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Watershed Modelling to Support Water Allocation and Planning in the Shawnigan Creek Watershed, Vancouver Island, B.C.

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Cover Photograph:
Shawnigan Lake from Old Baldy Mountain, Vancouver Island, B.C. (Source: Cowichan Valley Regional District)

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EXECUTIVE SUMMARY

An integrated, physically based, three-dimensional numerical model of surface water and groundwater flow has been developed for the Shawnigan Creek watershed on Vancouver Island, B.C. This watershed has been subject to heightened stress in recent years due to increased water use and contains many groundwater wells that are likely hydraulically connected to fully recorded streams. The numerical model supports water allocation and planning efforts by serving as a decision support tool to assist West Coast Region staff conjunctively manage surface water and groundwater resources.

Key objectives and outcomes of the project include:

- Quantifying annual and monthly water balances that describe the primary inputs and outputs from the watershed – including precipitation, evapotranspiration, streamflow, overland flow, and groundwater flow. Results highlight periods of the year where there is a surplus or deficit of water and how the relative importance of each component of the water balance changes through the year.
- Quantifying hydraulic connection between aquifers and streams. Results suggest that the magnitude of hydraulic connection between aquifers and streams can not only vary spatially and temporally but also change direction in specific locations at certain times of the year.
- Quantifying cumulative effects of combined surface water and groundwater use on the water balance and hydraulic connection between aquifers and streams. Results suggest that water use has a small influence on the water balance at the watershed scale but, depending on the direction of hydraulic connection, can lead to increased water losses from streams or reduced water gains to streams.
- Quantifying potential impacts of a future (conservative) climate projection on the water balance and hydraulic connection between aquifers and streams. Results suggest that the storage capacity of the subsurface could play a role in modulating future changes to climate. Increased water losses from streams could occur in the summer months while increased water gains to streams could occur in the winter months.

This project illustrates an approach to support the Province's efforts to conjunctively manage surface water and groundwater and provides watershed-specific information that can be used by statutory decision makers when considering water license applications. Future opportunities could include developing and applying similar numerical models to support water allocation and planning in other water-stressed areas of the province.

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ACRONYMS AND ABBREVIATIONS

AET	Actual Evapotranspiration
CMIP6	Coupled Model Intercomparison Project 6
DEM	Digital Elevation Model
ENV	Ministry of Environment and Climate Change Strategy
ET	Evapotranspiration
FOR	Ministry of Forests
GCM	General Circulation Model
GWELLS	Provincial groundwater well database
HGS	HydroGeoSphere
LAI	Leaf Area Index
masl	Metres Above Sea Level
MBWD	Mill Bay Waterworks District
PET	Potential Evapotranspiration
PGOWN	Provincial Groundwater Observation Well Network
SSPs	Shared Socioeconomic Pathways
WLRS	Ministry of Water, Land and Resource Stewardship
WSA	*Water Sustainability Act*

1. INTRODUCTION

1.1 Context

The *Water Sustainability Act* (WSA) came into effect in 2016 (Province of British Columbia, 2016) and with it came many challenges. Licensing groundwater use amidst times of water scarcity, drought, climate variability, and in areas where industry and land development continue to impact B.C.'s groundwater resources is both an opportunity and challenge.

The WSA mandates that operation of groundwater pumping wells must not cause, or be likely to cause, a significant adverse impact to an aquifer or a hydraulically connected stream. As a result, assessments of interaction between aquifers and streams (i.e., hydraulic connection) are needed by provincial staff when administering the WSA. Statutory decision makers must also consider cumulative effects and sustainability when managing surface water and groundwater resources.

Desktop approaches have been used to estimate the likelihood of hydraulic connection between aquifers and streams (Wei et al., 2016). This project attempts to build on this previous work by advancing an (integrated modelling) approach that can expand spatial and temporal understanding of hydraulic connection and, at the same time, assess cumulative effects from water use and climate change. Numerical models can be particularly valuable in situations where aquifers are hydraulically connected to sensitive or fully recorded streams and in watersheds that are at or near allocation limits and may be subject to recurring Temporary Protection Orders.

1.2 Objectives

This pilot study illustrates an approach to develop and apply an integrated numerical model in support of water allocation and planning efforts to conjunctively manage surface water and groundwater.

Project objectives are:

- *Objective 1:* Quantify annual and monthly water balances that describe the primary inputs and outputs from the watershed – including precipitation, evapotranspiration, streamflow, overland flow, and groundwater flow.
- *Objective 2:* Quantify hydraulic connection between aquifers and streams, including assessment of how the magnitude of hydraulic connection varies spatially and temporally and if its direction changes in specific locations at certain times of the year.
- *Objective 3:* Quantify cumulative effects of combined surface water and groundwater use on the water balance and hydraulic connection between aquifers and streams.
- *Objective 4:* Quantify potential impacts of a future (conservative) climate projection on the water balance and hydraulic connection between aquifers and streams.

The model developed herein serves as a decision support tool that provides statutory decision makers with watershed-specific information that can be used when considering water license applications. It is best suited for addressing watershed-scale questions and detailed use at the well-scale is not recommended. It can be used, with partners, to provide support to water management initiatives such as the Shared Water Management Decision-Making Framework with Malahat Nation or the Cowichan Valley Regional District's Drinking Water and Watershed Protection Program (CVRD, 2020). Future opportunities could include developing similar models in water-stressed watersheds elsewhere in the region or across the province.

1.3 Modelling Approach

Recognizing that traditional numerical models have focused on either the movement of water above (surface water models) or below (groundwater models) the ground surface, integrated numerical models represent a significant advancement and offer the ability to simultaneously consider the movement of water above and below the ground surface – and the interaction between the two domains. A schematic of such a model is shown in Figure 1.

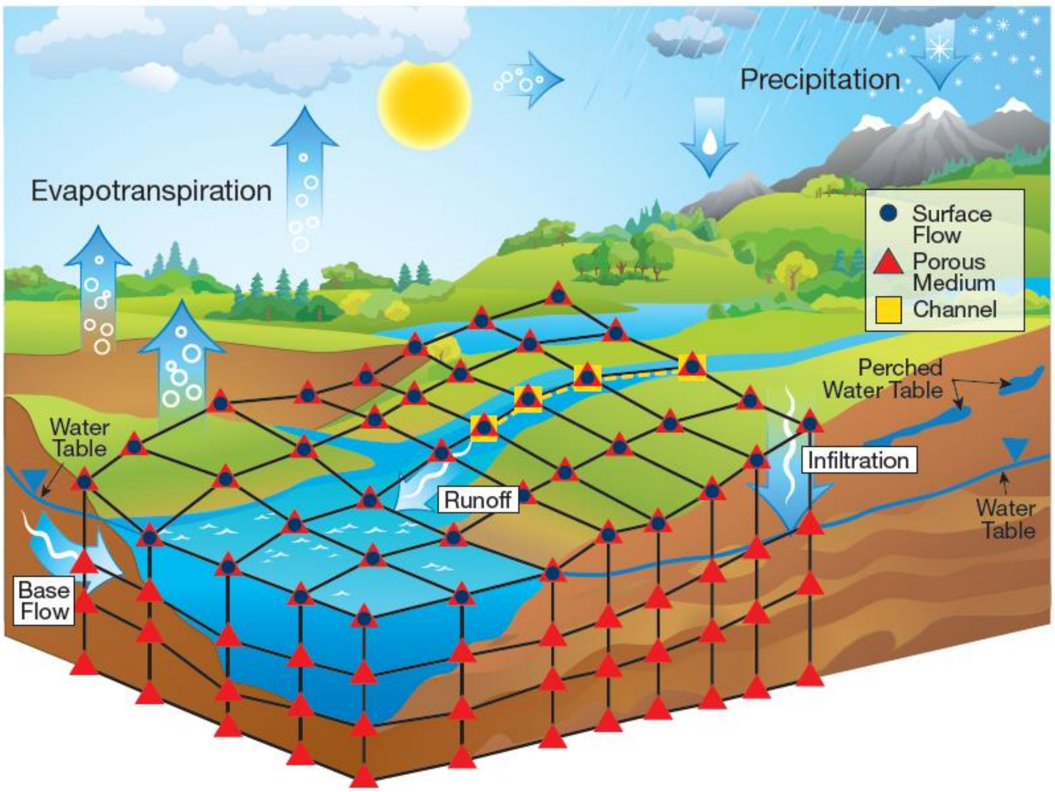

Figure 1: Schematic of an integrated numerical model (Aquanty, 2015a).

As knowledge and computational resources (Freeze and Harlan, 1969; Simmons et al., 2019) have increased, various attempts to couple surface water models and groundwater models have been developed. Approaches include:

1) Separate and/or manually linked:

   A surface water model and a groundwater model are developed separately and exist in separate software programs. Governing flow equations in the surface water model and groundwater model are solved separately and output from one model is used as input to the other model. A user must link the models manually through input and output files for each program. Recharge estimated by a surface water model is often assigned as input to a groundwater model and baseflow estimated by a groundwater model is often assigned as input to a surface water model. Examples of surface water models commonly coupled to groundwater models include HSPF (Bicknell et al., 1997) and HEC-HMS (U.S. Army Corps of

Engineers, 2012). Examples of groundwater models commonly coupled to surface water models include MODFLOW (McDonald and Harbaugh, 1988) and FEFLOW (Diersch, 2014).

2) Loosely coupled:

   A surface water model and a groundwater model are automatically linked within a single software program and output from one model no longer needs to be manually linked to the other model. The surface water model and groundwater model are often referred to as domains since both are within one numerical model. Governing flow equations within the surface water domain and the groundwater domain are solved separately and information is passed between the domains. Examples of loosely coupled models include GSFLOW (Markstrom et al., 2008) and MIKE-SHE (DHI, 2023).

3) Tightly coupled:

   A surface water model and a groundwater model are fully integrated within a single software program. Governing flow equations within the surface water domain and groundwater domain can be solved simultaneously with information passed between the domains at all time steps. Examples of tightly coupled models include MODHMS (Panday, 2004; HGL, 2008), HydroGeoSphere (Aquanty, 2015a; 2015b), and ParFlow (IGMC, 2023).

Each approach can involve various hydrologic processes and spatial discretizations. For example, a groundwater model may be coupled to a stream network capable of routing flow but may not have the ability to simulate runoff to that stream network. Similarly, a surface water model may be coupled to a one-dimensional groundwater model to simulate infiltration through variably saturated media. For these reasons, modelling approach and code selection is a critical aspect of any modelling project as each code incorporates different process representations, can have different spatial discretizations, can solve the governing flow equations differently, and therefore produce varied results.

In this pilot study, an integrated numerical model was developed using a tightly coupled approach that includes porous media, overland flow, channel flow, and evapotranspiration domains.

2. STUDY AREA

The Shawnigan Creek watershed is located on southeastern Vancouver Island, approximately 30 km northwest of Victoria (Figure 2). It has an area of approximately 127 km^2 and ranges in elevation from approximately 650 masl in the headwaters south of Shawnigan Lake to sea level along Saanich Inlet at Mill Bay. Bounded by hydrologic divides that surround Shawnigan Lake, Cobble Hill, and Mill Bay, the Shawnigan Creek watershed is the largest and most populated watershed in the South Cowichan region of Vancouver Island. The upper watershed has been primarily used for forest management and timber harvesting activities whereas the lower watershed has been primarily developed for agriculture and residential use.

Most streams in the watershed have been either fully recorded or fully recorded with exceptions (an operational term that implies a water source is fully allocated and no more water licenses can be granted from that source). Shawnigan Creek, the watershed's primary watercourse, drains from Shawnigan Lake to Saanich Inlet at Mill Bay and has been fully recorded since 1953. Shawnigan Lake has been fully recorded since 2005, with exceptions for domestic use. Fully allocated streams have led to a shift towards groundwater use in recent decades – which now has also become stressed. Aquifers 197, 203, and 206 (described in later sections of this report) have notations for possible water shortages and hydraulic connection to fully recorded streams. Future demand on groundwater is expected to increase with growth and development pressure in the watershed.

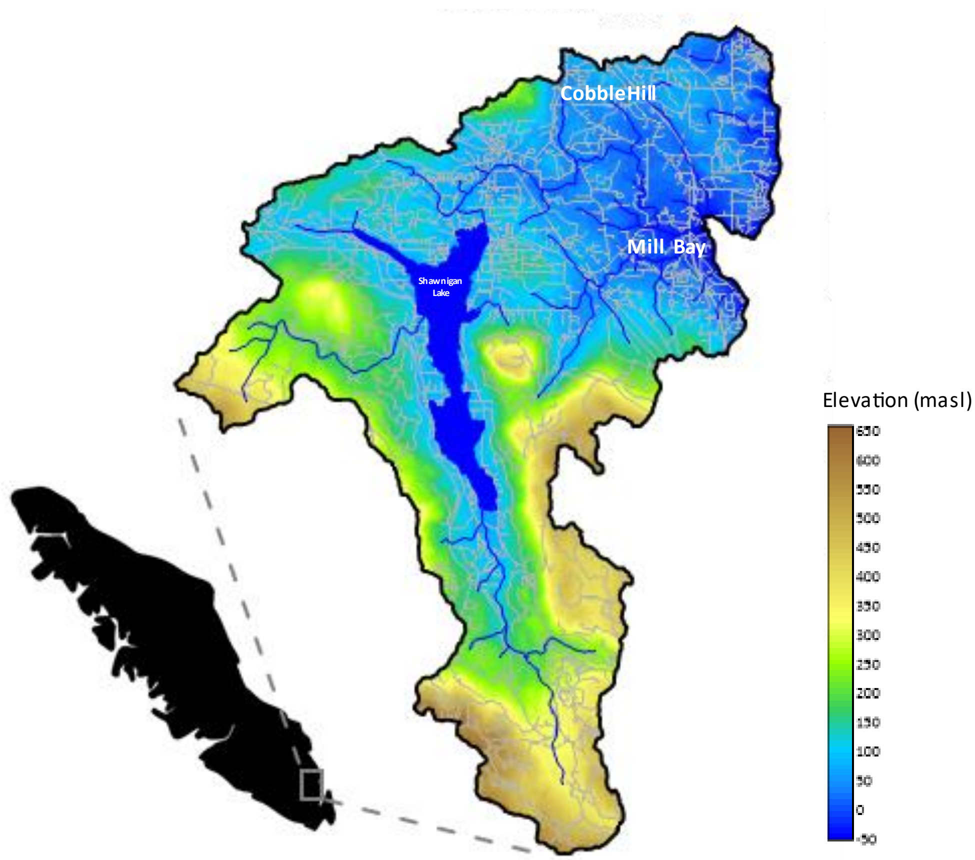

Figure 2: The Shawnigan Creek watershed.

