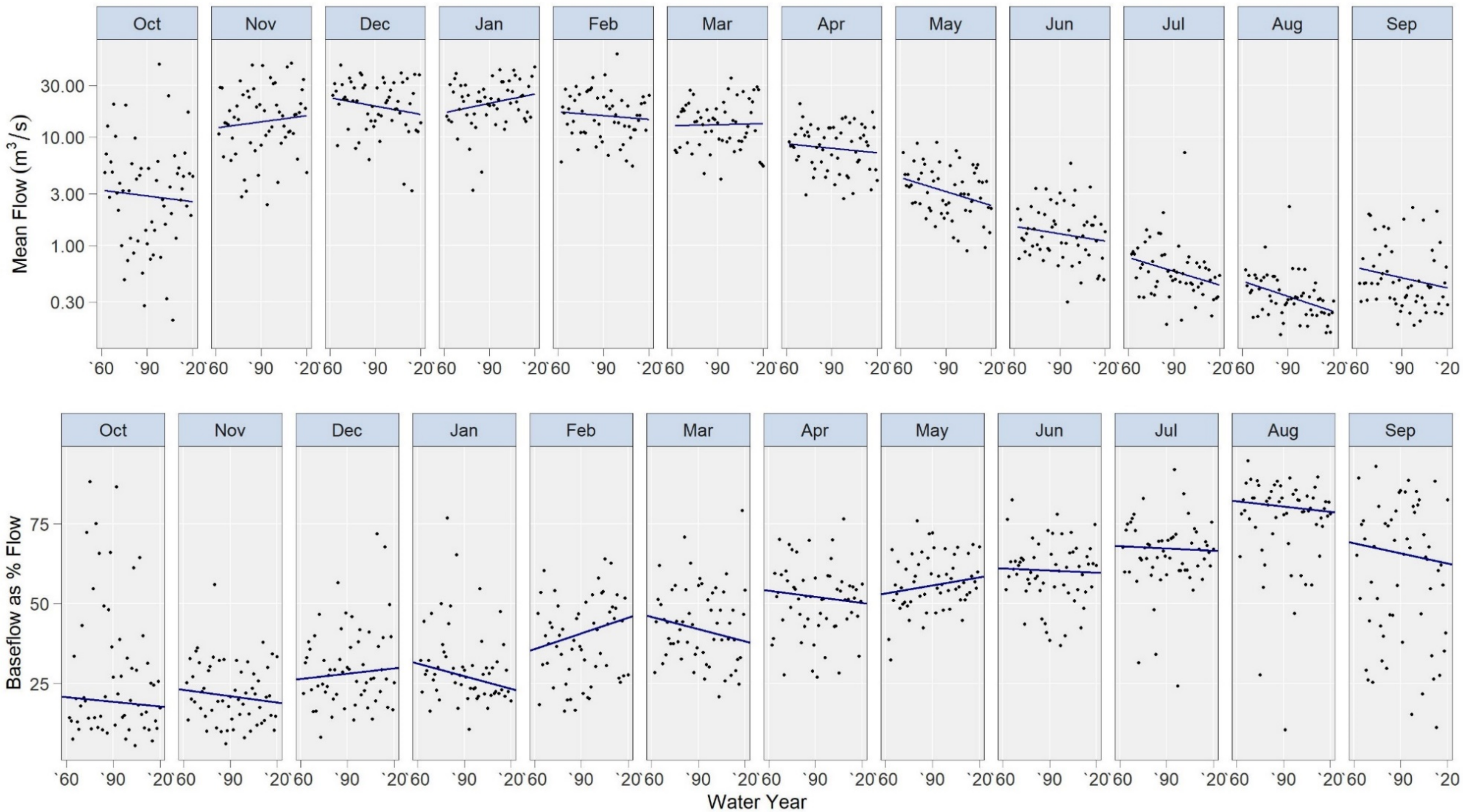


Figure 4.23 Long-term monthly trends in runoff and baseflow at WSC gauge.

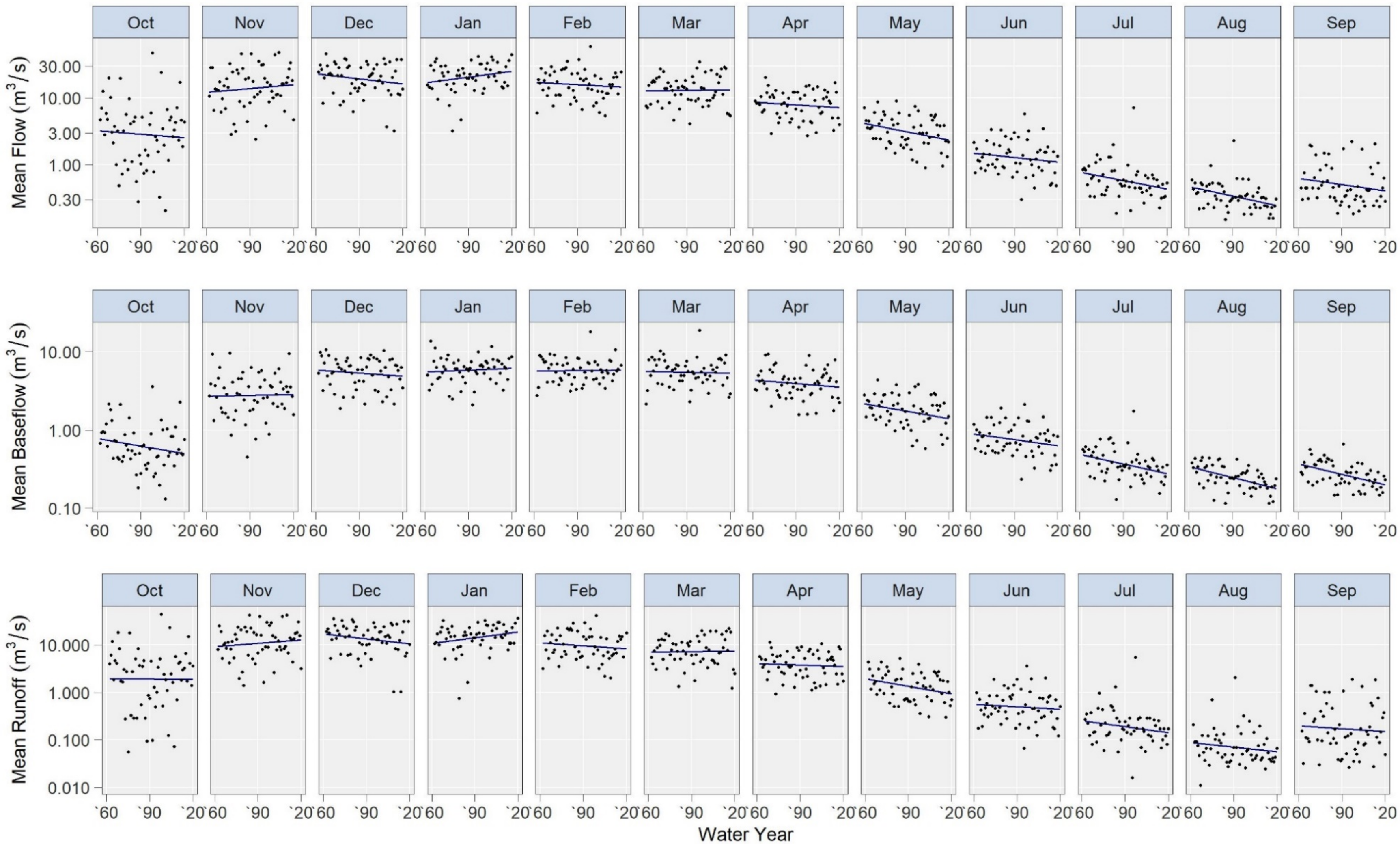


Figure 4.24 Long-term trends in annual baseflow and total discharge at WSC gauge.

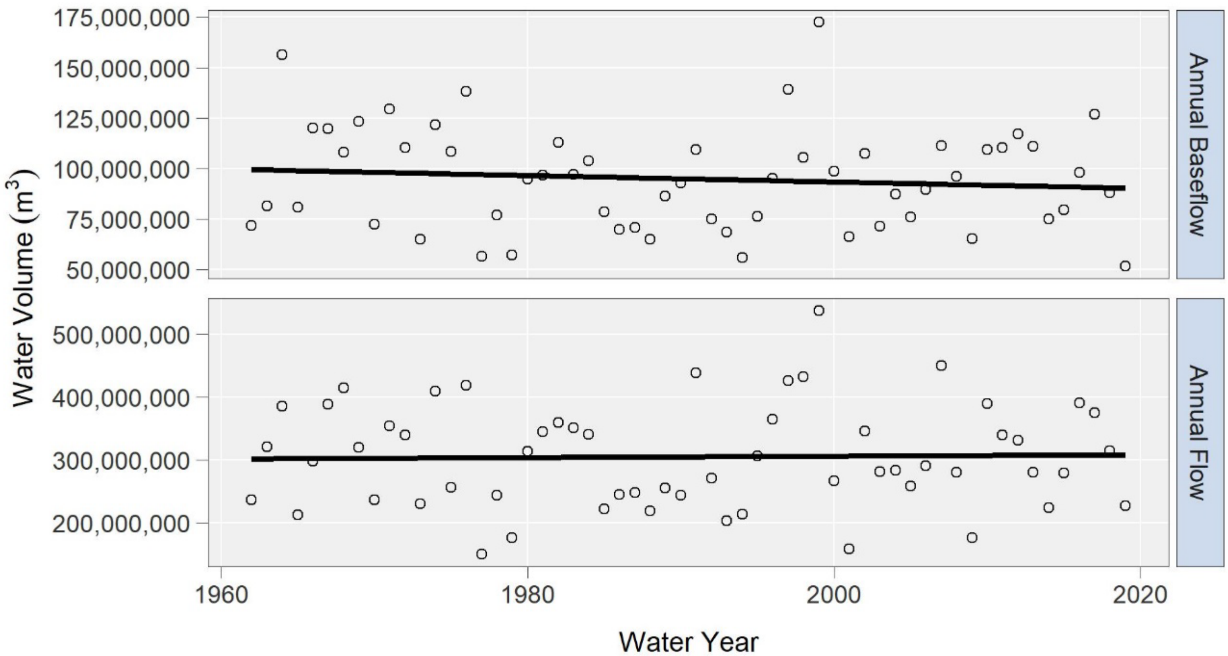


Figure 4.25 Average monthly baseflow at WSC gauge organized by decade.