3. CONCEPTUAL MODEL

The building blocks of a numerical model are strongly rooted in a well-described conceptual model. The Shawnigan Creek watershed has been the subject of many foundational studies, including aquifer mapping, characterization, water budgets, and assessments of hydraulic connection (Harris and Usher, 2016; Hammond et al., 2019; WWAL, 2018; 2021; 2022b; 2023). The conceptual model for the watershed, including aspects on climate, topography and drainage, land cover, soils, hydrostratigraphy, and groundwater is shown in Figure 3. Development of this conceptual model (from top down) is described in subsequent sections of this report.

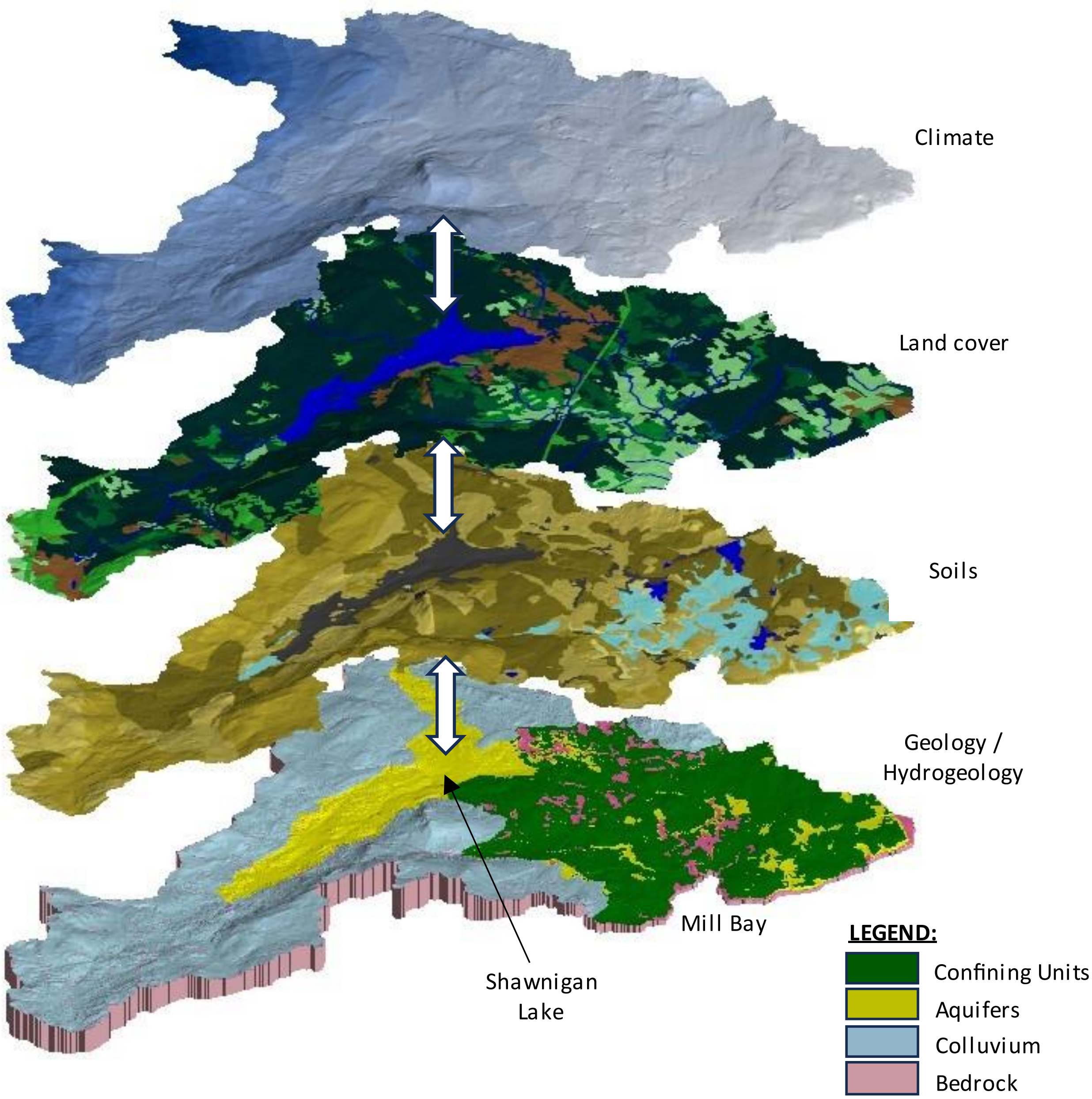

Figure 3: Conceptual model of the Shawnigan Creek watershed.

3.1 Climate

Although southern Vancouver Island receives a small amount of snowfall during the winter months, the watershed is known to be rain-dominated. A climate station (ID: 1017230) is located near Shawnigan Lake and has been recording precipitation and temperature data since 1911. Annual-average precipitation at the Shawnigan Lake climate station for the period of record (1911-2022) is approximately 1,200 mm with, on average, 90 mm falling as snow.

Monthly-average (1911-2022) precipitation and temperature are shown in Figure 4. Winter months (November, December, and January) are relatively wet with the watershed receiving approximately 200 mm/month of precipitation. Summer months (June, July, and August) are drier with the watershed receiving less than 50 mm/month of precipitation. Transition months (or shoulder seasons) generally have intermediate amounts of precipitation. Snowfall is intermittent and historically limited to the months between November and March. Monthly-average (1911-2022) temperature is less than 5ºC during the winter months and increases to more than 15ºC in the summer months. Minimum and maximum monthly-average temperatures suggest an approximate 5ºC to 10ºC range in monthly-average temperature within any given month, with a larger range in the summer months.

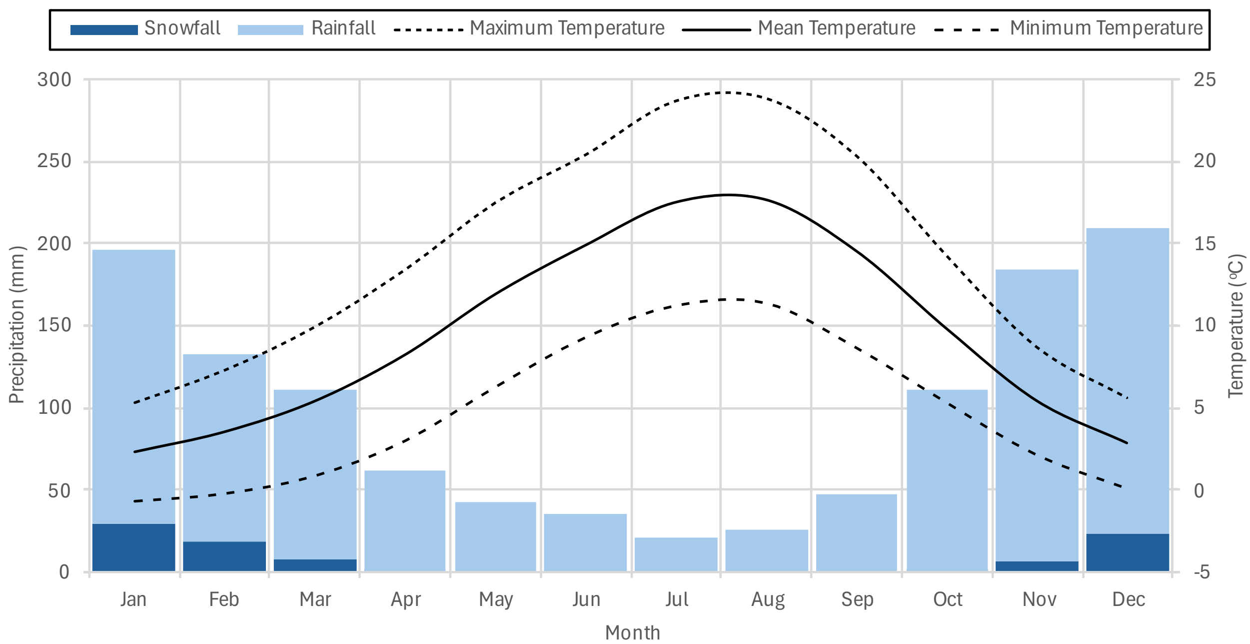

Figure 4: Monthly-average (1911-2022) precipitation and temperature.

Spatially distributed precipitation and potential evapotranspiration (Hargreaves reference evaporation) grids are available for the extent of the watershed from the ClimateBC web portal (Wang et al., 2016). ClimateBC is a web application that downscales historical and future projections of spatially distributed climate normal data from PRISM (Daly et al., 2008; Mahony et al., 2022). Multiple climate normal periods are available from ClimateBC; the most recent period (1991-2020) was selected for this project as it generally coincides with the increased development of groundwater resources that has occurred within the watershed in recent decades.

Annual normal (1991-2020) precipitation and potential evapotranspiration are shown in Figure 5 and Figure 6, respectively. A relationship between precipitation and elevation is evident, with precipitation increasing from approximately 900 mm in the lower watershed near Saanich Inlet to upwards of 1,800 mm in the upper watershed above Shawnigan Lake. An inverted relationship between potential evaporation and elevation is also evident, with potential evaporation increasing from approximately 600 mm in the upper watershed above Shawnigan Lake to upwards of 700 mm in the lower watershed near Saanich Inlet.

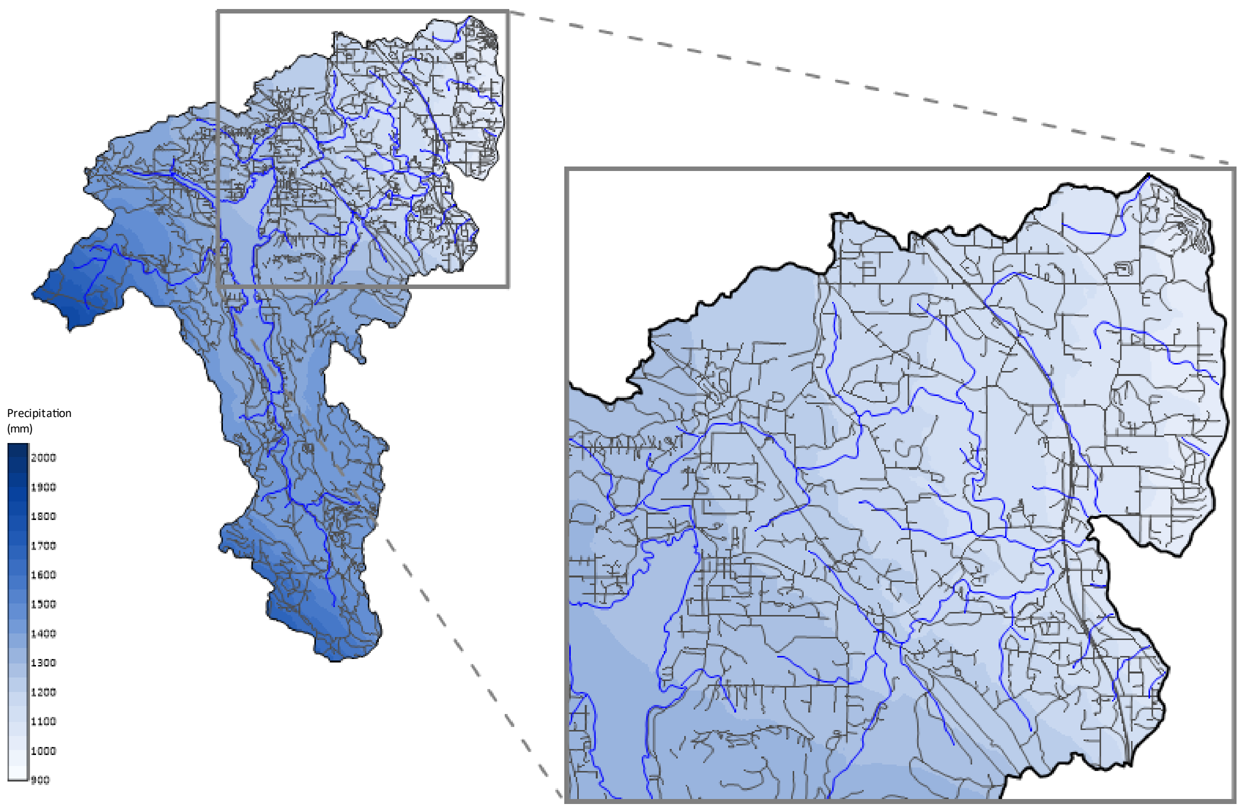

Figure 5: Annual normal (1991-2020) precipitation.

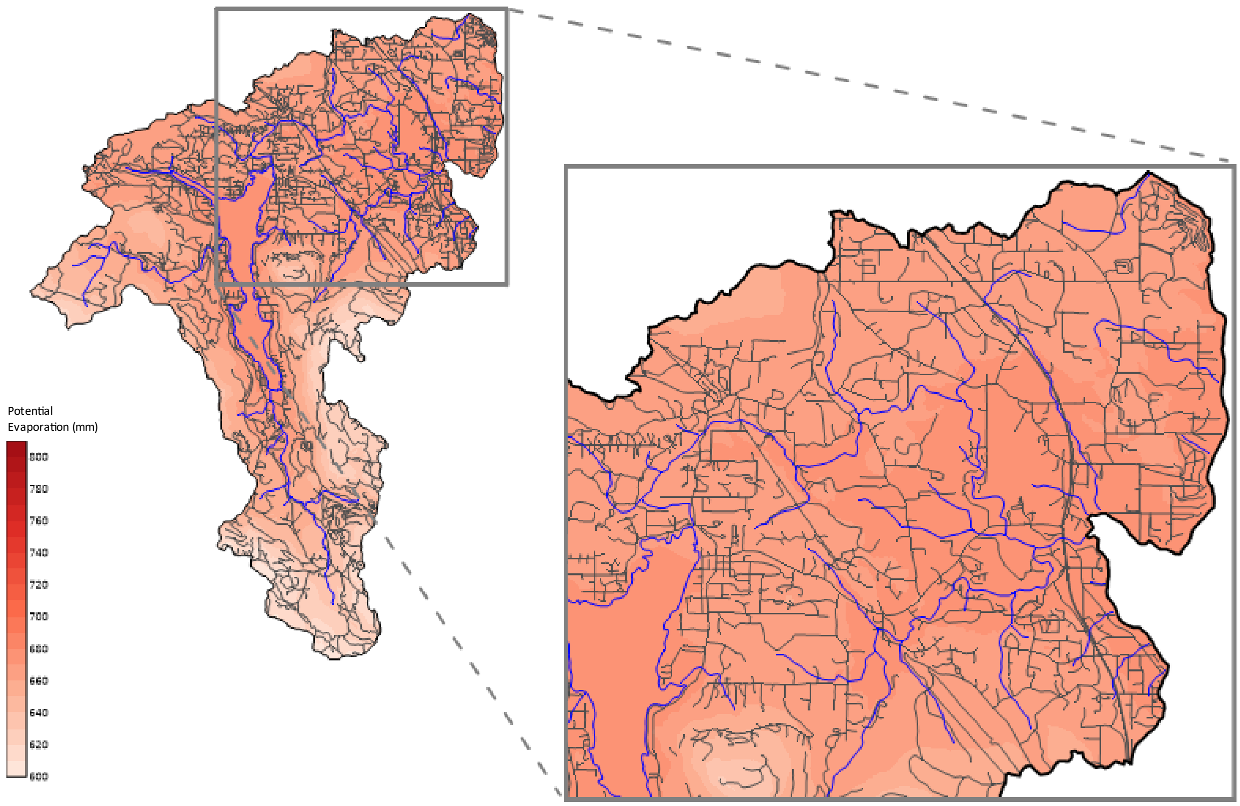

Figure 6: Annual normal (1991-2020) potential evapotranspiration.

Monthly normal (1991-2020) precipitation and potential evapotranspiration are shown in Figure 7 and Figure 8, respectively. The relationship between precipitation and elevation is maintained throughout the year with precipitation increasing from less than 50 mm in the summer months to more than 300 mm in the winter months. The inverted relationship between potential evapotranspiration and elevation also is maintained throughout the year with potential evapotranspiration increasing from less than 20 mm in the winter months to more than 100 mm in the summer months.

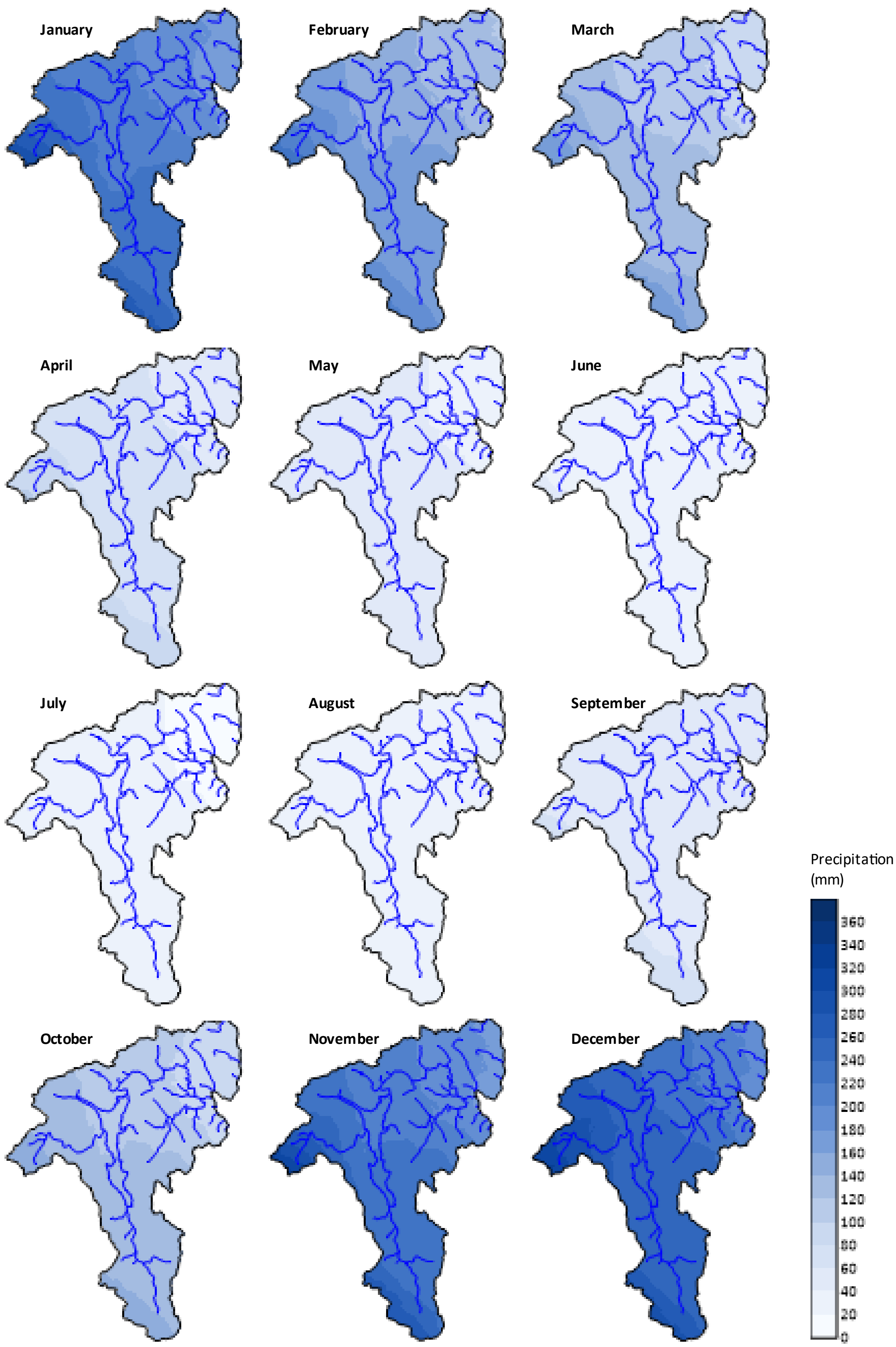

Figure 7: Monthly normal (1991-2020) precipitation.

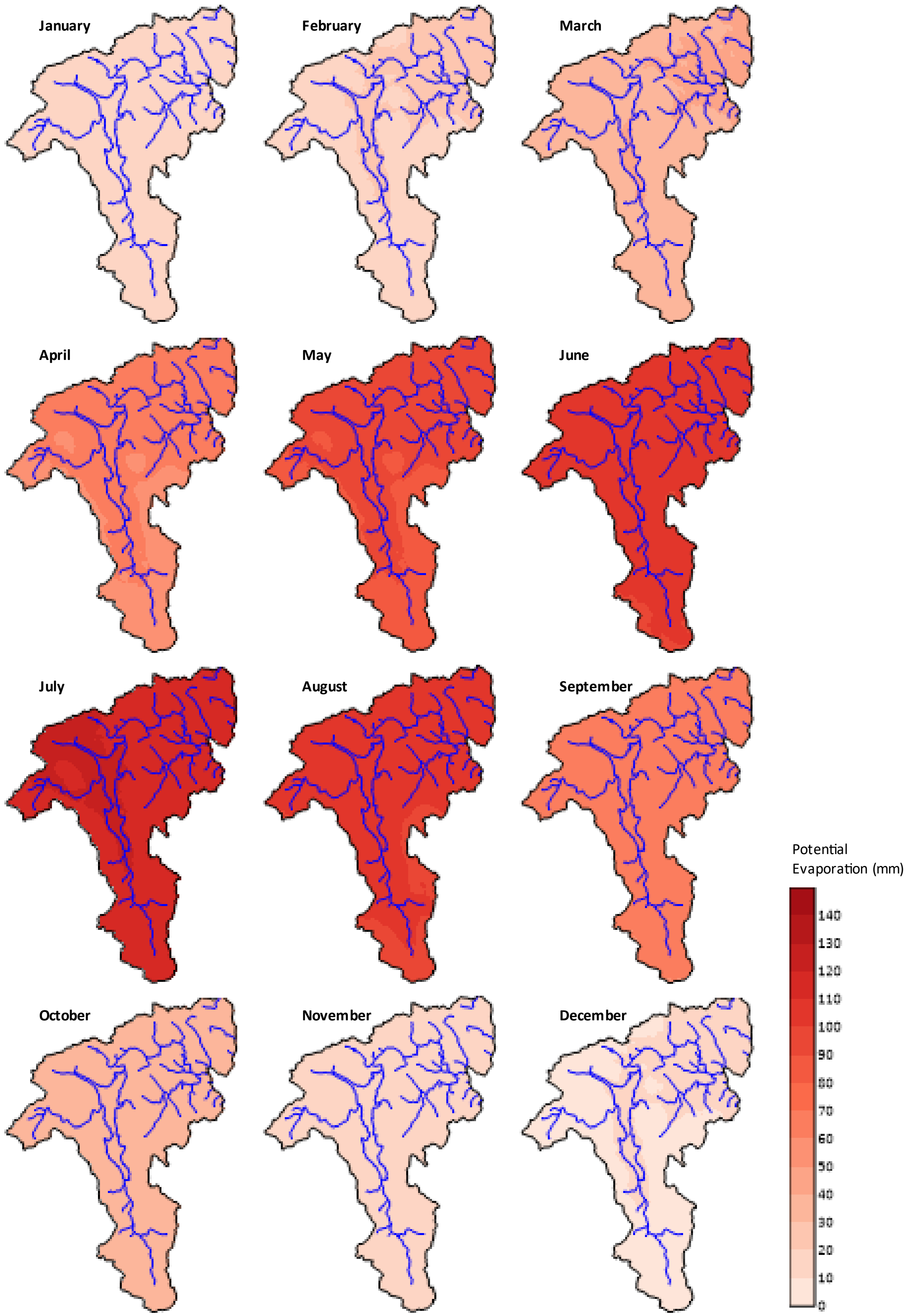

Figure 8: Monthly normal (1991-2020) potential evapotranspiration.

3.2 Topography and Drainage

A Digital Elevation Model (DEM) of the watershed was developed by combining (stitching together) topographic data from various sources. Data were collected and superimposed in the following order (i.e., in the reverse order of precedence):

1. Canada-wide DEM (NRCan, 2011);
2. LiDARBC data that mostly covered coastlines (GeoBC, 2019);
3. LiDAR data (provided by Cowichan Valley Regional District) that covered a large portion of the lower watershed; and
4. Bathymetry contours for Shawnigan Lake (ENV, 1977).

Minor corrections were made to the combined DEM to ensure that streams formed on the land surface and drained in the correct direction along mapped channels from the B.C. Freshwater Atlas (GeoBC, 2023). Minor corrections were required, for example, in areas where culverts beneath roadways were not accurately identified in the DEM. Most minor corrections were needed along major roadways and in the vicinity of Mill Bay and were primarily for smaller streams that drain directly into Saanich Inlet at Mill Bay (by creating small depressions in the topography and allowing water to move across the road). The DEM and stream network are shown in Figure 9.

Streams originate in the headwaters above Shawnigan Lake and generally drain eastward towards Saanich Inlet at Mill Bay. Shawnigan Creek flows west to east, from Shawnigan Lake to Saanich Inlet at Mill Bay. Tributaries to Shawnigan Creek include McGee Creek (to the west of Shawnigan Lake), Van Horne Creek (to the south of Shawnigan Lake), and Handysen Creek (to the east of Shawnigan Lake).

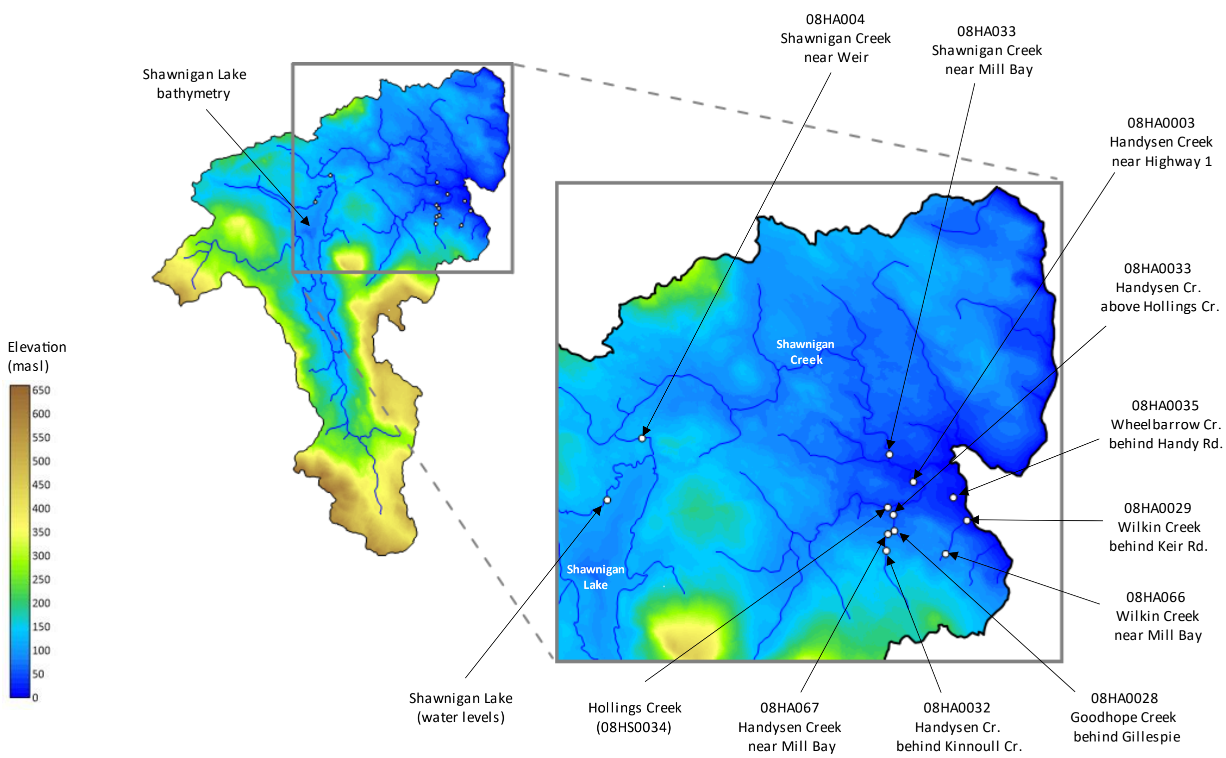

Figure 9: Topography, drainage, and streamflow monitoring stations.