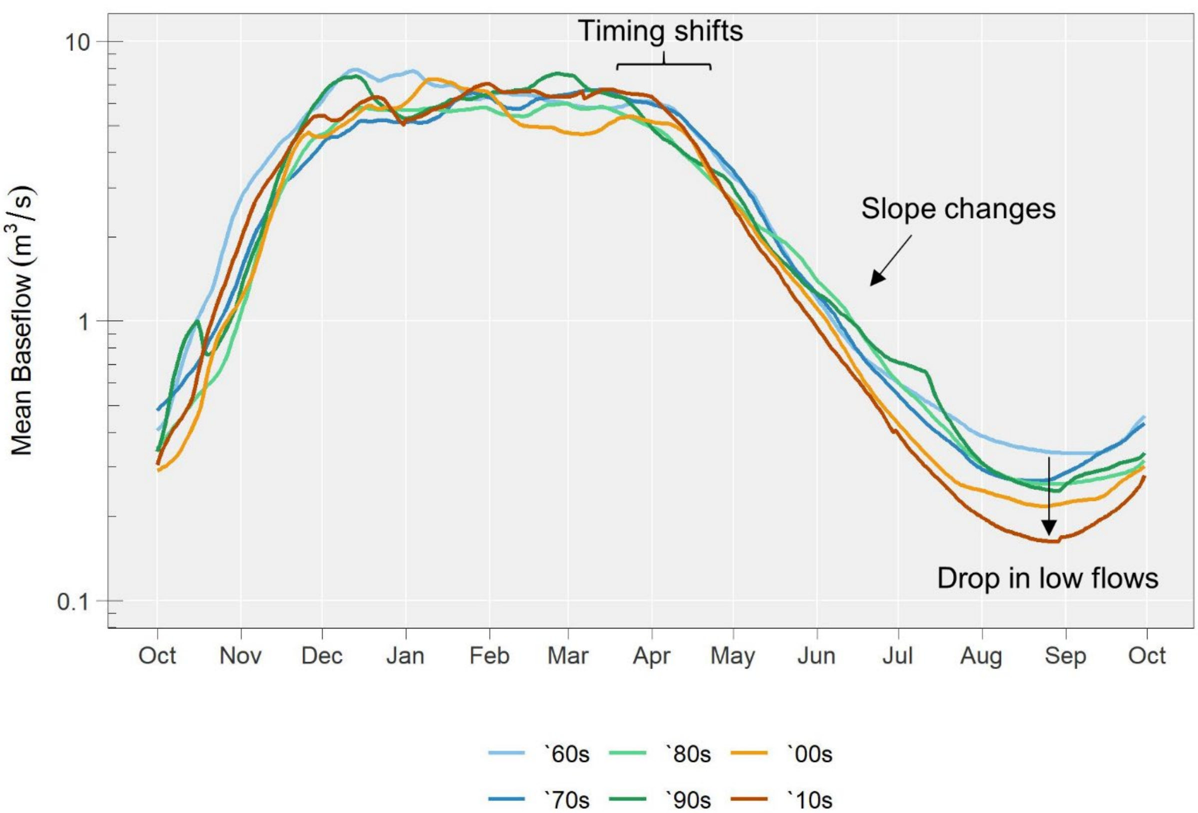
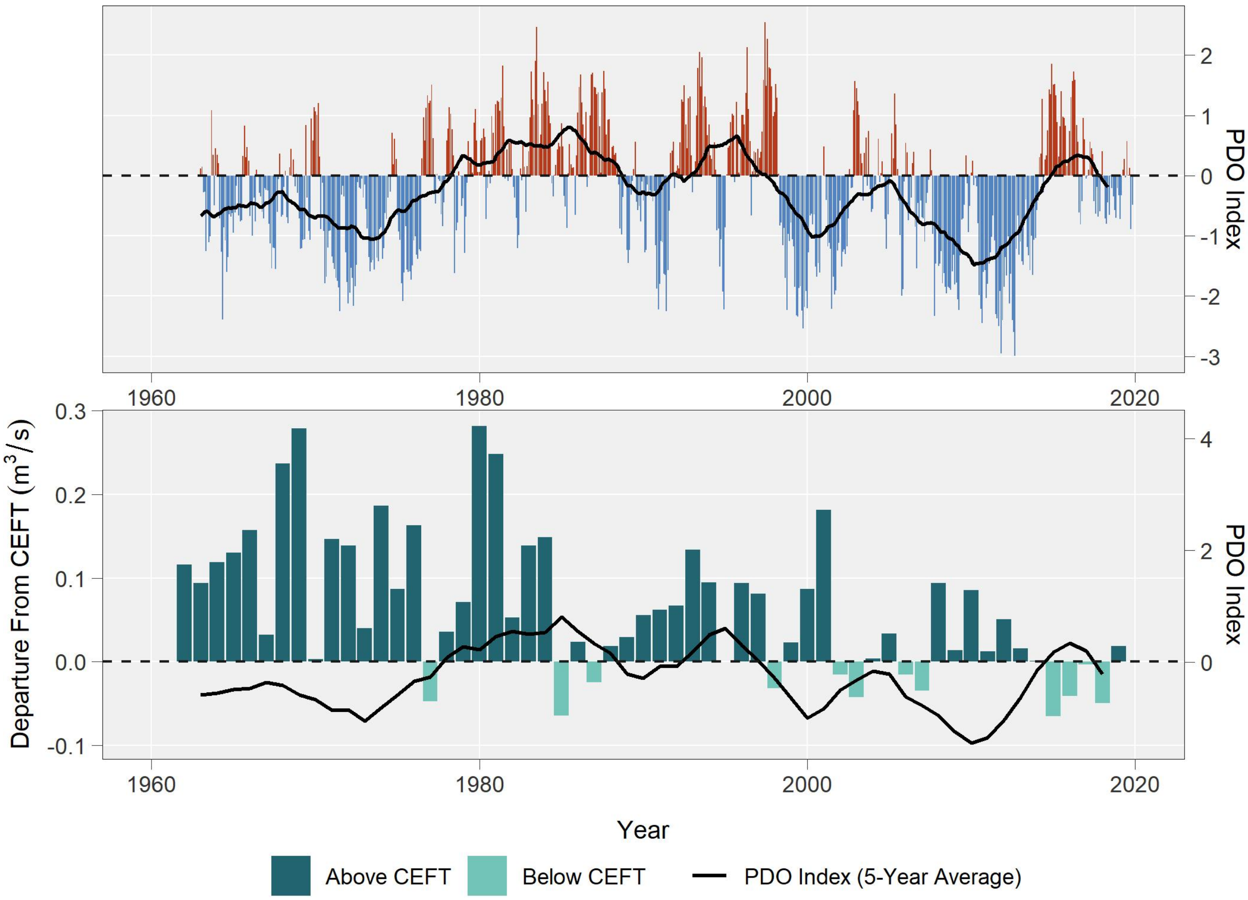


Figure 4.26 Time series comparison of magnitude of 7-day low flows with PDO index.



Note: Figure presents the departure of annual 7-day summertime flows from the lower critical environmental threshold value of 0.18 m^3/s. Flows above the critical environmental flow threshold (CEFT) are shown in dark green, and those below the threshold shown in light green. The top panel shows annual PDO index values in red (positive values) and blue (negative values) together with 5-year running average. Monthly PDO index values downloaded from https://www.ncdc.noaa.gov/teleconnections/pdo/

Table 4.7 Changes in magnitude of daily flows by decade and flow percentile.

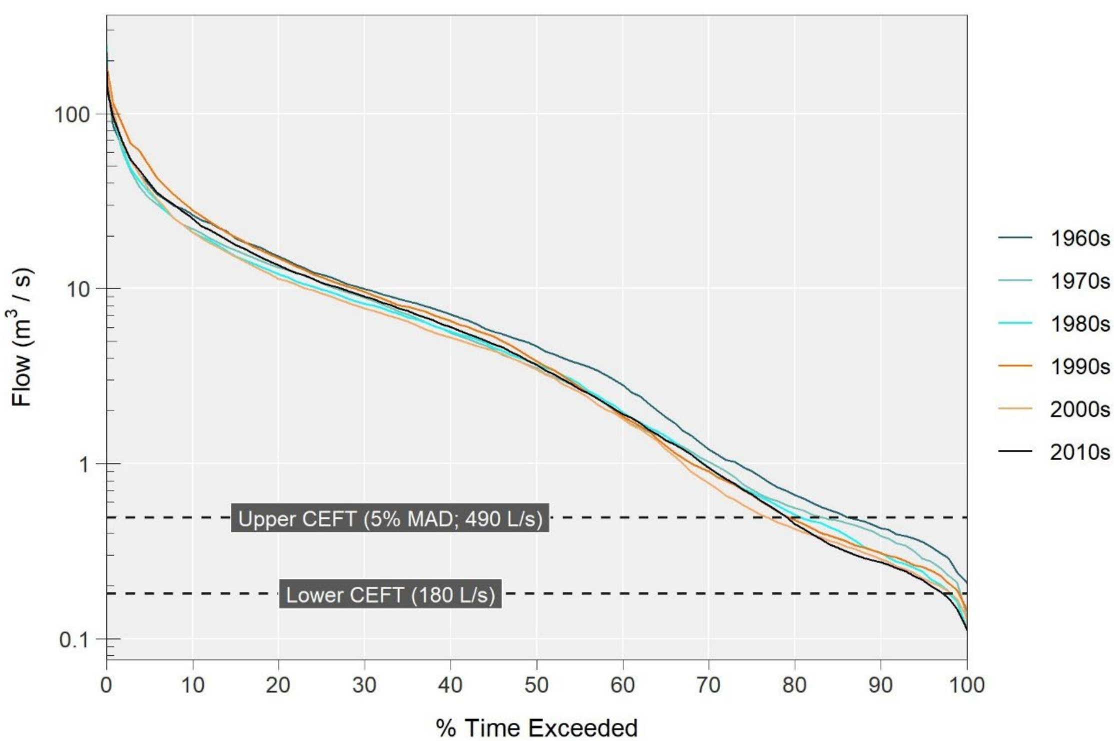
Decade	2nd Percentile Flow	20th Percentile Flow
1960s	0.28	0.66
1970s	0.23 (-0.05)	0.56 (-0.10)
1980s	0.18 (-0.05)	0.51 (-0.05)
1990s	0.20 (+0.02)	0.47 (-0.04)
2000s	0.18 (-0.02)	0.42 (-0.05)
2010s	0.17 (-0.01)	0.45 (+0.03)

Note: change in flow magnitudes from previous decade shown in brackets.

Figure 4.27 Annual 7-Day low flow magnitude compared to 5-year running average PDO Index.

Note: Running average PDO Index corresponds to that shown in Figure 4.26.

Figure 4.28 Frequency duration curve by decade for WSC 08HA003.



Note: Frequency duration curve by decade developed for all daily flows recorded in each decade.

Table 4.8 Climate Variables for the Highest and Lowest 7-Day Low Flows.

	Water Year	Flow (m^3/s)	JJA Drought (days)	JJA Precip. (mm)	JJA Temp. (ºC)
Highest 15 7-Day Low Flows	1964	0.299	12	119	15.7
	1965	0.310	28	64	16.8
	1966	0.338	18	83	15.7
	1968	0.417	23	121	16.2
	1969	0.459	27	56	16.8
	1971	0.327	19	95	16.2
	1972	0.319	32	109	16.5
	1974	0.367	25	88	15.8
	1976	0.343	12	111	14.9
	1980	0.462	27	173	15.3
	1981	0.428	35	106	16.0
	1983	0.319	25	152	15.9
	1984	0.329	18	64	15.8
	1993	0.314	12	118	16.3
	2001	0.362	16	134	16.0
Average	**1976**	**0.359**	**22**	**106**	**16**
Lowest 15 7-Day Low Flows	1970	0.183	24	41	16.5
	1977	0.132	36	67	17.0
	1985	0.116	31	56	17.0
	1987	0.155	18	39	17.0
	1995	0.180	19	134	16.9
	1998	0.148	31	88	18.0
	2002	0.165	26	62	17.2
	2003	0.138	24	26	18.0
	2006	0.165	23	61	17.6
	2007	0.145	23	103	17.1
	2014	0.181	19	32	18.4
	2015	0.115	16	57	19.3
	2016	0.139	18	62	18.1
	2017	0.177	32	49	18.3
	2018	0.131	32	34	18.3
Average	**2001**	**0.151**	**25**	**61**	**18**

4.2.3 Water Demand

The growth in annual groundwater and surface water demand was calculated for both the entire watershed, and the area upstream of the WSC gauge 08HA003 (Figure 4.29). The start of the analysis in WY 1904 corresponds to the date of the first issued water license on June 20th, 1904. Licensed water use remained relatively low in number until the mid-1940s. Since the mid-1950s, water demand has increased by nearly 3-fold in the watershed, though this increase is less pronounced in the upstream watershed. This analysis suggests that if water demand in the upstream watershed is a significant causal factor in the decline in summertime flows at the WSC gauge, then the effect would likely be amplified downstream from the WSC gauge (due to the larger rise in water use). These findings are in line with community concerns (Section 1; Modus 2020).

Since about 1980, licensed surface water demand in the watershed has been constant but groundwater use has continued to increase. Water demand for the entire Koksilah watershed was approximately 7.51 Mm^3/yr for WY 2019 (Figure 4.29). The area upstream of 08HA003 made up approximately 38% of the watershed's annual demand at 2.88 Mm^3/year.

4.2.4 Groundwater Level Analysis

Results from the groundwater level trend analyses conducted on PGOWN data are provided in Table 4.9 and Figure 4.30. The location of these monitoring wells in shown in Figure 2.7 and Figure 2.8. There are two wells, OW297 and OW298, that are now inactive, but have historical manually collected quarterly water level data. There are two observation wells, OW430 and OW431, with sufficient continuous record lengths to show seasonal and annual variations. These wells are screened in bedrock and sand and gravel aquifer materials, respectively. Both these wells show seasonal variation, with higher groundwater levels from January to April and lower levels in late summer, from July to October. There is an approximate 2 metres seasonal variation in groundwater levels. A review of the PGOWN network, completed by Hatfield (2020), included trend analysis for observations wells with records longer than 5 years. Both these observations wells were classified as having stable groundwater levels.

Data for recently activated observation wells (OW488, OW489 and OW493) is too short for analysis (<2 years). These three observation wells monitoring groundwater levels immediately adjacent to the Koksilah River and are therefore expected to provide valuable data to inform sustainable groundwater management and groundwater-surface water interactions in the future.

Figure 4.29 Cumulative water demand for entire watershed and upstream watershed.

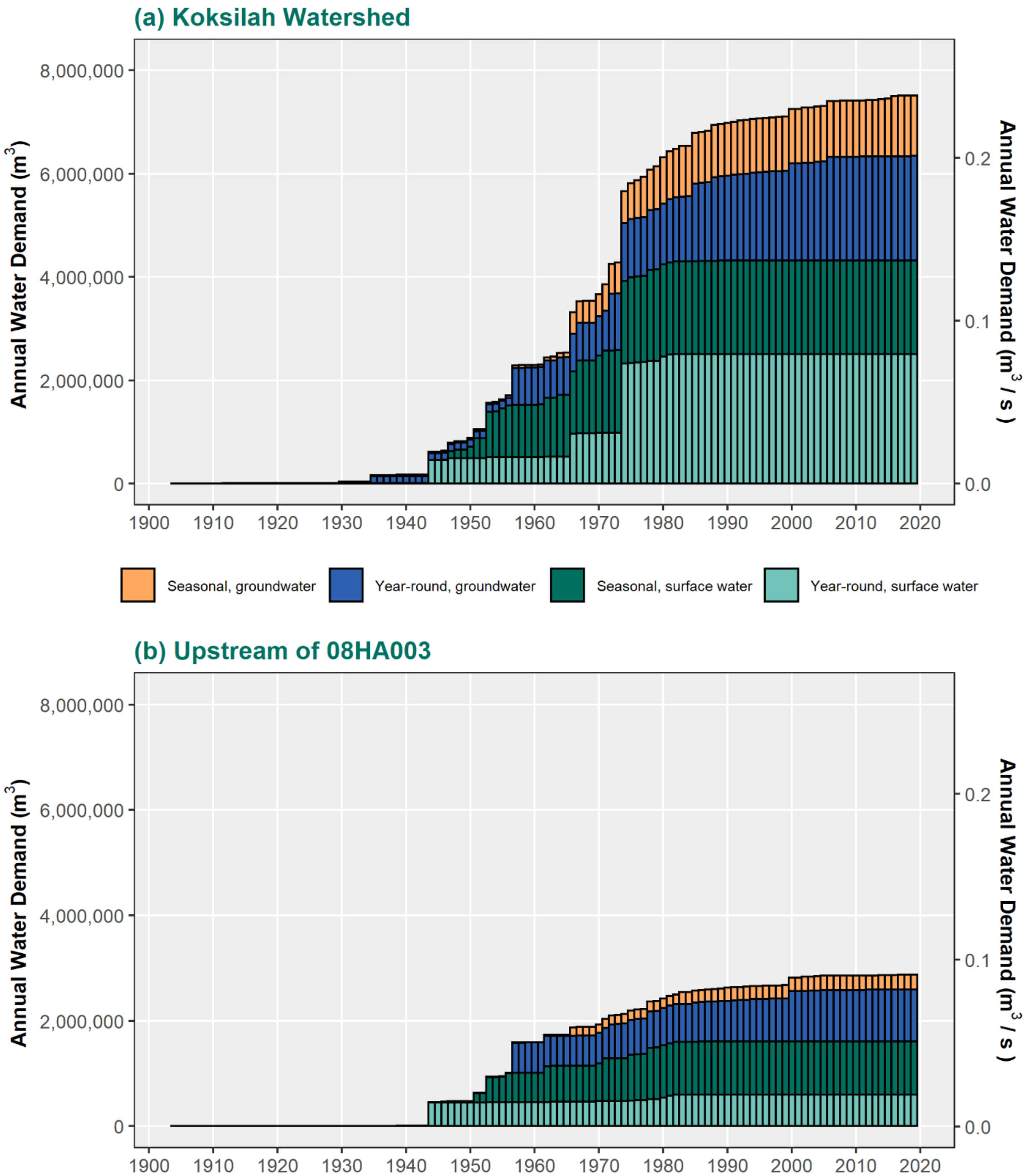


Figure 4.30 Water levels for provincial groundwater observation network (PGOWN) wells.

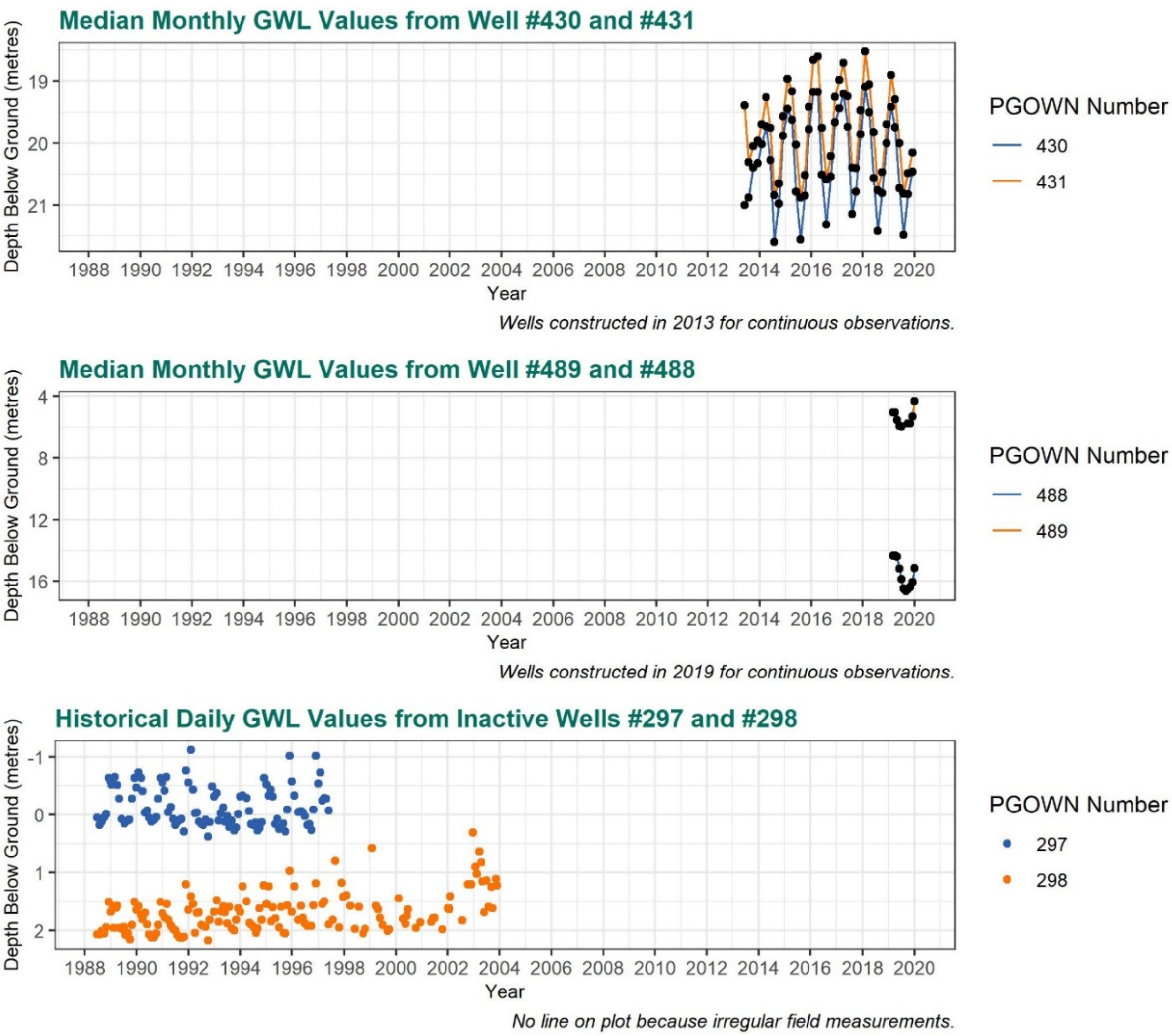


Table 4.9 Observation well monitoring records and water level trend analyses.

Aquifer Number	Type	Provincial Groundwater Observation Wells	Water Level Mann-Kendall Trends/ Comments
185	Sand and gravel	Not monitored	N/A
186	Sand and gravel	#298 – historical (1988 to 2003)	currently inactive
188	Sand and gravel	#297 – historical (1887 to 1999)	Currently inactive
197	Sand and gravel	#234 – historical (n/a)	Currently inactive
		#488 – active (2019 to 2020)	Time series too short for analysis
		#489 – active (2019 to 2020)	Time series too short for analysis
198	Bedrock	#430 – active (2013 to 2020)	Stable (trend = -0.0503), s*ig* = 1
		#493 – active (2020)	Time series too short for analysis
199	Sand and gravel	#431 – active (2013 to 2020)	Stable (trend = -0.0831), s*ig* = 1
201	Sand and gravel	Not monitored	N/A
202	Bedrock	Not monitored	N/A

4.2.5 Streamflow Depletion due to Groundwater Use

Figure 4.31 compares annual groundwater demand and calculated streamflow depletion (using the Glover method) for the portions of the watershed upstream and downstream of WSC gauge 08HA003 (i.e., adding up groundwater use and streamflow depletion for entire watershed). This comparison illustrates that calculated streamflow depletion lags only slightly behind inferred groundwater demand, which is consistent with the analysis provided in Figure 4.17, which suggested that most (70%) water use in the watershed is associated with SDFs of less than one year. For 2019, calculated streamflow depletion is around 94% of inferred groundwater demand (Figure 4.31).

Estimated monthly surface water demand and streamflow depletion for the upstream watershed averaged over the WY 1962-2019 analysis period are shown in Figure 4.32. This analysis reflects the seasonal water use weights applied from Table 3.1 and illustrates that in July (at the time of highest seasonal water demand), the combined effects of surface water and groundwater demand on the Koksilah River will be about 4.5 times the impact felt during the non-irrigation period.

Figure 4.31 Comparison of annual groundwater demand and streamflow depletion.