Hollings Creek is the largest tributary of Handysen Creek. Most of the headwater streams (order 1 streams) are ephemeral and have flows only in response to precipitation events and no flows during the dry season. The named tributaries are mostly perennial streams with only a few being intermittent – that is streams with flows sustained from smaller upstream tributaries, groundwater and snowmelt, and may not have flowing surface water. Perennial streams (with flows throughout the year) receive water from upstream sources and/or groundwater and maintain continuous surface flows; these streams do not experience drying except during more extreme drought conditions. Streamflow has been monitored at gauging locations shown in Figure 9.

The Water Survey of Canada has monitored streamflow at four locations in the watershed, although these gauging stations are no longer active. Two stations were along Shawnigan Creek: 08HA004 (near the Shawnigan Weir) and 08HA033 (near Mill Bay, above the confluence with Handysen Creek). A third station (08HA066) was located on Wilkin Creek and a fourth (08HA067) was located on Handysen Creek. Periods of record for these gauging stations are variable and are shown in Figure 10. Hydrographs vary year to year and indicate peak flow in the winter months (when there is substantial rainfall) and low flow in the summer months (when there is little to no rainfall, and likely supported by groundwater).

Additional streamflow monitoring has been conducted by the Province of B.C. in areas adjacent to Mill Bay. Seven gauging stations were monitored intermittently between 2016 and 2020, primarily on the Handysen Creek tributary during the summer months to collect data on low flow. Periods of record for these gauging stations are variable and are shown in Figure 11. Hydrographs vary year-to-year and are considered incomplete but provide data during the low flow season and can be a good indicator of available groundwater flows.

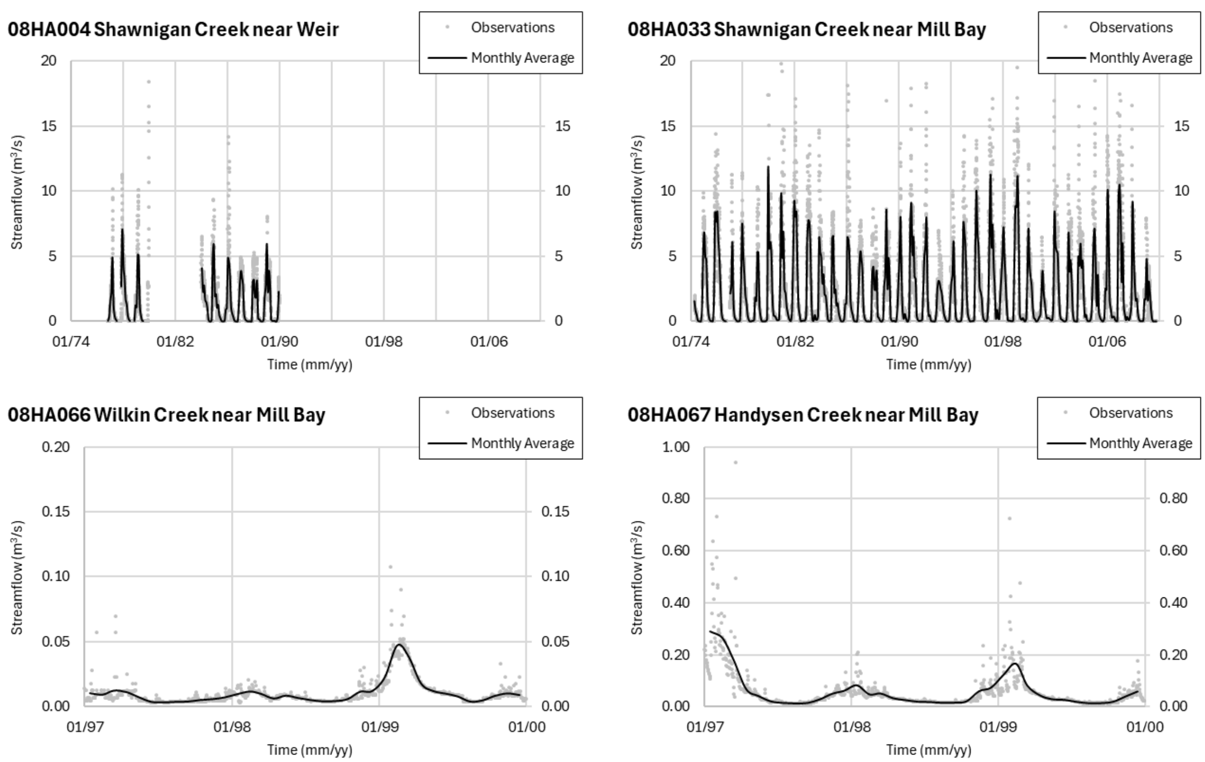

Figure 10: Observed streamflow at historical Water Survey of Canada gauging locations.

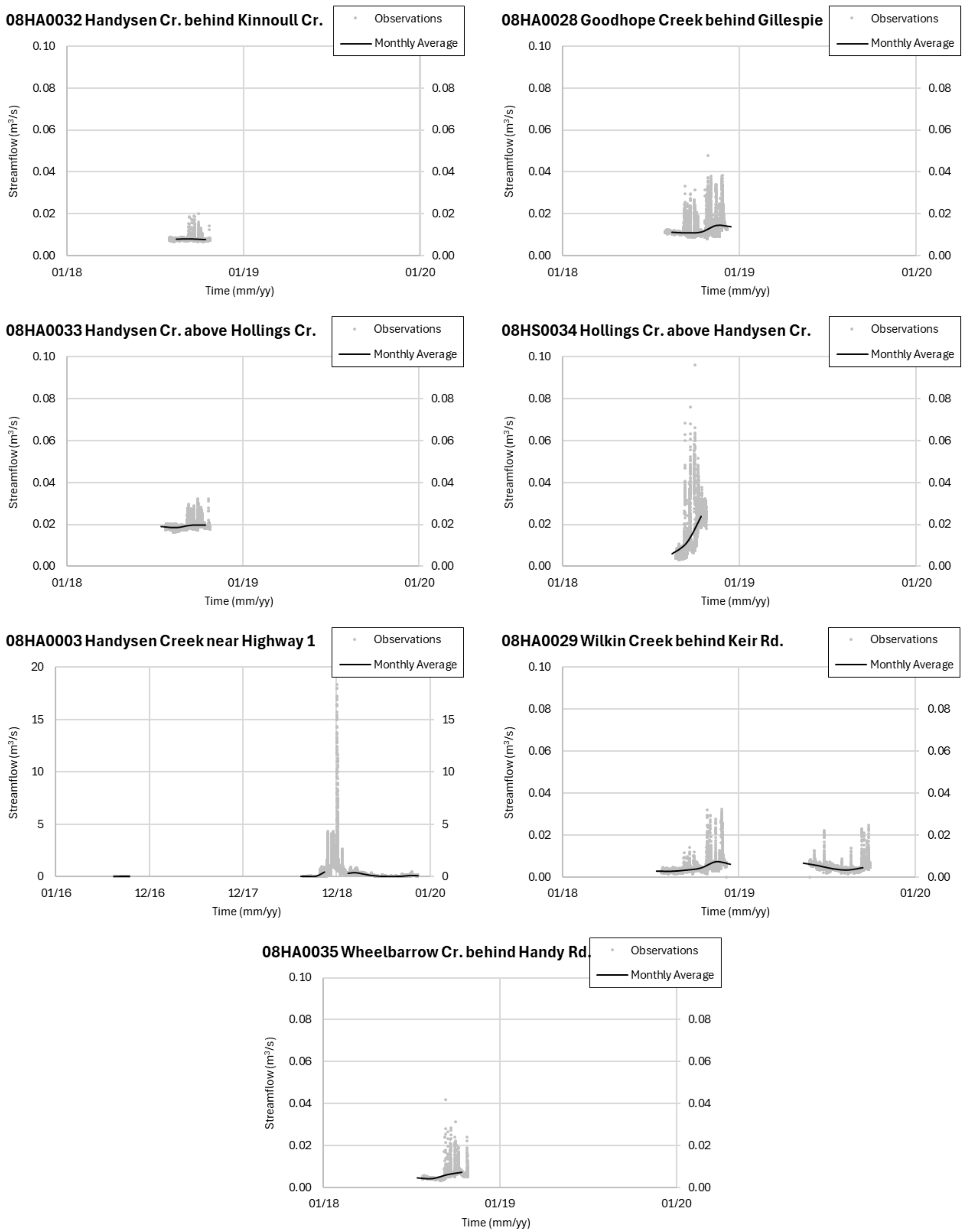

Figure 11: Observed streamflow at historical Province of B.C. gauging stations.

Shawnigan Lake, the largest waterbody in the watershed, has an area more than 500 ha and a storage capacity of approximately 65 million m^3. Observed water levels at the Shawnigan Lake pump station were provided by the Cowichan Valley Regional District and are shown in Figure 12. Water level in Shawnigan Lake fluctuates a small amount throughout the year, with higher water level in the winter months (when there is substantial rainfall) and lower water level in the summer months (when there is little to no rainfall). Water level in Shawnigan Lake can be influenced by the Shawnigan Weir located near the lake outlet (Ecora, 2019).

Observed streamflow and water elevation data shown in Figure 10, Figure 11, and Figure 12 are available for download and use from the Province of B.C.'s Aquarius database (Province of B.C., 2023a) and B.C. Water Tool (Foundry Spatial, 2023).

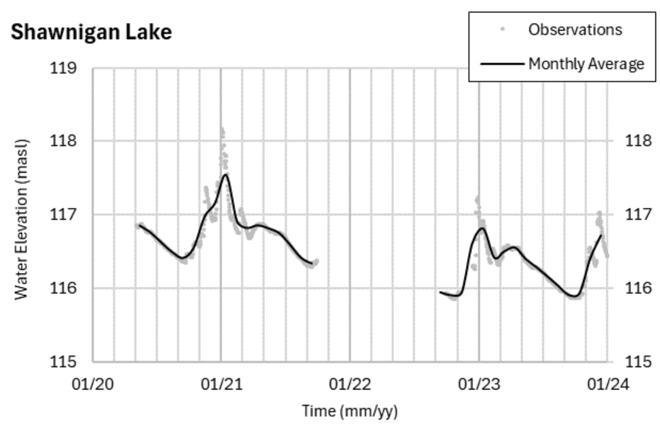

Figure 12: Shawnigan Lake water elevation.

3.3 Land Cover

Land cover in the watershed is classified according to the B.C. land cover classification system (B.C. Land Cover Classification Scheme, 2002) and includes water, exposed land, herb, shrub, and three types of treed areas: broadleaf, coniferous, and mixed. Land cover is shown in Figure 13.

Land cover plays an important role in routing precipitation to streams and calculating actual evapotranspiration. Manning's n (also known as the friction coefficient) influences how quickly water is routed across the land surface and depends on land cover class. Leaf Area Index (LAI) and rooting depth influence the calculation of actual evapotranspiration and depend on land cover class. Literature values for Manning's n (USGS NRCS, 2021), LAI (Chen, 2002), and rooting depth (Canadell, 1996) were assigned to each land cover type in the numerical model and modified during calibration.

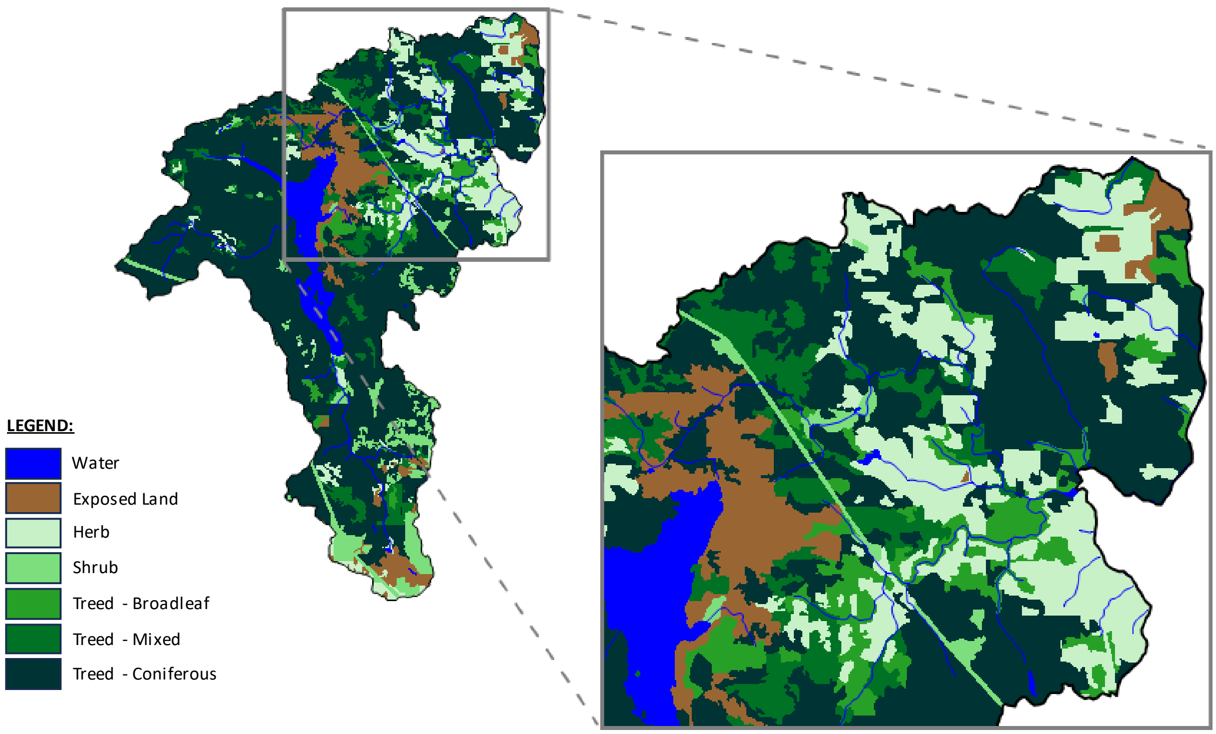

Figure 13: Land cover in the Shawnigan Creek watershed.

3.4 Soil Classification

Soils in the watershed have been classified by texture in the B.C. Soils Information Finder Tool (B.C. SIFT, 2018) as shown in Figure 14. Soil classes are delineated based on percentages of sand, silt, and clay and include sand, loamy sand, sandy loam, loam, silt, and clay. Loamy sand is defined as 70% to 90% sand with less than 15% clay, sandy loam is defined as 45% to 80% sand with less than 20% clay, and loam is defined as 25% to 50% sand with less than 30% clay. Most of the watershed is underlain by various types of loams, with a significant portion of the lower watershed underlain by silts. These silts are likely related to Vashon Till deposits that are known to exist in these areas.