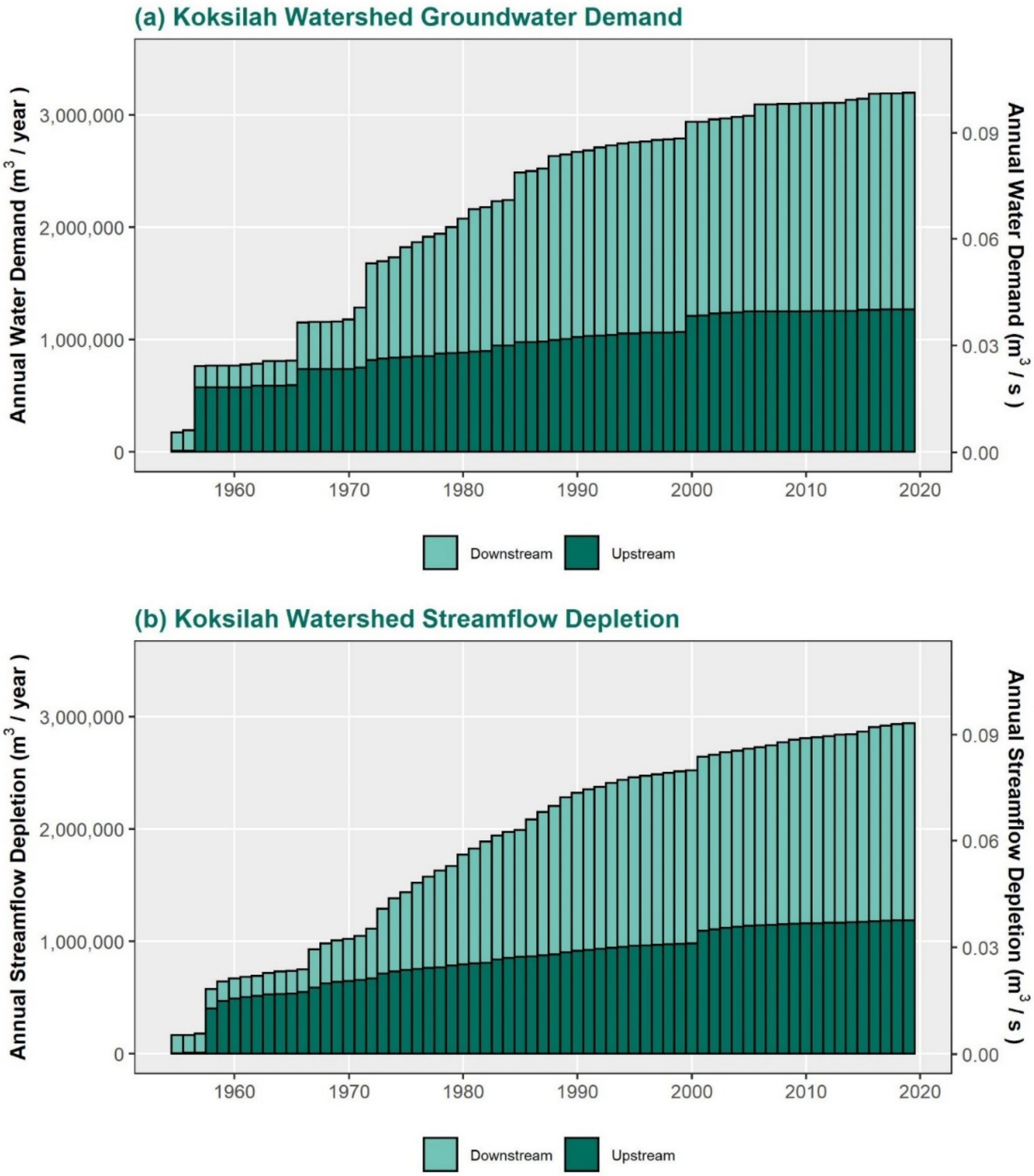
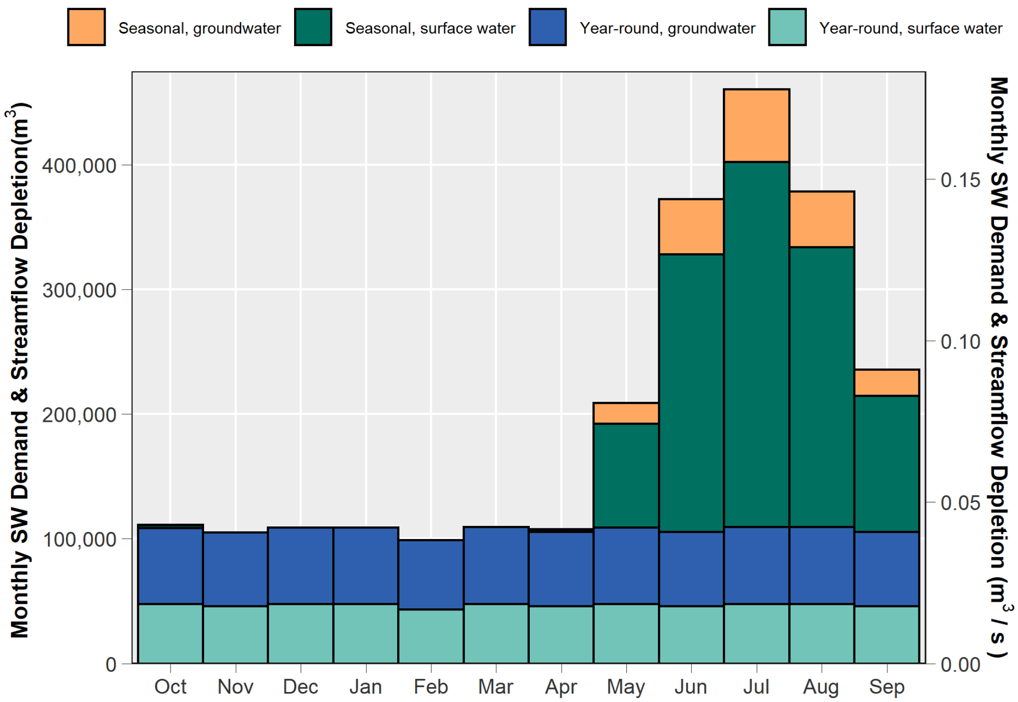


Figure 4.32 Average monthly surface water demand and streamflow depletion for upstream watershed (1962-2019).



4.2.6 Flow Naturalization

Gauged and naturalized flows for WSC gauge 08HA003 are shown in Figure 4.33. It illustrates the marked difference between gauged and naturalized flows, under lower (summer) flow conditions, due to the removal of surface water diversions (direct effect) and streamflow depletion associated with groundwater use (indirect effect) on recorded flows since 1962 (logarithmic scale used to emphasize changes). During the summer months, gauged flows frequently drop below 0.3 m^3/s, especially in recent years. In contrast naturalized flows that have had the effects of water demand removed no longer drop below 0.3 m^3/s. Under higher flow conditions there is minimal influence from water demand on recorded flows, which matches the fact that water demand is only a small proportion of the watershed annual water balance (Section 4.1.6).

NHC (2020) presented an analysis of annual 7-day low flows on the Koksilah River and concluded that there is “a statistically significant downward trend in 7-day low flows on the Koksilah River since the beginning of continuous record in 1955”. The NHC 7-day low flow analysis was repeated for data collected since 1962 and using both gauged and naturalized flows (Figure 4.34). The gauged flows show the same significant declining trend as noted by NHC. For the naturalized flows, the declining trend is reduced in magnitude but not removed entirely. The slope of the trend line on the gauged flows suggests an annual decline of 0.00277 m^3/s in 7-day low flows over the 57-year record of analysis. For the naturalized flows, this annual decline inferred from the trend line is -0.00201 m^3/s. Therefore, following flow naturalization, the remaining trend in 7-day flow flows is 73% of the declining trend in the gauged flows. This suggests that 27% of the decline in 7-day low flows at the WSC gauge is explained by increasing water demand in the upstream watershed, while 73% of this decline is associated with other factors. Greater impacts on summertime flows may be expected in the downstream watershed due to greater water demand. This is explored further in Section 5.3.

Figure 4.33 Monthly gauged and naturalized flows for WSC gauge.

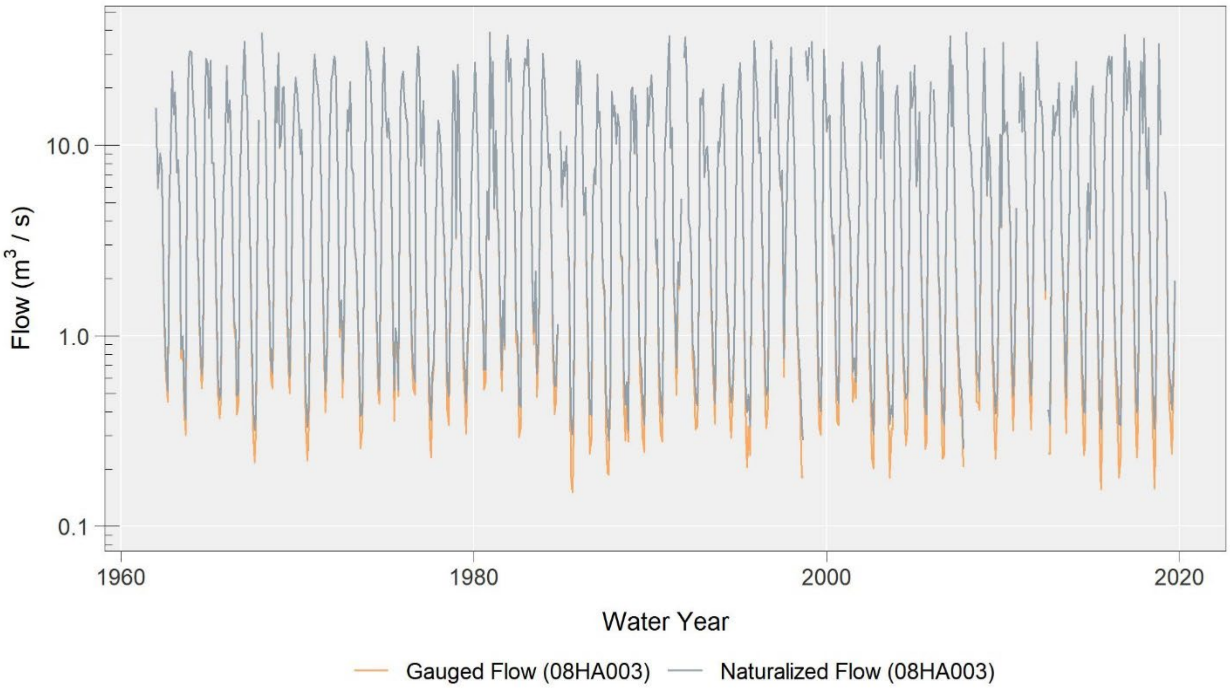
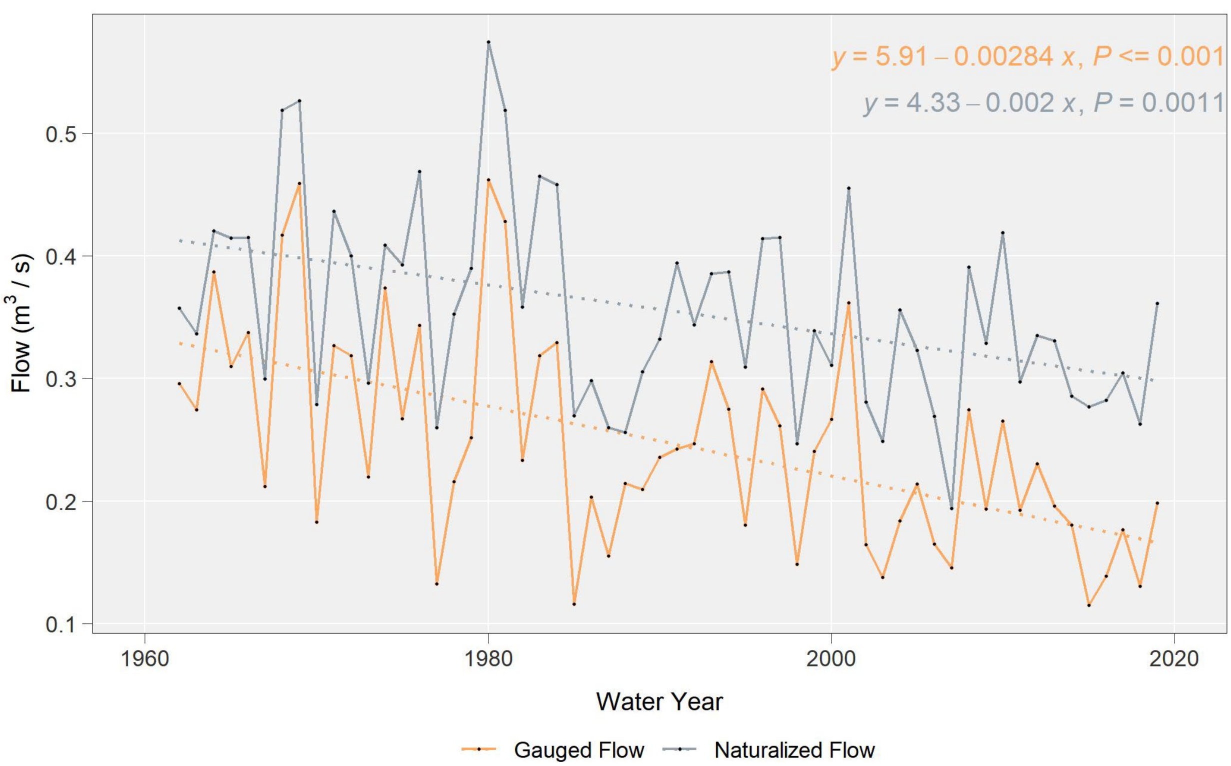