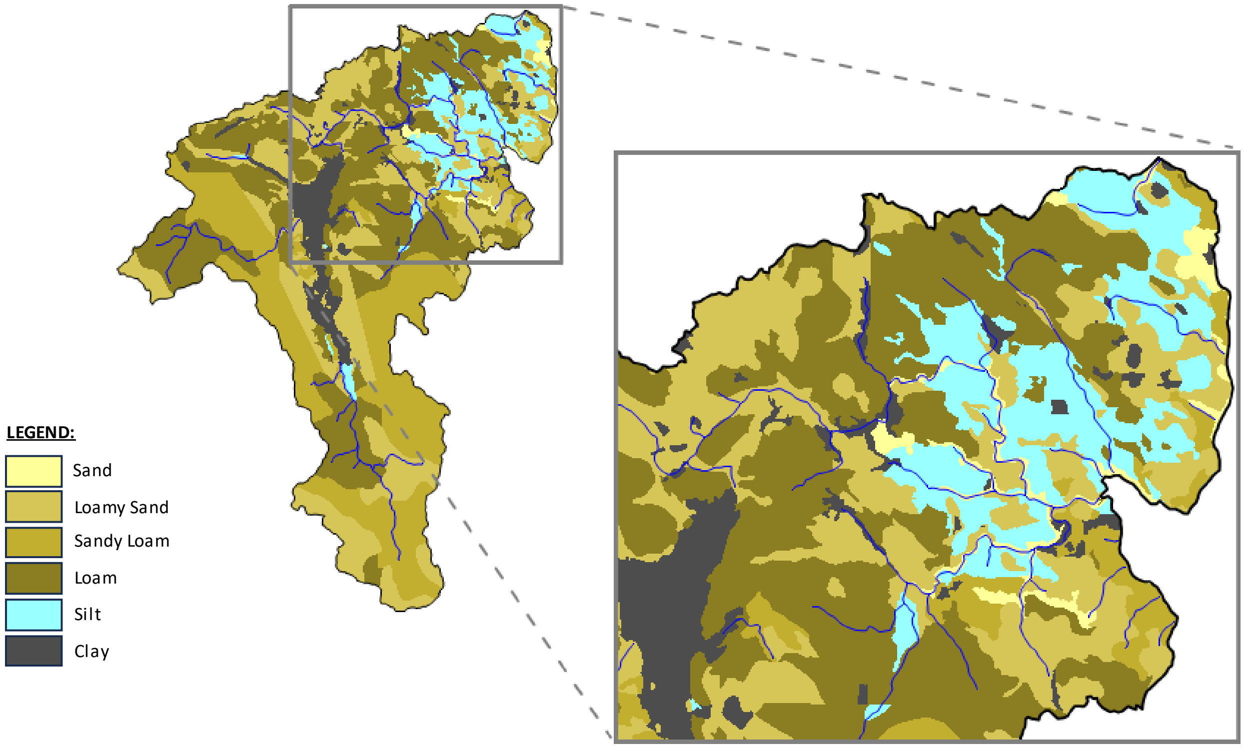

Figure 14: Soil classification in the Shawnigan Creek watershed.

Variably saturated soils influence the ability of the subsurface to infiltrate water. As soil dries, its water content and relative hydraulic conductivity decrease, thereby limiting infiltration. Conversely, as soil wets, its water content and relative hydraulic conductivity increase and infiltration is promoted.

Soil moisture retention curves were developed using the van Genuchten (1980) method. Saturation (S) of soil was calculated as:

$$S = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \begin{cases} [1 + (-\alpha\psi)^n]^{-m} & \psi < 0 \\ 1 & \psi \geq 0 \end{cases}$$

Where S is saturation, θ is water content, θ_r is residual water content, θ_s is saturated water content, ψ is pressure head, and α, n, and m (1-1/n) are fitting parameters.

Relative hydraulic conductivity (K_r) was calculated as:

$$K_r = S^{0.5}\left[1 - \left(1 - S^{1/m}\right)^m\right]^2$$

Soil class average values (USDA, 1999) were used in these equations to develop soil moisture retention curves and relative permeability functions. These parameters are shown in Table 1.

Soil Class	θ_r []	θ_s []	α [m^{-1}]	n []	m []	K_s [ms^{-1}]
Sand	0.053	0.375	3.5	3.2	0.685	7.4E-04
Loamy Sand	0.049	0.390	3.5	1.7	0.427	1.2E-04
Sandy Loam	0.039	0.387	2.7	1.4	0.310	4.4E-05
Loam	0.061	0.399	1.1	1.5	0.321	1.4E-05
Silt	0.050	0.489	0.7	1.7	0.404	5.1E-07
Clay	0.098	0.459	1.5	1.3	0.202	1.7E-08

Table 1: Soil parameters.

Soil moisture retention curves and relative permeability functions are shown in Figure 15 for each soil class. These relationships are hysteretic and are used to model the retention and movement of water through the unsaturated soils above the water table. Saturation approaches 1 (i.e., 100%) at smaller negative pressures (i.e., close to the water table) and subsequently, as saturation approaches 1, relative hydraulic conductivity approaches 1 (i.e., the hydraulic conductivity of the variably saturated soil approaches the hydraulic conductivity of fully saturated soil). At larger negative pressures (i.e., above the water table), saturation decreases and relative hydraulic conductivity is reduced.

Soil moisture retention curves and relative permeability functions were assigned to the corresponding soil type (shown in Figure 14) in soil layers of the numerical model and modified during calibration.

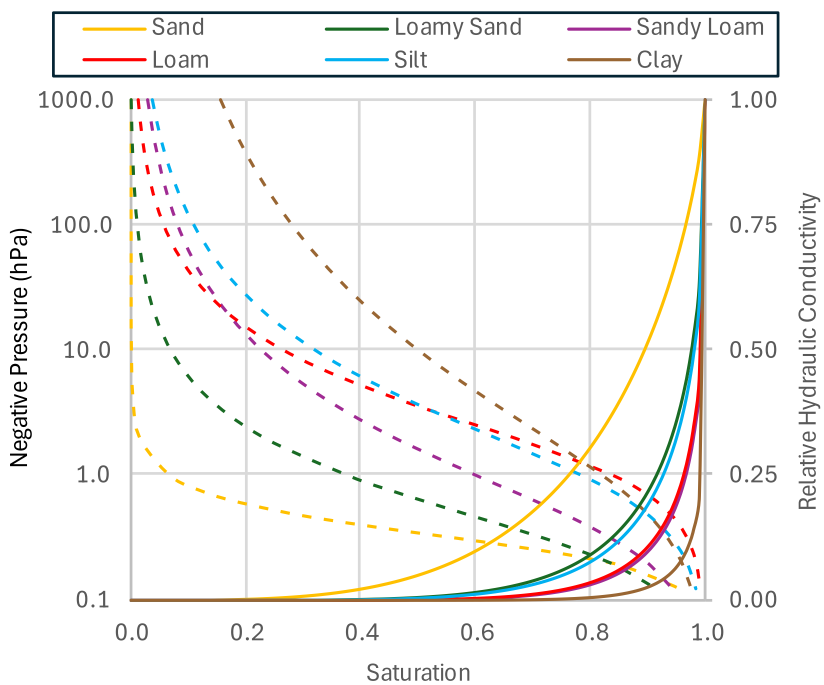

Figure 15: Soil moisture retention curves and relative permeability functions.

3.5 Hydrostratigraphy

Like many other watersheds in the region, the geology of the Shawnigan Creek watershed is complex, with thin surficial deposits mantling variably fractured bedrock. Surficial geological units include (from youngest to oldest): Salish Sediments (discontinuous deposits of deltaic/fluvial sands and gravels, with some silt and clay), Capilano Sediments (discontinuous deposits of marine/glaciomarine silts and clays), Vashon till (continuous deposits of compacted gravel, sand, silt, and clay), Quadra Sand (continuous deposits of glaciofluvial sands and gravels), and Dashwood Drift (discontinuous till-like deposits). The primary water-bearing surficial unit is the Quadra Sand while the Vashon Till acts as a (semi-) confining unit to the underlying Quadra Sand. Bedrock geological units include the fractured Wark, Colquitz, Bonanza Group and Leech River Formations. Surficial and bedrock geology has been described in previous works (for example: Clague, 1976; Blyth et al., 1993; Cui et al., 2017).

The GWELLS database (WLRS, 2023) contains more than 2,500 water well records within the watershed. Leapfrog (Seequent, 2023) was used to aid in classification and/or reclassification of borehole lithology intervals using a combination of queries and Leapfrog's interval selection tool that allows the user to group lithology intervals in a three-dimensional environment. Borehole lithology data were interpreted into hydrostratigraphic units and layers as shown in Figure 16. Distinctions were made between surficial and bedrock lithology intervals and between inferred high permeability (Quadra Sand and Dashwood Drift) and low permeability (Capilano Sediments and Vashon Till) surficial materials. High permeability surficial units comprise aquifer 197 (Cherry Point), aquifer 205 (Shawnigan Lake), and aquifer 206 (Mill Bay).

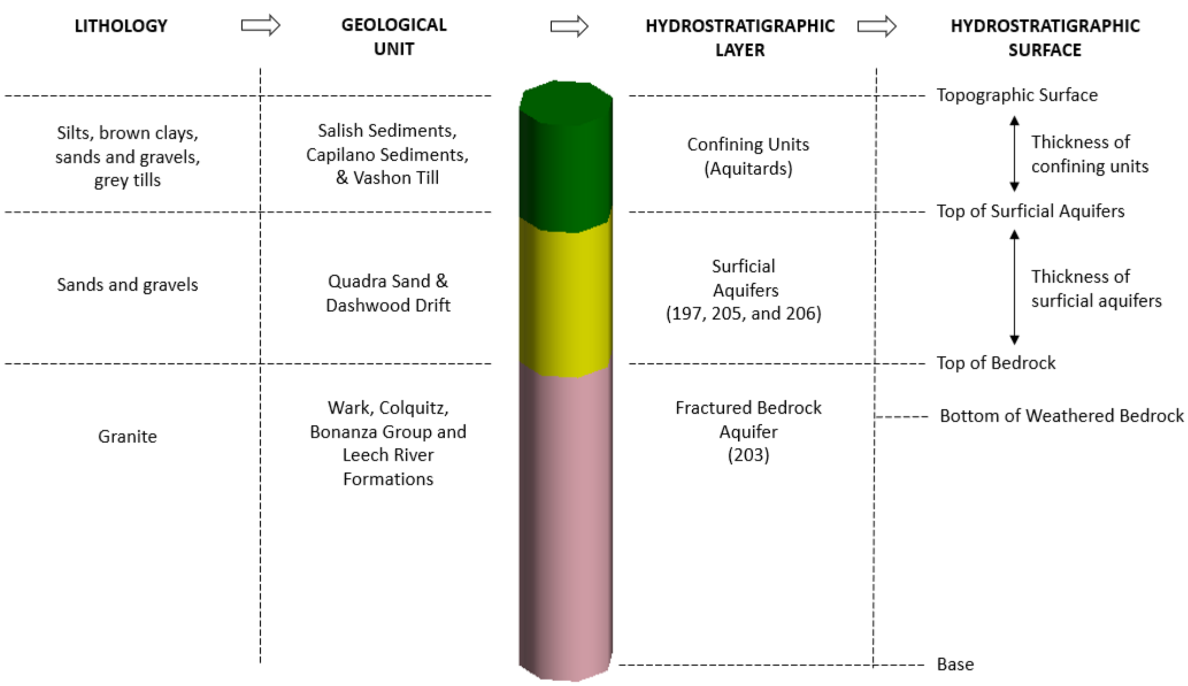

Figure 16: Hydrostratigraphy.

Surficial borehole lithology data were classified borehole-by-borehole and classified using texture with a procedure that first identified intervals indicative of Vashon Till (i.e., grey till) and subsequently classified intervals above and below. High permeability sand and gravel intervals below the inferred Vashon Till were classified as Quadra Sand/Dashwood Drift (not differentiated). Intervals above the inferred Vashon Till were generally discontinuous and of small thickness and were grouped with the Vashon Till (i.e., Salish Sediments and Capilano Sediments were not interpreted). Discrepancies exist in GWELLS borehole lithology records between reported textures in similar intervals of immediately neighbouring boreholes. These discrepancies were addressed through visualization of the borehole lithology data in three-dimensions and classifying based on both the borehole lithology data and correlation in a three-dimensional space, which sometimes required modification of the lithology descriptor based on proximity to other boreholes. For example, borehole lithology intervals of 'grey till' and 'hard, firm, grey sand and gravel' may both be classified as Vashon Till if immediately next to one another and situated in a similar interval within the borehole.

Bedrock elevations at borehole locations were used to interpolate (ordinary kriging) the top of bedrock surface shown in Figure 17 using Surfer (Golden Software, 2023). Bedrock elevation at each borehole location was calculated by subtracting the depth to bedrock from the topographic surface in boreholes that contained a bedrock contact. If a borehole did not contain a bedrock contact, the bedrock elevation was estimated by subtracting the total thickness of surficial material from the topographic surface, to ensure that the interpolated top of bedrock surface remained below the maximum depth of the borehole. Top of bedrock was interpolated for areas with reasonable coverage of control points (i.e., within the interpolation extent in Figure 17 and below a topographic elevation of 150 masl), compared to the topographic surface, and constrained to remain below it. In areas of the watershed with sparse coverage of control points (i.e., outside the interpolation extent in Figure 17), top of bedrock was inferred to be 5 m below the topographic surface based on estimates of bedrock elevation from borehole lithology records in the vicinity of Shawnigan Lake.