Figure 4.34 Long-term trends in gauged and naturalized 7-day low summertime flows for WSC gauge.



4.2.7 Historical Forest Cover Changes

The effects of historical forest cover changes documented for the watershed on relative evapotranspiration are analyzed in Figure 4.35. The assumed ET values for recovering forest stands of different age relative to those of an old growth forest are identical to the relationship expressed in Table 3.4. The calculated ET values relative to 1954 conditions are based on the presence of different forest age classes in the upstream watershed and entire watershed at different points in time, as expressed in Table 3.3, based on data provided by the Cowichan Station Area Association.

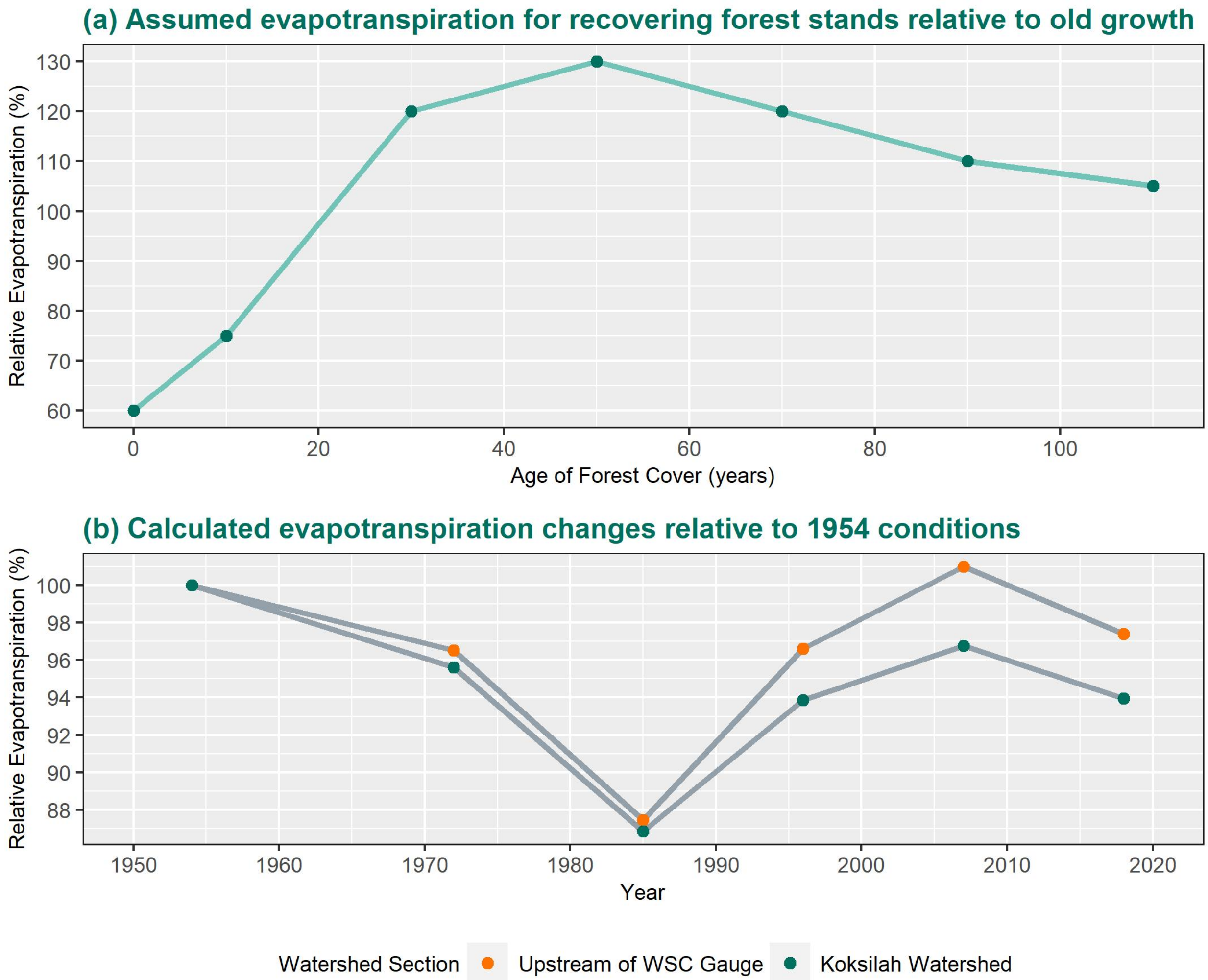
Pritchard et al. (2019) indicated that in the middle and upper elevations of the watershed, industrial logging of second growth forests began in the early 1980's, and since about 2001 most of the harvesting has been in these younger forests. Consequently, in mid-1980s there was a mix of forest age classes in which clear-cuts, and very young recovering stands were dominant (Table 3.3). These stands have depressed ET relative to an old growth forest (Table 3.4). As a result, watershed ET may have been depressed in the mid-1980s to about 87% of 1954 conditions, leading to greater water availability in the watershed (this may explain the slope changes evident in Figure 4.25; Section 4.2.2.2). In more recent decades, significant forest regrowth has occurred following the intense logging period and currently there is a wider mix of forest stands of different ages in the watershed, with some areas (i.e., with clear cuts or very young trees) having depressed ET relative to an old growth forest while other areas may have increased ET relative to that of an old growth forest (i.e., immature-mature forest stands in the 40-50-year age range). The current effect of forest cover change may be on the order of a 2% (upstream watershed) to 6% (entire watershed) reduction in ET relative to a hypothetical situation in which the watershed is entirely old growth (Figure 4.35). The decline in predicted relative watershed ET from 2007 to 2018 appears to be explained by the proportion of young-immature forest stands in the watershed being at a maximum in 2007. These 40-60-year-old stands have the highest relative ET value (Figure 4.35), consistent with what the literature suggests (Section 3.4.1).

The analysis as presented herein is high level because there is considerable uncertainty and generally a lack of local evapotranspiration data for forest stands of different ages and physiological characteristics (Section 3.4.1). The analysis also did not assess ET changes due to conversion of forest land for agricultural purposes (i.e., land use change), nor did the analysis take into consideration variations in ET between elevation bands in the watershed, or seasonality. Nevertheless, the analysis is deemed sufficient to identify possible causal factors of hydrological change and their relative importance. Recommendations for future more detailed analyses required to guide watershed management decisions are provided in Section 6.0.

4.2.8 Urbanization

Based on Figure 2.3, areas of urban development comprise about 0.5% of the upstream watershed and 1.2% of entire watershed. This ignores urban-agricultural mixes which are a much larger watershed proportion but will have low-density development. If groundwater recharge is reduced by 10% to 50% due to impervious areas in the areas of urban development, then this would lead to a recharge reduction on the order of 0.05-0.25% for the upstream watershed and 0.12-0.6% for the entire watershed. These relatively small changes in groundwater recharge are discussed further in Section 4.0.

Figure 4.35 Forest cover change effects on watershed evapotranspiration.



5.0 DISCUSSION

In the preceding section, the major factors affecting the decline in summertime flows in the upstream watershed as recorded at the WSC gauge were evaluated. This includes a possible decline in summertime precipitation, an increase in temperature which may have led to increases in evapotranspiration reducing water availability in the watershed, historical forest cover changes in the watershed affecting water availability and a three-fold increase in groundwater and surface water demand since the 1960s. Of these factors, only the impact of the water demand increase on summertime low flows could be quantified directly through flow naturalization and the subsequent assessment of declining trend in 7-day low flows. In the sections below, the importance of the other factors is evaluated in an indirect and semi-quantitative fashion.

5.1 MAJOR FACTORS AFFECTING SUMMERTIME FLOWS AT WSC GAUGE

5.1.1 Water Demand

Based on the trend line shown in Figure 4.23, there has been an approximate 0.22 m^3/s change in August low flows from 1962 to 2019 (Table 5.1). About 24% of this change is associated with a reduction in runoff (0.053 m^3/s) while 76% of this change is associated with a reduction in baseflow (0.17 m^3/s). Part of these declines in runoff and baseflow at the WSC gauge are explained by an increase in August water demand and streamflow depletion from 1962 to 2019 in the upstream watershed, which has been quantified as amounting to 1.49×10^5 m^3 (0.056 m^3/s). This increase in August water demand represents 26% of the decline in August low flows (0.22 m^3/s), an assessment that corresponds well to the 7-day low flow trend analysis, which attributed 27% of the low flow decline to increased water demand (Section 4.2.6).

5.1.2 Declining Summertime Precipitation Affecting Runoff

A decline in summertime precipitation is expected to be reflected in a corresponding reduction in the hillslope runoff component of streamflow generation during the summer. Lowest summertime flows typically occur in August and this month is the focus of the analysis below.

The increase in August water demand and streamflow depletion (Section 5.1.1) can be split as 9.06×10^4 m^3 surface water use and 5.80×10^4 m^3 streamflow depletion from groundwater use (Table 5.1). The groundwater use (streamflow depletion) component can be unambiguously associated with the reduction in baseflow at the WSC gauge, but surface water use will affect streamflow in the river, which cannot be distinguished between runoff or baseflow. However, an end member analysis can be conducted in which surface water use withdrawals are "attributed" either to runoff or baseflow (in a way this is 'naturalizing' the individual runoff and baseflow components to account for surface water withdrawals) to assess the potential range in their contributions to the overall August flow declines. This end member analysis suggests that the portion of the runoff and baseflow declines not explained by rising water demand accounts for between 8-24% and 50-66% of the long-term August flow decline, respectively (Table 5.1). These contributions are therefore attributable to other factors (climate change, forestry, etc.), which is analyzed further below.

The assessed decline in August precipitation of 8.2 mm from 1962 to 2019 (representing a 1.86×10^6 m^3 loss over the upstream watershed) is much greater than the decline in August low flows (320% of 5.82×10^5 m^3; Table 5.1) and therefore can explain all of the observed declining trend in runoff. However, the slope of the declining trend in August precipitation is poorly resolved and statistically non-significant (Figure 4.18). Therefore, there is considerable uncertainty in the actual magnitude of the August precipitation decline. A further complicating factor in the above analysis is interaction of the forest canopy with precipitation such that a significant proportion of small summertime storms is likely intercepted by the tree canopy and subsequently lost to evaporation. These complicating factors have not been incorporated in the analysis.

Table 5.1 Relative contributions to August low flow declines from 1962 to 2019.

Variable	Change from 1962 to 2019						Comment
	m^3/month	m^3/s	mm/ month	% of total decline August flow	% relative to runoff decline	% relative to baseflow decline	
August monthly flow changes							
Total	-5.82E+05	-0.221	-2.55	100%	n/a	n/a	Figure 4.23
Runoff, R	-1.40E+05	-0.053	-0.61	24%	n/a	n/a	
Baseflow, B	-4.42E+05	-0.168	-1.94	76%	n/a	n/a	
Upstream water demand contribution to low flow decline							
Total	1.49E+05	0.057	0.65	26%	106%	34%	Water demand analysis
Surface water, SW	9.06E+04	0.034	0.40	16%	65%	20%	
Streamflow depletion, SD	5.80E+04	0.022	0.25	10%	41%	13%	
Climate change (precipitation) contribution to runoff decline							
Incorporating SW withdrawals	-4.94E+04	-0.019	-0.22	8%	35%	n/a	
Not including SW withdrawals	-1.40E+05	-0.053	-61	24%	100%	n/a	
Climate change (evapotranspiration) contribution to baseflow decline							
Incorporating SW + GW withdrawal	-2.93E+05	-0.111	-1.29	50%	n/a	66%	
Incorporating only GW withdrawals	-3.84E+05	-0.146	-1.68	66%	n/a	87%	

Note: analyses presented are for the upstream watershed upgradient of the WSC gauge.

5.1.3 Evapotranspiration Affecting Groundwater Recharge

Table 5.1 also provides an estimate of the potential range in 'naturalized' baseflow reductions (during the low flow month of August), which reflect inclusion of the effects of streamflow depletion as well as either 0% or 100% of surface water withdrawals. This analysis suggests that only a small portion of the August baseflow decline (13-34%) is attributable to rising water demand, with the remainder (66-87%) of this baseflow decline being attributable to a reduction in groundwater recharge (ignoring changes in groundwater storage). The factors that are driving this groundwater recharge decline account for between 50% and 66% of the overall decline in August low flows at the WSC gauge and are assessed below.

Groundwater recharge, which is water that crosses the water table, originates as infiltration at the land surface (or as infiltration beneath a surface water body or water that is temporarily ponded on the land surface (ponded infiltration). Quantitatively, groundwater recharge is strongly tied to near-surface water balance processes such as precipitation, hillslope runoff, evapotranspiration, and soil moisture storage. Increases in evapotranspiration are expected to occur in response to well documented rising temperatures in the watershed, which may in turn also impact groundwater recharge rates. Generally, the assessment of effects of climate change on groundwater in British Columbia is subject to large uncertainty bounds (Allen 2009). For example, Allen et al. (2014) found in a province-wide review that late summer groundwater levels appear to have lowered across the province but trends in recharge were more variable, both positive and negative, and generally non-significant. Their assessment was complicated by factors such as the varied nature of the climate in different parts of the province, which determines the hydrologic regime (pluvial, snow, glacial, mixed), the complexity of the aquifer system as it relates to the relationship between groundwater and surface water, and the distant sources of many rivers in the mountainous regions of the province (Green et al. 2011).

The strong linkage between groundwater recharge and evapotranspiration is also evidenced by a review of forest management effects on groundwater in BC (Smerdon et al. 2009), which indicated that "in all of the landscapes, a rise in the water table can be expected to follow forest harvesting, though the magnitude and duration of this increase vary according to the area's geology and topography". In regions like the coastal basins and lowlands, increases in water table elevation have been measured in the order of 50 cm. At Carnation Creek on west Vancouver Island, a 30–50 cm rise in water table persisted for 10 years following harvest (Fannin et al. 2000). Therefore, the short-term increase in water availability (decrease in evapotranspiration) following forest harvesting is expected to lead to a short-term increase in groundwater recharge as evidenced by rising water tables. Conversely, in young to immature regenerating forests ET is expected to be increased relative to mature stands (Section 3.4.1), such that groundwater recharge will be reduced. These initial increases and subsequent decreases in groundwater recharge mimic those seen in the review of forest management effects on summertime low flows, which is not surprising given the important role of groundwater in maintaining these summertime low flows. Immediately following forest harvesting, low flows tend to increase (Moore et al. 2000) while summer low flows became more severe (i.e., lower) about two decades or so following harvest (Moore et al. 2000), with this decrease in low flows persisting up to 50 years (Perry and Jones 2016; Cobble et al. 2000).The effects of forest management on groundwater recharge are therefore considerably more complex than expressed as a community concern (Section 1.0), which is not surprising given that the concerns are based on indirect observations.

Groundwater recharge is expected to predominantly occur during the wet season (as exemplified by seasonal variations in groundwater levels; Figure 4.30) but may happen year-round depending on soil moisture conditions and summertime precipitation events. The potential factors affecting groundwater recharge in the Koksilah watershed are therefore evaluated on an annual basis (Table 5.2).

Table 5.2 Evapotranspiration effects on groundwater recharge.

Variable	Change from 1962 to 2019			Reference	Change from reference	Source
	m^3/yr	m^3/s	mm/yr	mm/yr		
Annual baseflow changes						
Baseflow	-8.00E+06	-2.54E-01	-3.51E+01	4.15E+02	-8%	Figure 4.23
Upstream groundwater use	6.76E+05	2.15E-02	2.96E+00	1.60E+01	19%	Figure 4.31
Net change (recharge)	-7.32E+06	-2.33E-01	-3.21E+01	N/A	N/A	
Annual evapotranspiration changes						
Temperature rise	9.64E+06	3.06E-01	4.23E+01	8.30E+02	5%	Figure 4.20
Forest cover change	-3.78E+06	-1.20E-01	-1.66E+01	8.30E+02	-2%	Figure 4.35
Net change (recharge)	5.86E+06	1.86E-01	2.57E+01	N/A	N/A	

Note: analyses presented are for the upstream watershed upgradient of the WSC gauge. Reference values correspond to Table 4.6. A positive change in evapotranspiration will lead to a negative net change in recharge.

The analysis shown in Table 5.2 suggests that on an annual basis, baseflow (groundwater discharge) to the Koksilah River upstream of the WSC gauge has been reduced by about 8%. Like the findings for August, the increase in annual groundwater demand only accounts for a portion (8%) of the total annual baseflow reduction. By inference, the remaining (92%) annual net change in baseflow reflects a reduction in groundwater recharge (i.e., ignoring groundwater storage changes). Ignoring potential changes in groundwater storage (i.e., a possible long-term decline in groundwater levels and pressures in the aquifers associated with a loss in recharge) may be reasonable because evidence for groundwater level declines is lacking (Figure 4.30). The inferred reduction in groundwater recharge of about 32 mm is a change of 8% relative to the baseline estimate of 415 mm (Table 4.6). This 32 mm loss may appear small compared to the large annual precipitation on the watershed, but groundwater provides a sustained input to the Koksilah River during the summertime period with little rainfall. For context, an annual recharge loss of 32 mm is the equivalent of about one month of summertime precipitation.

The analysis further suggests a 2% decrease in ET in the upstream watershed associated with historical forest cover changes while the effect of increasing temperatures is predicted to be a 5% increase in ET relative to baseline (Table 5.2). The large role of temperature driven increases in evapotranspiration is consistent with Yates and Strzepek (1994). The authors compared four watersheds, of which three are have some similarities with the Koksilah watershed, and assessed changes in PET based on temperature increases, including a +3 degree rise like that observed in the Koksilah watershed. It was determined that PET may increase by 3-5% for every degree temperature increase, which would suggest an up to 15% increase in PET for a three-degree temperature rise. The predicted temperature driven increase in PET from 1962 to 2019 for the Koksilah watershed therefore appears consistent with the literature.

The combined effect of forest cover change and climate (i.e., temperature) change driven alterations to watershed scale ET is estimated to be a loss of 25.7 mm in the upstream watershed, which can account for the majority (80%) of the predicted reduction in annual baseflow attributable to a loss in recharge (32.1 mm; Table 5.2). Given the large uncertainty bounds in the analysis, this level of agreement is considered satisfactory. It is noted that the temperature driven increase in ET could both be higher or lower (Figure 4.19) while considerable uncertainty also exists in the historical forest cover change analysis and evapotranspiration values for forest stands of different age (Section 3.4.1). The main finding from the analysis is that a temperature driven rise in watershed evapotranspiration appears to be a major factor in affecting the decline in recharge and baseflows, which accounts for 50 to 66% of the decline in summer (August) low flow (Table 5.1). The analysis presented in Table 5.2 further suggests that this decline could have been even more dramatic but appears to have been muted (offset) by a reduction in ET associated with forestry (i.e., due to the timing of forest cover changes, and resultant dominance of clear cuts and very young trees). Signatures of this mitigating effect of historical forest management may be evident in the slower rate of decline of springtime baseflows in the 1980s and 90s (slope changes in Figure 4.25) and the temporally reversal in decline of 2^{nd} percentile low flows in the 1990s (Table 4.7). This mitigating effect of forest cover change on water availability has been abating since the 1980s (Figure 4.35).

Indications from the literature of possible future trajectories of forest ET in the watershed and its impact on Koksilah River low flows are variable. Moore et al. (2020) found that studies focused on medium to large catchments (tens to thousands of kilometers in area) either had no statistically significant relations between warm-season low flows and forest disturbance, or inconsistent responses, and generally a lack of reliable data. Coble et al. (2020) indicate that in larger watersheds the magnitude of low flow responses attenuates downstream as a broader mosaic of stand ages occurs and multiple hydrological periods are represented, a finding that may be pertinent to the downstream portions of the Koksilah watershed. However, as a cautionary note, Segura et al. (2020) suggest that high evapotranspiration from rapidly regenerating vegetation, including planted Douglas-fir appeared to explain the persistence of streamflow deficits after logging, with results of their study indicating that 40- to 50-yr rotations of Douglas-fir plantations can produce persistent, large summer low flow deficits (Perry and Jones 2016). It is noted that these findings are largely based on Oregon studies and are not necessarily directly transferable to eastern Vancouver Island because 40- to 50-year-old stands in one ecoregion can be different in another. However, as an overarching theme, the future trajectory of forest cover change driven effects on water availability in the watershed is expected to depend on the mix of forest types and age classes present, with some distributions possibly leading to increased water availability while different distributions could emphasize water shortages.

5.2 OTHER FACTORS POTENTIALLY AFFECTING LOW SUMMERTIME FLOWS

Several other possible factors have been hypothesized as possibly being a factor in affecting low summertime flows in the watershed (Section 1.0). These possible factors are reviewed below.

5.2.1 Snow

About 17% of MAP has been estimated to fall as snow in the watershed (Section 4.1.1), with a significant portion of this snowfall (i.e., on the order of 65%) likely melting intermittently during winter warming periods based on comparison of PAS with nearby Tripp Meadows snow course (SWE) data. The absence of sustained high flows through April and May suggests that spring snowmelt from higher elevations is a minor component of the annual runoff budget, although the high flows during winter may either be rain-dominated or a mixture of rain and snowmelt from different elevations. A decline in snowfall amounts has been noted for the watershed (Figure 4.18), which is consistent with community observations (Section 1.0). Regional snow courses also suggest a decline in snowpack and earlier snowmelt in the last decade (Figure 4.19). These regional changes in snow accumulation and melt did not appear to correlate directly to the timing changes noted for the onset of the gradual decline in baseflows around early April (Figure 4.25;

Section 4.2.2.2). However, snow accumulation and melt may also be impacted by forest cover change. It is generally held (e.g., Pike et al. 2010) that more snow will accumulate in clear cut areas (due to absence of forest cover interception of snowfall) and that this larger snowpack will melt faster (due to more incident solar radiation; less shading by forest canopy), effects that can possibly (although not unambiguously) be correlated to the flow decline timing shifts. Overall, changes in snow processes are expected to be a relatively small factor in the declining summertime low flows.