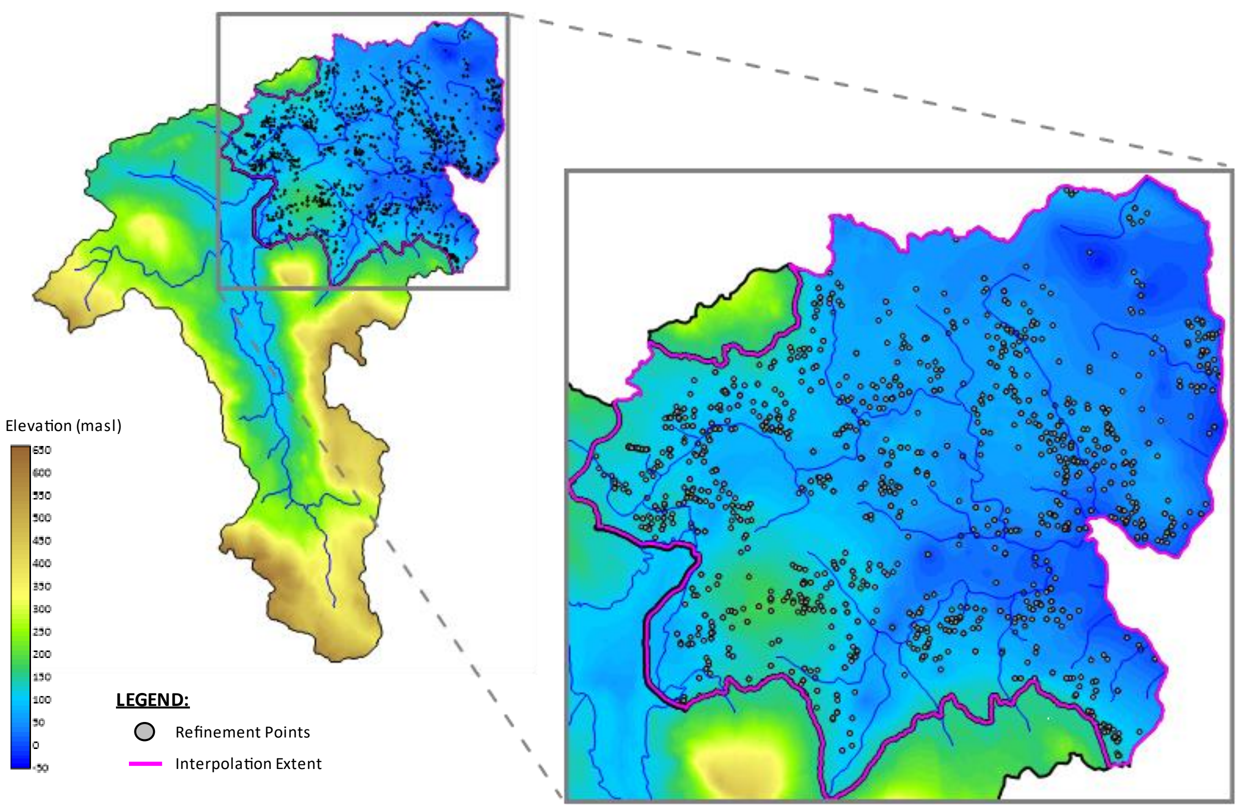

Figure 17: Interpreted top of bedrock.

The volume between the interpreted top of bedrock surface and topographic surface contains provincially mapped surficial aquifers 197 (Cherry Point) (WLRS, 2020a), 205 (Shawnigan Lake) (WLRS, 2020c), and 206 (Mill Bay) (WLRS, 2020d) as well as an overlying confining unit. The material between the interpreted top of bedrock surface and the topographic surface on hillsides (i.e., above 150 masl) around Shawnigan Lake was inferred to consist of colluvium. The volume below the interpreted top of bedrock surface contains provincially mapped bedrock aquifer 203 (Shawnigan Lake/Cobble Hill/Mill Bay) (WLRS, 2020b).

Thickness of aquifer material at borehole locations was interpolated (ordinary kriging) to create an isopach map as shown in Figure 18 using Surfer (Golden Software, 2023). The isopach was added to the interpreted top of bedrock to generate an interpreted top of surficial aquifer surface, compared to the topographic surface and constrained to remain below it. The remainder of the volume between the interpreted top of surficial aquifers' surface and the topographic surface was inferred to be the thickness of the confining units, where present. This approach was taken to ensure that aquifers were continuous across their inferred extents and constrained within the extent of the provincially mapped aquifer polygons. Vertices along the boundaries of the provincially mapped aquifer polygons were incorporated into the interpolation as zero thicknesses, although aquifer 206 (Mill Bay) and aquifer 197 (Cherry Point) were allowed to connect along their shared boundary. In areas of the watershed with sparse coverage of control points (i.e., outside the interpolation extent in Figure 18), aquifer thickness was inferred to be 5 m based on estimates of surficial material thickness from borehole lithology records in the vicinity of Shawnigan Lake.

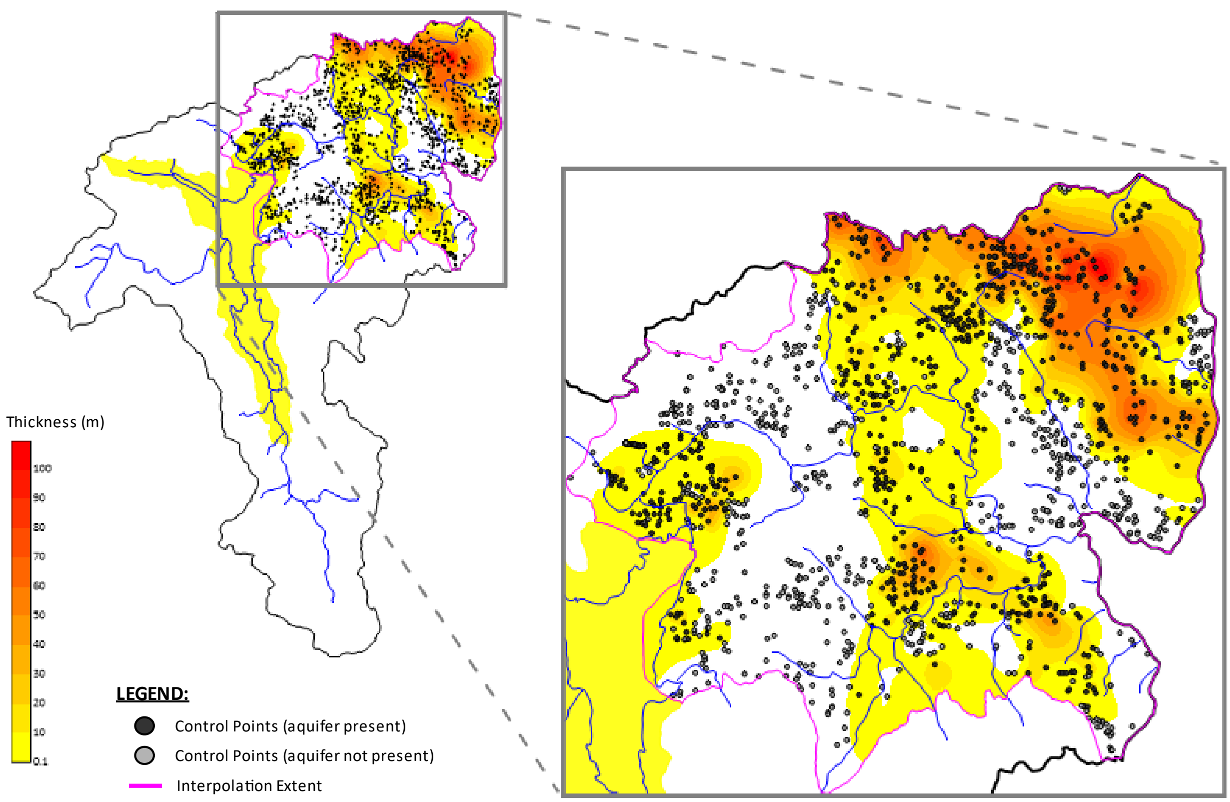

Figure 18: Interpreted thickness of aquifers.

As described above, the thickness of confining units was not interpolated but instead calculated based on subtracting the interpreted top of surficial aquifers' surface from the topographic surface. The resulting isopach is shown in Figure 19. Borehole locations shown in Figure 19 do not control the interpolation but are included to show where thicknesses of confining units are present. Comparing the thickness of confining units at borehole locations to the isopach yields some discrepancies but there is generally agreement between the two. The interpreted thickness of confining units (Figure 19) varies from other studies (WWAL, 2023) but differences are small and can likely be attributed to variations in classification of the borehole lithology data from GWELLS.

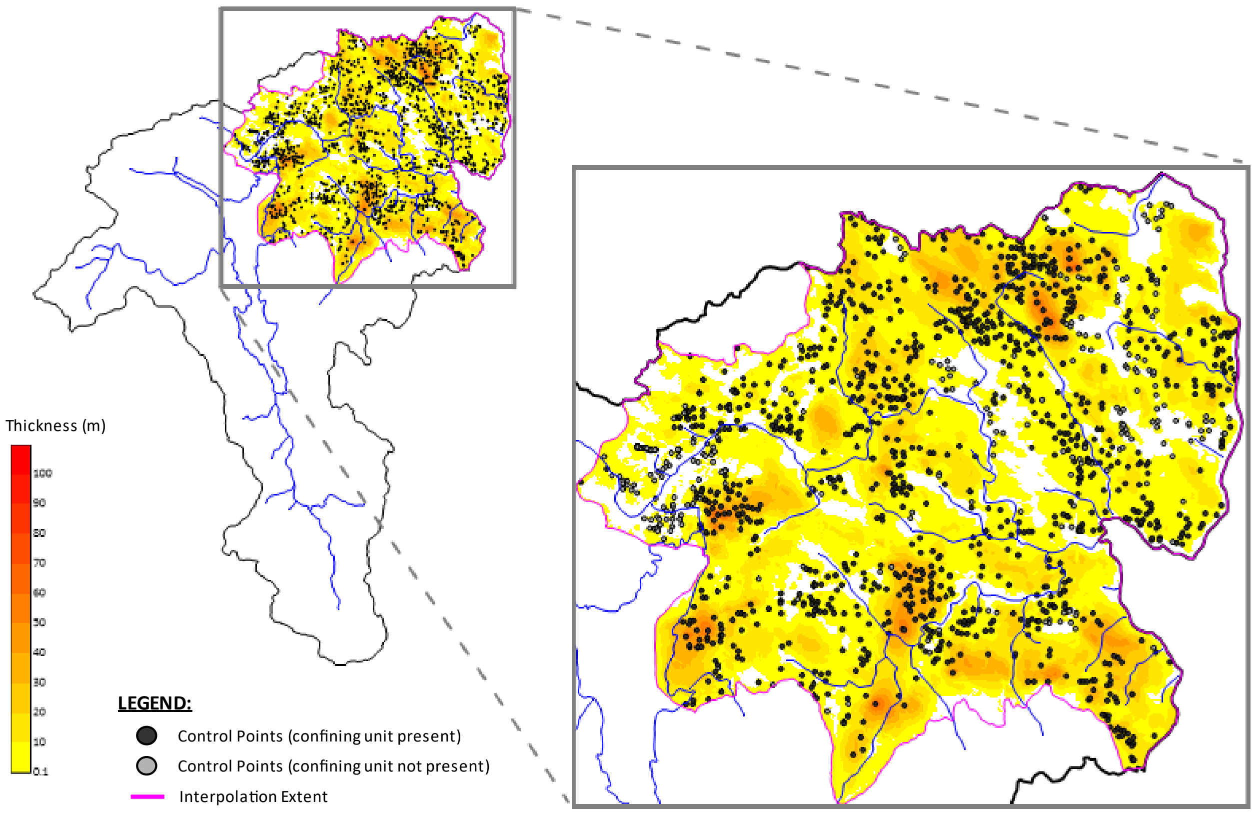

Figure 19: Interpreted thickness of confining units.

Borehole lithology data and interpreted hydrostratigraphic surfaces were imported into Leapfrog (Seequent, 2023) and visualized in three-dimensions as shown in Figure 3. The three-dimensional visualization accompanies this report in a separate viewer file that has ability to pan, rotate, and zoom to visualize raw and processed borehole lithology data and slice cross sections through the interpreted hydrostratigraphic surfaces.

Available hydraulic testing data for unconsolidated aquifers (206) and bedrock aquifers (203) are summarized in Table 2.

Parameter	Units		Aquifer 206	Aquifer 203
Transmissivity (Ref: WWAL, 2018)	[m^2/d]	Min. to Max.	0.1 to 1,620	0.3 to 19
	[m^2/d]	Average	198	6.1
	[m^2/d]	Geometric Mean	54	3.2
Hydraulic Conductivity (Ref: GWELLS)	[m/s]	Min. to Max. (n)	4.2×10^{-5} to 3.9×10^{-2} (17)	7.3×10^{-6} to 2.4×10^{-4} (5)
	[m/s]	Geometric Mean	3.7×10^{-4}	4.4×10^{-5}
Storativity (Ref: GWELLS)	[-]	Min. to Max. (n)	2.4×10^{-5} to 2.3×10^{-3} (5)	5.6×10^{-4} to 5.6×10^{-1} (1)
	[-]	Geometric Mean	2.3×10^{-4}	5.6×10^{-4}

Table 2: Aquifer hydraulic properties.

3.6 Groundwater

The GWELLS database (WLRS, 2023) contains more than 800 depth-to-water records within the watershed. These records, usually reported at time of drilling, were correlated with provincial aquifers and assumed to be generally representative of long-term average conditions. Depth-to-water was converted to a groundwater elevation by subtracting the depth-to-water from the elevation of the topographic surface. Only 63 of the more than 800 wells (or boreholes) with a depth-to-water measurement contained information on the depth of the well screen. Many boreholes completed in surficial materials are open bottom while many boreholes completed in bedrock are open for the full extent of the bedrock interval within the borehole.

Groundwater elevation from GWELLS (WLRS, 2023) for surficial (unconsolidated) and bedrock aquifers is shown in Figure 20. Groundwater elevations trend downwards nearer to Saanich Inlet. Note that outliers were not removed from the dataset. Groundwater elevations shown in Figure 20 were used for calibration.

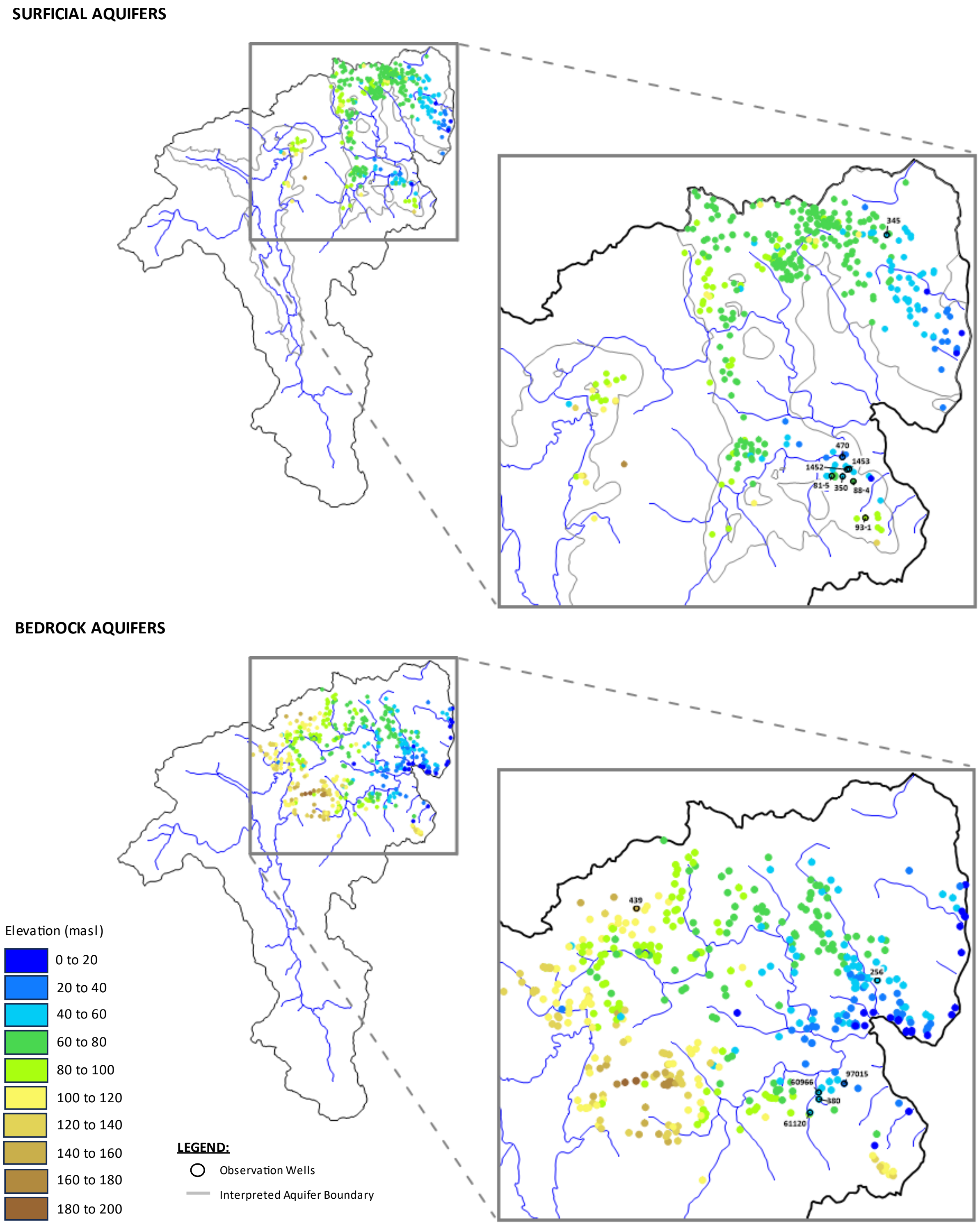

Figure 20: Observed groundwater elevation (GWELLS).

Time variable groundwater elevations are available from the Provincial Groundwater Observation Well Network (PGOWN) and data provided by Mill Bay Waterworks District. Monitoring wells with available transient groundwater elevation data are shown in Figure 21 (surficial aquifers) and Figure 22 (bedrock aquifers). Well details are summarized in Table 3.

Well Name	Well Tag Number	Easting	Northing	Status	Aquifer
OW256	35369	459167	5390370	Inactive	203
OW345	75531	459322	5392814	Active	197
OW350	81555	458501	5388332	Inactive	206
OW380	46810	458080	5388160	Inactive	203
OW439	113013	454680	5391707	Active	203
OW470	114847	458497	5388691	Active	206
81-5	94363	458300	5388340	Active	206
88-4	85202	458700	5388240	Active	206
93-1	69141	458925	5387562	Active	206
60966	122307	458073	5388286	Active	203
61120	122306	457912	5387911	Active	203
97015	97015	458550	5388451	Active	203
1452	56015	458584	5388459	Active	206
1453	56016	458622	5388469	Active	206

Table 3: Monitoring wells with available transient groundwater elevation data.

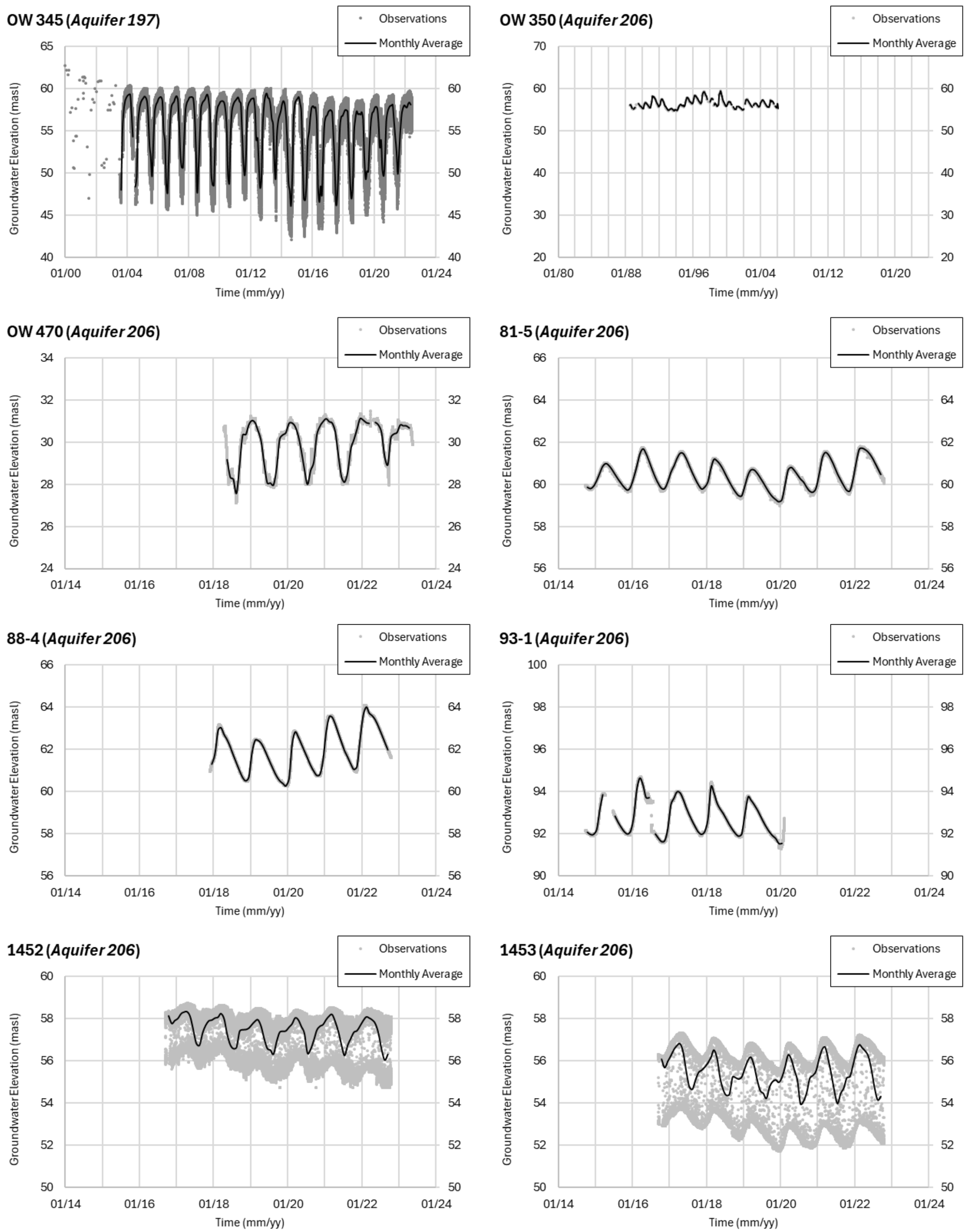

Figure 21: Observed groundwater elevation in surficial aquifers.

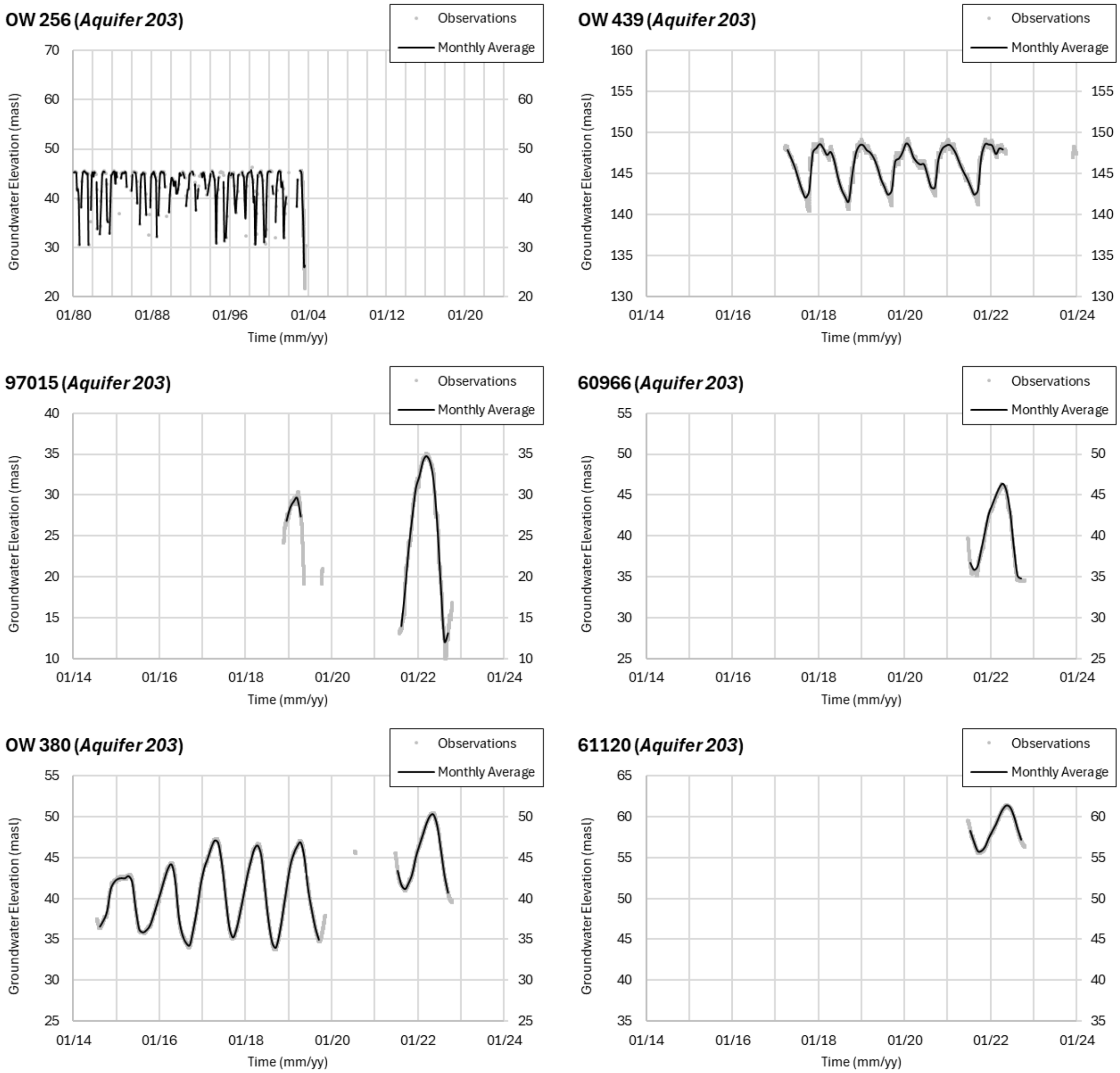

Figure 22: Observed groundwater elevation in bedrock aquifers.

Publicly available observed groundwater elevation data shown in Figure 21 and Figure 22 are available for download and use from the Province of B.C.'s Aquarius database (Province of B.C., 2023b) and Groundwater Level Data Interactive Map (Province of B.C., 2023a). Data is also available on the B.C. Water Tool (Foundry Spatial, 2023).

4. NUMERICAL MODEL

4.1 Code Selection

Both surface water and groundwater flow were considered simultaneously by applying an integrated modelling code capable of simulating Richard's equation for variably saturated groundwater flow with the Saint Venant equations for overland flow. Considering project objectives, desirable features of a potential code are listed in Table 4 and common codes (GSFLOW, MIKE-SHE, MODHMS, HydroGeoSphere [HGS], and ParFlow) were assessed against these features.

Desirable Feature	GSFLOW	MIKE-SHE	MODHMS	HGS	ParFlow
3D Variably Saturated Groundwater Flow	No	No	Yes	Yes	Yes
2D Overland Flow	Yes	Yes	Yes	Yes	Yes
1D Channel Flow	Yes	Yes	Yes	Yes	Yes
Evapotranspiration	Yes	Yes	Yes	Yes	Yes
Tightly Coupled	No	No	Yes	Yes	Yes
Unstructured Mesh	No	No	No	Yes	Yes
Graphical User Interface	No	Yes	Yes	Yes	No
Technical Support	No	Yes	No	Yes	No
Low Cost	Yes	No	No	No	Yes

Table 4: Comparison of common integrated modelling codes.

HydroGeoSphere (Aquanty, 2023) was selected as it incorporates the most desirable features. Additional information on HGS is available in its theory manual (Aquanty, 2015a) and reference manual (Aquanty, 2015b). Although guidelines for integrated modelling do not exist, model development generally followed conventional guidelines (ENV, 2012).

4.2 Numerical Mesh

AlgoMesh (HydroAlgorithmics, 2023) was used to generate the two-dimensional numerical mesh as shown in Figure 23. The numerical mesh is variably refined with elements ranging in size from approximately 2 m to 200 m depending on proximity to features of interest. Lines, polygons, and points that represent the stream network, extent of Shawnigan Lake, and pumping and observation wells were incorporated into the numerical mesh with precise locations. The two-dimensional numerical mesh is comprised of 19,820 nodes and 38,943 elements, which is substantially less than conventional groundwater models to accommodate multiple flow domains and detailed hydrologic and hydrogeologic processes. A three-dimensional numerical mesh comprised of triangular prisms was generated from the two-dimensional numerical mesh based on hydrostratigraphic layering and is described in section 4.3.