5.2.2 Urban Development

Recharge reduction on the order of 0.05-0.25% for the upstream watershed and 0.12-0.6% for the entire watershed are projected because of urban development. A 0.5% recharge reduction would correspond to approximately 2 mm on an annual basis from the baseline estimate (Table 4.6) which is less than 10% of the predicted ET driven change (Table 5.2). Therefore, urban development is not expected to be a major factor affecting summertime flows in the Koksilah River. However, it is possible that culvert design, stormwater outfalls, rural deforestation/land clearing for residential development, non-point source pollution (i.e., from agricultural land conversion) and other factors could affect habitat quality in the downstream portions of the Koksilah watershed, possible impacts that have not been evaluated in this study.

5.2.3 Agricultural Land Use Conversion

Agricultural land use conversion is one of the main aspects of land use change that has occurred in the watershed. Early harvesting of second growth forests was primarily in low elevation areas, presumably to increase agricultural lands (Pritchard et al. 2019). Corresponding effects on watershed evapotranspiration were not yet considered in the evaluation of historical forest cover changes (Section 4.4.1) but could be evaluated in future more detailed water balance studies aimed at informing water management decisions (Section 6). The effects of agricultural land use on low flows were predominantly reflected in the water demand analyses (Sections 4.2.3 and 4.3). Agricultural return flows (i.e., infiltration of excess irrigation water) may also need to be considered in future more detailed water balance modelling.

5.2.4 Roads

There are approximately 1,410 km of road in the Koksilah watershed (Pritchard et al. 2019). This includes maintained and overgrown forest roads, as well as paved and gravel roads used for agriculture and to access residential and industrial areas. Road density appears to be consistent across the watershed with an average of 4.5 kilometers of road for every square kilometer of land (Pritchard et al. 2019). With an assumed road width of about 5 m this would amount to approximately 2% of land disturbance.

According to Moore et al. (2020), forest roads and their drainage systems have three main effects on streamflow generation: the enhanced generation of infiltration-excess overland flow over relatively impervious road surfaces, the interception of subsurface flow and conversion to surface flow in ditches, and the routing of road surface runoff and intercepted subsurface flow to the stream channel via drainage structures (ditches, culverts, etc.). The net effect of roads could be to reduce baseflow contributions to late summer streamflow. However, a road network that is well connected to the stream channel could conceivably increase streamflow contributions from summer stormflow during rain events. The net effect of roads and the magnitude of this effect would depend on their layout, design, and construction, especially in relation to the connectivity of surface flow paths between roads, ditches, and stream channels.

Based on the above review, the overall effect of roads on summertime low flows is difficult to assess without taking its specific layout into account in a watershed model. However, at a high level it can be said that roads should not lead to a net loss of water unless they divert water across a watershed boundary (instances of this are expected to be limited) but may affect the timing of flows. To address such effects more specifically requires watershed modelling, explicitly representing the road network layout and drainage system in the landscape. Examples of such detailed model simulations of road network effects on watershed hydrology are relatively rare but include a model developed for the Carnation Creek watershed (e.g., Beckers and Alila 2004).

Road related effects on water quality may be a more important consideration. Moore et al. (2020) and Reid et al. (2020) indicate that roads introduce significant quantities of debris into a stream channel can indirectly affect summertime low flows because the impacted stream channel can experience channel widening, the loss of roughness, and the loss of pool depth, which all effectively reduce the quantity of available habitat during the late summer low-flow season for any given discharge (Reid et al. 2020).

5.2.5 Karst

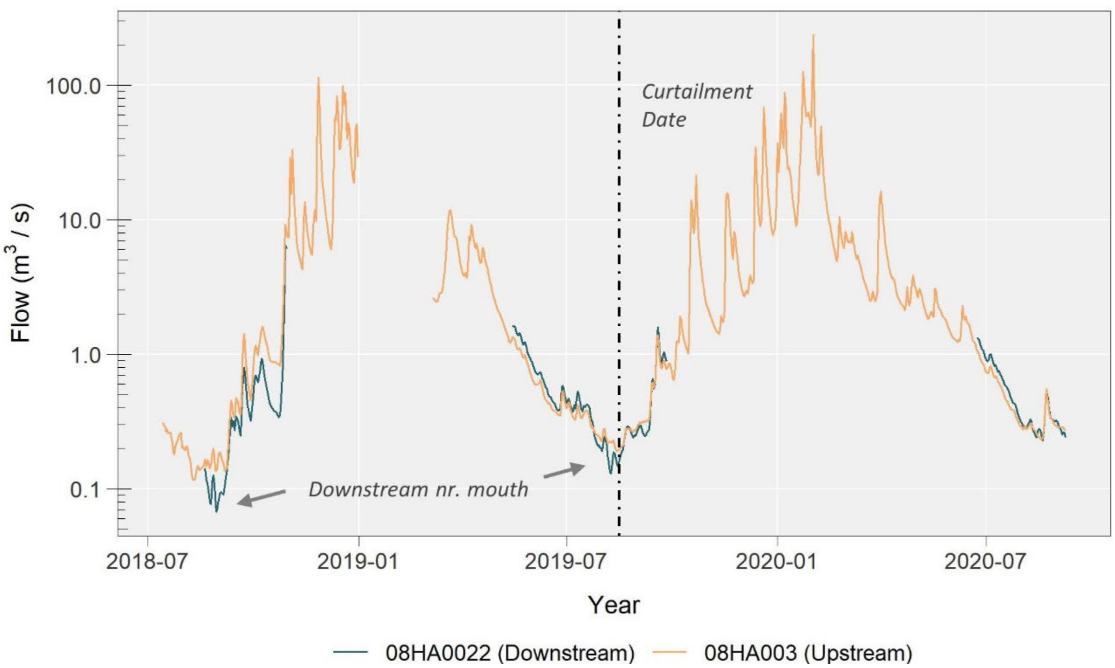
Karst presence is possible in different portions of the watershed (Figure 2.6). Pritchard et al. (2019) note that in that it is known that caves exist in the watershed, it is possible that karst formations do occur at some of these potential sites. Marble Falls is one location on the Koksilah River where limestone is present, however the degree or presence permeable karst formations associated with the limestone deposits and their interrelationship to the river is not known (Barroso and Wainwright, in press). Karst ecosystems are distinct due to limestone substrate, higher nutrient supply and cool, moist conditions. Karst ecosystems often support unusual or rare plant and animal species, both on the surface and underground (Pike et al. 2010). Karst stream systems may also provide protective sites for fish with cool stream temperatures throughout the year. Karst is vulnerable to forest disturbance, including the introduction of non-native materials into recharge areas and the possible redirection of road runoff and sediment into sinkholes. Karst requires specific management guidelines. Interim guidelines were therefore established in BC (RISC 2001). Overall, while it is not expected that any karst disturbance by forestry activities would have a direct impact on low flows in the watershed (i.e., an impact on the watershed water balance), it is recommended that the role of karst in maintaining aquatic habitat is studied and possible karst disturbance is evaluated in this context.

5.3 ADDITIONAL CHANGES IN DOWNSTREAM WATERSHED

Only a short-term monitoring record exists for the downstream portion of the Koksilah River at FLNRORD operated gauge 08HA0022 (Koksilah River at Trestle). A comparison of flows from this downstream gauge operated concurrently with the upstream WSC gauge since summer 2018 is provided in Figure 5.1. Both stations show similar patterns in flow, with the largest annual losses in flow occurring alongside the driest summer months (July – September). Station 08HA0022, which is located further downstream on Koksilah River, tends to have lower late summer flows than 08HA003, which suggests greater impacts on water availability for environmental (aquatic) protection, with greater water use intensity in this portion of the watershed being the suspected causal factor of the lower flows. Under normal circumstances, flows at the downstream gauge would be expected to be higher than those at the upstream gauge.

The impact of temporary water use curtailments on flows at the downstream gauge is also evident in Figure 5.1. The order was issued on August 16, 2019, and repealed on September 18, 2019, when river flows increased. Immediately following the curtailment, discharge at both stations increased slightly, to a larger degree at the downstream FLNRORD gauge compared to the upstream WSC gauge. These differing responses also suggest a larger impact from water demand on summertime low flows in the downstream portions of the watershed. In addition to the curtailment order, patterns of water demand and usage might have been impacted by voluntary reductions in response to communications with water users in the basin throughout the summer period (Barroso and Wainwright, in press). Flows at both gauges subsequently increased more dramatically in response to fall precipitation. While the temporary water use curtailment was successful (NHC 2020), it was considered a short-term solution that was implemented to address the imminent threat to fish populations. A better understanding of all potential factors affecting summertime low flows is required to provide a common understanding of the water sustainability problem, which provided the impetus of this hydrologic change analysis.

Figure 5.1 Comparison of 2018-2020 daily flow data for downstream FLNRORD gauge and upstream WSC gauge.



Note: Panels cover entire range available from station 08HA002 (August 20, 2018 – September 8, 2020). The curtailment on August 19, 2019 is shown as a dashed line. Flow data from 2018 is subject to relatively high uncertainty due to limited manual measurements.

Preceding analyses suggested the following regarding the relative importance of causal factors affecting summertime low flows at the upstream WSC gauge from preceding analyses:

- Evapotranspiration reducing groundwater recharge was determined to be the most important factor explaining 50-66% of the low flow decline.
- Water demand was the second ranked factor, explaining 26% of the low flow decline.
- The decline in summertime precipitation reducing runoff was deemed the third major factor, explaining 8-24% of the decline in low flows.

The assessed decline in August precipitation is much greater (320%) than the decline in August low flows (Section 5.1.2) and therefore can explain all the observed declining trend in runoff. However, the slope of the declining trend in August precipitation is poorly resolved and considerable uncertainty in the actual magnitude of the August precipitation decline remains. As such, the decline in August flows is attributed first to increased water demand (highest degree of certainty) and ET, which have lower uncertainty. The residual change in August flows was then ascribed to changes in precipitation to arrive at the above inferences.

It should be further be noted that there may be a 7% downward bias in the water demand estimates used in this study (Section 4.1.3). However, this introduces only a relatively minor level of uncertainty which was not carried forward in the calculations.

Table 5.3 Relative importance of factors affecting summertime low flows at the upstream gauge (upstream watershed) and downstream gauge (gauge).

Causal Factors	Upstream watershed		Entire Watershed	
Water Demand	26%		48%	
Evapotranspiration reducing groundwater recharge	66%	50%	46%	35%
Summertime precipitation decline affecting runoff*	8%	24%	6%	17%

Note: Two values are provided for each climate change causal factor and for each portion of the watershed (upstream/entire), which reflect the uncertainty ranges discussed in the text. The percentages are organized in such a manner that they add up to 100%.

The relative importance of these factors for the entire watershed (i.e., as measured at the downstream FLNRORD gauge) was extrapolated from the detailed assessments conducted at the upstream gauge by contemplating that only 38% of water demand occurs in the upstream watershed (i.e., affecting the WSC gauged flows as well as the FLNRORD gauged flows) while the remaining 62% of water demand occurs downstream of the WSC gauge and therefore only affects the FLNRORD gauged flows. The relative importance of water demand as assessed at the upstream gauge was therefore scaled by (38+62=100)/38 after which percent contributions of all three causal factors were renormalized to add up to 100%.

The extrapolation exercise suggests the following for the relative importance of causal factors affecting summertime low flows at the downstream FLNRORD gauge:

- Water demand is estimated to be the most important factor and could account for 48% of the low flow decline.
- The other primary cause of the decline, which can account for the remaining half (52%) of the decline, is climate change induced changes in evapotranspiration and precipitation.
    - Evapotranspiration reducing groundwater recharge was determined to be the second major factor explaining 35-46% of the low flow decline.
    - The remainder of the declining flows are attributed to declines in precipitation (6-17%).

Overall, water demand is therefore estimated to explain about half of the decline in summertime low flows in the watershed while the other half appears to be explained by climate change effects (increasing temperatures and evapotranspiration combined with reduced summertime precipitation). As noted in Section 5.1.3, some of the trend in declining low flows appears to have been mitigated by historical logging activities, with this mitigating effect having been strongest in the 1980s and 1990s but having dissipated in the recent decade.

As a reality check on the above assessment the concurrent flow record for the WSC gauge and the FLNRORD gauge were compared for the period August 20 to 31, 2018. August data for 2019 were not used as it was impacted by the curtailment order while 2020 data available did not fully capture the low flow period (Figure 5.1). Measured flows at the FLNRORD gauge averaged 0.0996 m^3/s. Measured flows at the WSC gauge were 0.158 m^3/s over the same period. Extrapolating the measured flows at the WSC gauge to account for the larger drainage area at the FLNRORD gauge (282 km^2 listed for 08HA045 at Koksilah River below Kelvin Creek versus 228 km^2 for WSC gauge) yields a predicted (i.e., expected) flow at the FLNRORD gauge of 0.196 m^3/s. Therefore, there is a flow deficit (measured minus predicted) of 0.0964 m^3/s at the downstream gauge that may be attributable to increased water demand pressures. The August 2018 downstream water demand was estimated as 0.19 m^3/s and could therefore indeed explain all the estimated flow deficit at the FLNRORD gauge. However, there is substantial uncertainty in this assessment due to the short concurrent data record.

5.4 ENVIRONMENTAL FLOW NEEDS CONSIDERATIONS

The provincial *Water Sustainability Act* and Environmental Flow Needs (EFN) Policy (BC ENV 2016) are key statutes that provide the foundation around aquatic risk associated with water quantity alterations/extractions in BC. Additionally, Fisheries and Oceans Canada (DFO) has a regulatory mandate to protect natural flow regimes to support riverine ecosystems occupying Pacific Salmon (including Steelhead; *Oncorhynchus mykiss*; e.g., DFO 2013).

Based on review and application of the provincial EFN Policy Environmental Risk Management Framework (BC ENV 2016), the Koksilah River is categorized as a highly sensitive watercourse with a Level 3 risk rating, which, in essence, requires detailed (field-based) habitat-hydrologic studies to understand water quantity needs to improve and protect aquatic ecological conditions.

Environmental Flow Needs (EFN), also referred to historically as Instream Flow Requirements (IFR) in BC, are defined as the volume and timing of water flow required for proper functioning of the aquatic ecosystem of the stream (Water Sustainability Act 2016). Thresholds can be determined using a variety of methods, which are outlined in Provincial guidance and other documents (e.g., Ptolemy and Lewis 2002; Hatfield et al. 2003; Lewis et al. 2004; Hatfield et al. 2007; DFO 2013; Linnansaari et al. 2013) and cover desktop (coarse) and field-based (detailed) level of assessment.

Environmental flow requirements will vary in a stream (i.e., are location-specific), depending on several factors including natural/pre-existing flows and fish use. In practice, EFN thresholds should be derived to protect the most sensitive reaches of a watercourse, often identified based on data describing available habitat and fish species present based on key bioperiods (e.g., spawning/egg incubation, summer rearing/nursery, overwintering). In some cases, EFN values may consider the lower reaches of a stream, but often need to focus on key upstream reaches where disparity in water availability (and associated consequences) is greater (Linnansaari et al. 2013).

Most environmental flow studies involve species-specific considerations, such as presence, habitat use, temperature, and food availability (Linnansaari et al. 2013). Understanding when various life stages of fish species are present help inform how much flow protection is required, when it is required, and where it is required. These considerations are especially important in eastern Vancouver Island watersheds, which can support a combination of resident freshwater and anadromous fish species; in particular, spawning and rearing habitats for the five species of Pacific Salmon (*Oncorhynchus sp.*) and trout including Steelhead/Rainbow trout (*Oncorhynchus mykiss)* and Coastal Cutthroat Trout (*Oncorhynchus clarkii clarkii*).

Pritchard et al. (2019) provides a summary of the anadromous and resident fish community that use the Koksilah River and watershed, offering an illustration of known species presence and distribution within the watershed. Given the dynamic fish community and documented stresses in the Koksilah River, any consideration around deriving flow needs to improve and protect aquatic habitat should first apply on-the-ground investigations to confirm species risk and support future opportunities more adequately for improvement (mitigation). Recommendations for study are provided in Section 6.

5.5 POTENTIAL FUTURE WATER SUSTAINABILITY SCENARIOS

Potential future water sustainability scenarios for the watershed could include:

- No change in water use but climate change continuing to get worse unabated (i.e., through absence of global action).
- Forest cover change (forestry) could make the low flow problem either better or worse or having only a very small effect. Of these three possible trajectories, a situation in which forest management continues to make the low flow problem better (i.e., a beneficial effect) seems unlikely in that it may require a level of logging intensity similar to 1980s situation. Therefore, only situations in which forestry has an overall negligible effect (through an appropriate mix of forest types and ages) or could have a detrimental effect (through an abundance of immature-mature trees requiring a lot of water) would seem plausible as a future trajectory.
- A situation in which there is more water use in future than is happening now (e.g., based on expected population rise and/or by considering the parcels flagged as having “potential irrigation use” (Section 3.2.3; Barroso and Wainwright, in press) to become active water users).
- A combined worst-case scenario of the above factors, which would entail unabated climate change, continued growth in water use and forestry having a detrimental effect on summertime low flows.
- Best case scenario for summertime low flows considering factors Cowichan Tribes and FLNRORD can control, which are (seasonal) water use (e.g., for example by considering crop types that do not need much irrigation or other water demand management measures), sustainable forest management practices that do not impact low flows, stream channel/aquatic habitat restoration efforts combined with global action on climate change which over time would dampen further effects (i.e., through the targeted upper limit on global temperature rise).

6.0 SUMMARY AND RECOMMENDATIONS

The analyses conducted in this study suggest that about half of the decline in summertime low flows in the watershed is explained by water demand, which is a firm assessment based on available data, and which is a factor that can be controlled through the development of a Water Sustainability Plan. The other half of the decline in low flows is associated with climate change effects that cannot be controlled through local watershed initiatives, and with these climate change effects likely continuing to get worse.

Another important finding from this study has been that the trend in declining low flows appears to have been mitigated by historical forest cover changes, with this mitigating effect having been strongest in the 1980s and 1990s but having dissipated in the recent decade. There is a risk that continued evolution (growth) of previously logged forest stands in the watershed could ultimately exacerbate the low flow problem as maturing trees continue to use more water. For example, in Oregon it has been found that 40- to 50-yr rotations of Douglas-fir plantations can produce persistent, large summer low flow deficits (Segura et al., 2020). It has now been about 40-50 years since the industrial logging period in the watershed. The future trajectory of forest cover change driven effects on water availability in the watershed is expected to depend on the mix of forest types and age classes present, with some distributions possibly leading to increased water availability while different distributions could emphasize water shortages. It is recommended that these uncertainties be addressed through a watershed-scale sustainable Forest Management Plan.

Ultimately, any forest management that seeks to mitigate long-term declines low flow declines must be informed by a mechanistic understanding of the underlying processes. However, as noted by Coble et al. (2020), basic mechanistic questions such as how water uptake by trees affects subsurface water storage and streamflow or how distribution of trees in the catchment (riparian versus upland) affect water use remain active topics of research. This is a challenge for the scientific community to address, with possible recommendations for detailed stand-level studies provided below.

The Water Sustainability Plan and watershed-scale Forest Management Plan should be supported by a detailed EFN assessment. The detailed EFN would include several technical components including (but not limited to) aquatic (fish) habitat assessment and specific fish species/community studies to verify presence and distribution, habitat use, and limiting factors. These studies would aim to associate seasonal minimum flow requirements for different fish species (life stages) present in the watershed, as well as document existing impacts on the stream channel environment, which may exacerbate those existing impacts from declining low flows. Expressed habitat concerns that could be investigated and documented with field-based studies along the Koksilah River and its tributaries within the context of an EFN study include: forestry-related aggradation and increase of river bedload, culvert design, stormwater outfalls, rural deforestation/land clearing, non-point source pollution impacts and overall variations in physical and chemical water quality. The potential role of karst in supporting aquatic habitat values could also be evaluated. These detailed field-based studies were beyond the scope of this desk-top hydrologic change assessments.

It is recommended that a robust water balance model is developed for the watershed (e.g., a fully distributed hydrological model). This model should target to address and simulate the major causal factors affecting low flows in the watershed and could subsequently be used to address "what if" scenarios that might play out over the next decades (explored in Section 5.5) and assess their potential impact on water sustainability and EFN.

Opportunities may exist for combining the water balance model with a numerical groundwater flow model (e.g., through an integrated groundwater-surface water model) although the capability requirements of such a model in representing evapotranspiration changes in a mechanistic (physically based) fashion would be a key consideration. Some of the capability requirements of hydrologic models for incorporating the effects of climate change were discussed in Beckers et al. (2009). While this review was not exhaustive and limited to models suitable for use in forest management applications, it does provide a reasonable overview of the main considerations for model selection. The water balance model, once developed, could also be used to inform decisions within the Water Sustainability Plan framework.

There are considerable uncertainties in the input parameters for the water balance of the watershed, which will lead to uncertainties in water balance modelling of future "what if" scenarios. Water balance uncertainties arise because climate (precipitation) monitoring only occurs at lower elevation and there remain uncertainties in total precipitation amounts at higher elevation and the relative importance of snowfall at these higher elevations. These uncertainties could be addressed by establishing climate monitoring and snow measurements in the upper watershed. There are also considerable uncertainties in actual evapotranspiration of forest stands of different ages and characteristics (i.e., different tree types and their height, crown closure, etc.). Studies could be conducted for select (recovering) forest stands (and possibly for select irrigated crops) to better quantify actual evapotranspiration (e.g., through flux tower experiments, sap flow measurements, rainfall interception experiments, soil moisture data collection or a combination thereof). The evapotranspiration studies might leverage where possible physical forest cover data (stand height, crown closure) owned by Mosaic Forests. The evapotranspiration studies would also benefit from the suggested additional climate data collection in the watershed. Funding for such studies could be obtained from scientific grants as they would address fundamental gaps in understanding that will aid forest management decisions in coastal watersheds in BC.

It was determined that water use in the lower portion of the watershed has a greater effect on low flows than water use higher up in the watershed. However, additional granularity may be required for informed water management decisions and to identify specific areas where water management should be prioritized. More work can be done to compare flows between the FLNRORD and WSC gauges as the concurrent data record becomes longer and confidence in the data from the FLNRORD gauge increases. The relative importance of water uses within smaller sub-areas (Kelvin Creek, Glenora Creek, Patrolas Creek and Koksilah River itself) for low flows in the mid- to lower portions river was also not yet investigated in further detail. This reflects in part the limitation of the Glover analysis and inferred groundwater-surface water connectivity from the Sivak and Wei (2019) study. Questions regarding how the spatial distribution of groundwater use affects Koksilah River low flows are better addressed through a numerical groundwater flow model that more explicitly represents the areas of inferred groundwater-surface water connectivity and the spatial arrangement of aquifers in the watershed. Additional streamflow monitoring of the tributary drainages will also help narrow down the identification of areas where water use is most problematic, would inform the calibration of numerical models and create refined understanding of hydraulic connectivity between groundwater and surface water.

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