Note that HGS allows the conceptual model to be mapped to the numerical mesh independently from the process that determines its structure. This allows for modification (refinement or de-refinement) of the numerical mesh without having to re-develop the entire model. As such, the numerical mesh shown in Figure 23 is intended to be a starting point and may need modification in specific areas of the watershed to address certain objectives in the future.

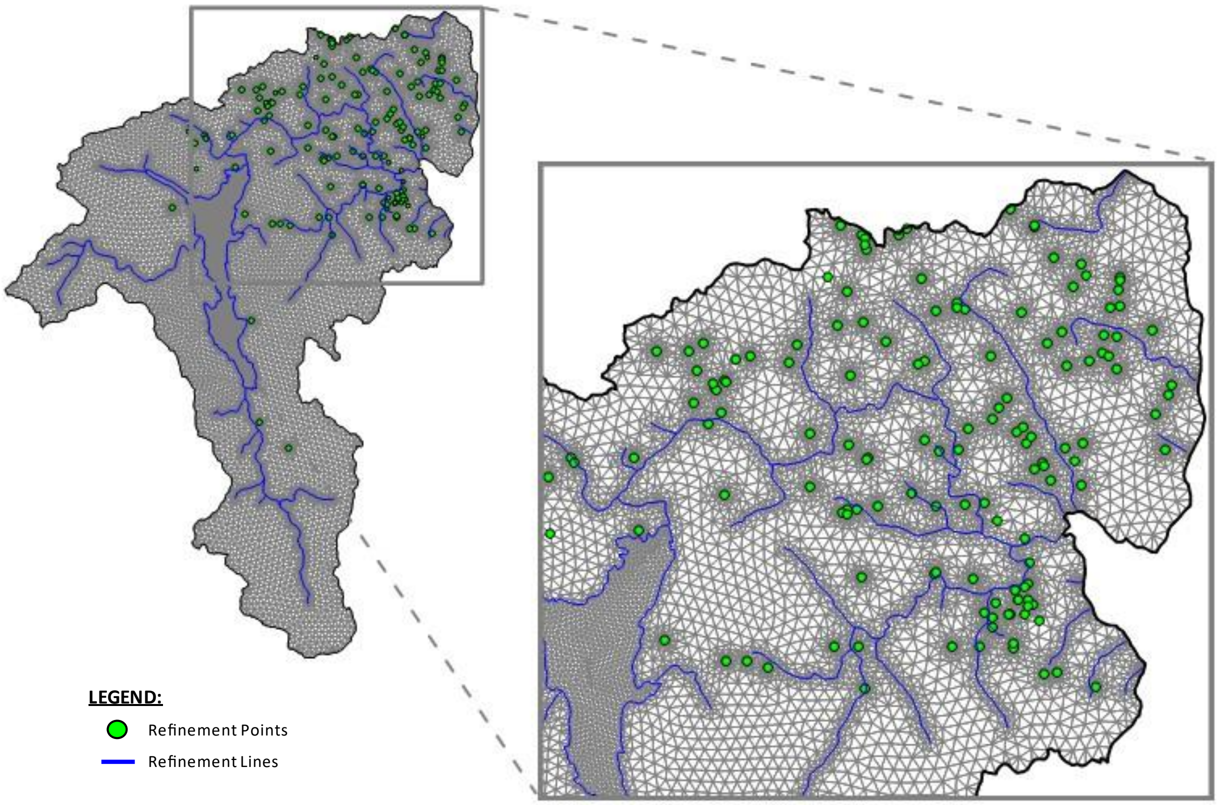

Figure 23: Two-dimensional numerical mesh.

4.3 Conceptualization

The three-dimensional numerical model was developed piecewise and includes domains for porous media, overland flow, channel flow, evapotranspiration, and well extraction. Each domain requires varied data inputs and parameterization that is discussed in this section.

Porous Media Domain

This domain is three-dimensional and consists of soil and hydrostratigraphic units across eleven (11) numerical layers. Twelve (12) sheets of nodes/elements (Figure 23) contain those eleven (11) numerical layers, with a total of 237,840 nodes and 428,373 elements. Note that numerical layers, as presented below, are numbered from top down but are numbered from bottom up in HGS.

- Layer 1: Upper soil (0 m to 0.5 m depth from topographic surface)
- Layer 2: Lower soil (0.5 m to 1.0 m depth from topographic surface)
- Layer 3: Confining units (representing Salish Sediments/Capilano Sediments/Vashon Till; variable thickness)
- Layer 4: Aquifers (representing Quadra Sand/Dashwood Drift; variable thickness)
- Layer 5: Weathered Bedrock (upper 10 m of bedrock)
- Layer 6: Bedrock A (10 m to 30 m depth from top of bedrock)
- Layer 7: Bedrock B (30 m to 60 m depth from top of bedrock)
- Layer 8: Bedrock C (60 m to 100 m depth from top of bedrock)
- Layer 9: Bedrock D (100 m to 150 m depth from top of bedrock)
- Layer 10: Bedrock E (150 m to 210 m depth from top of bedrock)
- Layer 11: Bedrock F (210 m to 350 m depth from top of bedrock)

Soil was inferred as a 1.0 m thick uniform layer and was based on shallow soil intervals observed in borehole lithology records in the watershed. Soil was split into two numerical layers, an upper and lower layer, to improve simulation of both variably saturated flow and evapotranspiration from the soil zone. Underlying numerical layers generally follow interpreted hydrostratigraphic surfaces as described in the conceptual model. Bedrock was simulated using an equivalent porous medium approach and was split into multiple layers to allow decreasing hydraulic conductivity with depth. Weathered bedrock was inferred as a 10 m thick uniform layer immediately below the bedrock contact and was based on observed weathered intervals in borehole lithology records in the watershed. The bottom of the numerical model was arbitrarily set to 350 m below sea level, an elevation lower than the bottom of any boreholes. Hydraulic conductivity and specific storage were assigned based on the conceptual model and modified during calibration.

Overland Flow Domain

This domain is two-dimensional and consists of one numerical layer situated on top of the porous media domain. Properties, most notably Manning's n, were applied to this numerical layer based on land cover types and modified during calibration.

Channel Flow Domain

This domain is one-dimensional and consists of linework that follows the inferred stream network from the headwaters above Shawnigan Lake to the watershed outflow into Saanich Inlet at Mill Bay. Channels were assumed to have a thin layer (0.5 m thick) of fine-grained sediment on the streambed with hydraulic conductivity of 1.0×10^{-7} m/s. Inclusion of the channel flow domain is optional and HGS would otherwise route precipitation on the land surface to topographic lows based on physics in the overland flow domain. However, incorporating a channel flow domain encourages flow along topographic lows and allows the generation of exchange fluxes between the channel domain and porous media domain (i.e., quantification of hydraulic connection), which was a core objective of this project.

Evapotranspiration Domain

This domain is two-dimensional and calculates actual evapotranspiration (AET) from potential evapotranspiration (PET) using Kristensen and Jensen (1975), an empirical approach that relies on LAI, canopy interception, and empirical coefficients (C1, C2, and C3). Water is apportioned between soil evaporation and soil transpiration by C1 and C2 whereas the release of water from soil is controlled by C3. Empirical coefficients were adjusted during calibration but ultimately set to 0.05, 0.05, and 1.0 for C1, C2, and C3, respectively. Canopy interception was assigned as 0, indicating that all precipitation reaches the land surface as throughfall. It is understood that canopy interception can play a role in the water balance and that this assumption may result in larger volumes of water arriving at the land surface than would otherwise occur. Despite this, and in the absence of data to parameterize canopy interception, this assumption was considered reasonable. Furthermore, LAI was kept constant throughout the year in the absence of more detailed time-variable information.

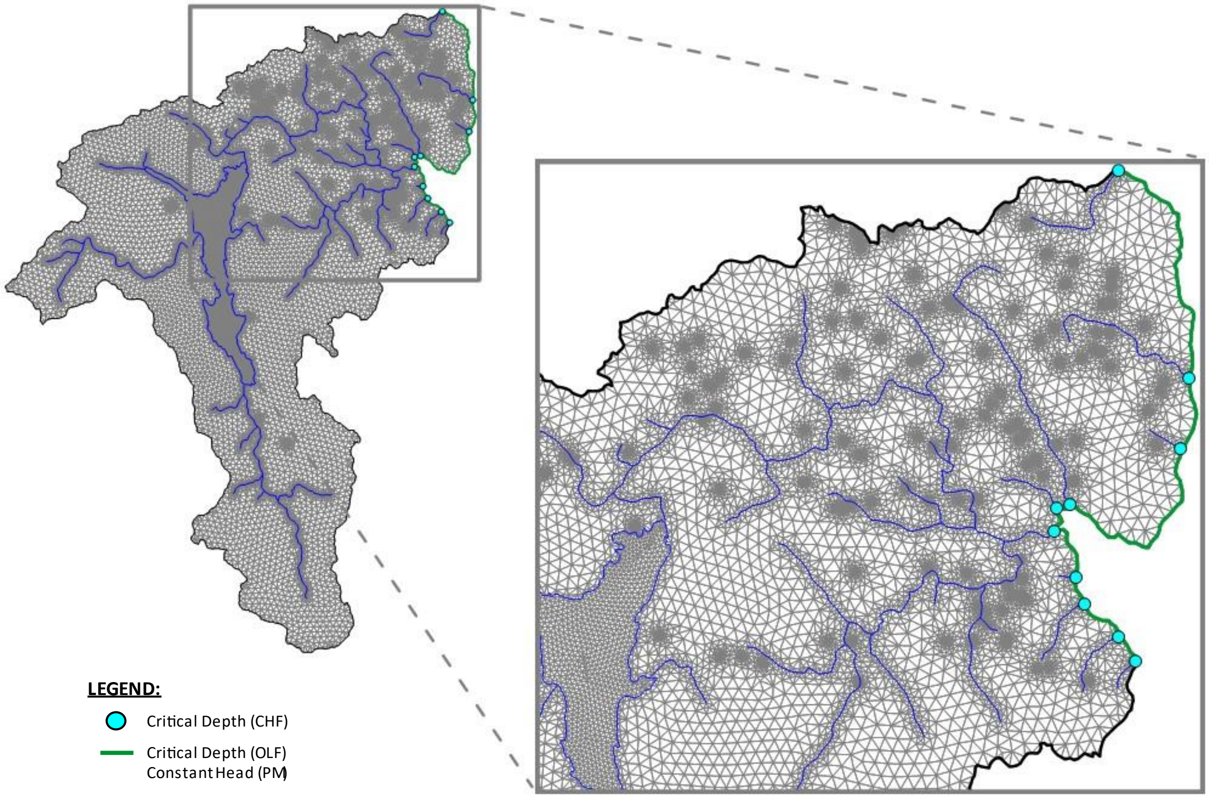

Figure 24: Boundary conditions.

Boundary Conditions

Precipitation was assigned as a rain (specified flux) boundary condition vertically downward onto the two-dimensional face of the land surface (overland flow domain). Precipitation was allowed to vary in both space and time as shown in Figure 7. Critical depth boundary conditions (Aquanty, 2015b) were assigned in the channel flow domain as shown in Figure 24 to allow water to exit the model where streams discharge to Saanich Inlet. Critical depth boundary conditions were also assigned along the watershed boundary in the overland flow domain to account for outflow directly into Saanich Inlet. Constant head boundary conditions (set to mean sea level) were assigned in the porous media domain along the eastern boundary of the model with Saanich Inlet. No flow boundary conditions were assigned along the (weak) hydrologic divide in the northern portion of the model. Note that a small amount of inter-basin flow across this boundary is likely due to groundwater pumping.

4.4 Initialization

The numerical model was developed as transient variably saturated and simulated using a control volume finite difference approach (Aquanty, 2015a). The dual node approach was used to connect various flow domains by way of coupling lengths (Aquanty, 2015a). The dual node approach is recommended by the software developer to improve numerical stability and generate exchange fluxes between domains. The coupling length was set to 0.01 m for all domains.

Initial parameter values were assigned to domains as described in the conceptual model and were modified during the calibration process. The numerical model was initialized (spun up) through a process of simulating annual normal precipitation and potential evapotranspiration for an arbitrarily long period, followed by simulating monthly normal precipitation and potential evapotranspiration for a period of 20 years. The numerical model proceeded to the next initialization stage once simulated changes in storage were very small. The initialization process allowed the numerical model to acclimate first to long-term average conditions and then to monthly-average conditions. It is important to note that initialization (spin up) is a time-consuming process that grows as the model becomes more complex. Monthly-average results presented in this report are output from a version of the model that simulates a single calendar year with monthly normal precipitation and potential evapotranspiration input and results from the last year of the 20-year simulation as initial conditions, where required.

Streamflow gauging locations and groundwater monitoring well locations were assigned in the numerical model based on coordinates and depth (if appropriate). Simulated results at these locations provided the basis to assess model performance.

4.5 Calibration

Calibrating an integrated numerical model is a complex process. Inclusion of detailed physics increases runtimes substantially and the number of parameters can be significantly higher than a conventional groundwater model or surface water model. A preliminary calibration was completed by manually modifying parameters in the porous media, overland flow, channel flow, and evapotranspiration domains such that simulated streamflow, surface water elevations, and groundwater elevations reasonably reproduced observed data. The preliminary calibration was completed as a two-step process, first simulating and comparing to long-term average conditions and secondly, simulating and comparing to monthly-average conditions.

Simulated versus observed long-term average groundwater elevations and streamflow are shown in Figure 25. Note that there are obvious outliers in the dataset (i.e., generally points that are very far from the simulated = observed line in Figure 25), however, no effort was made to cull the observed dataset based on quality of data. The observed data provided in Figure 25 are those that were obtained directly from GWELLS. Although likely minimal, some improvement to the calibration statistics would likely result if outliers were removed from the dataset. Considering the watershed scale, the time range over which these data extend (1950’s to present), and the potential inaccuracy in groundwater elevations (i.e., inaccuracy of DEM, uncertainty in well locations, stickup of measuring point above ground, etc.), simulated results were considered reasonable.

Calibration statistics for the long-term average simulation are shown in Table 5. Although some large residuals between simulated and observed groundwater elevation exist (likely a result of outliers), mean residuals are near zero, normalized root mean square error (NRMSE) is approximately 6% to 7%, and the coefficient of determination is near 0.90 or greater. A NRMSE less than 10% and a coefficient of determination greater than 0.90 is considered acceptable (ENV, 2012). Large and small residuals are generally distributed throughout the watershed, with larger residuals often at or near locations where groundwater pumping is thought to occur.

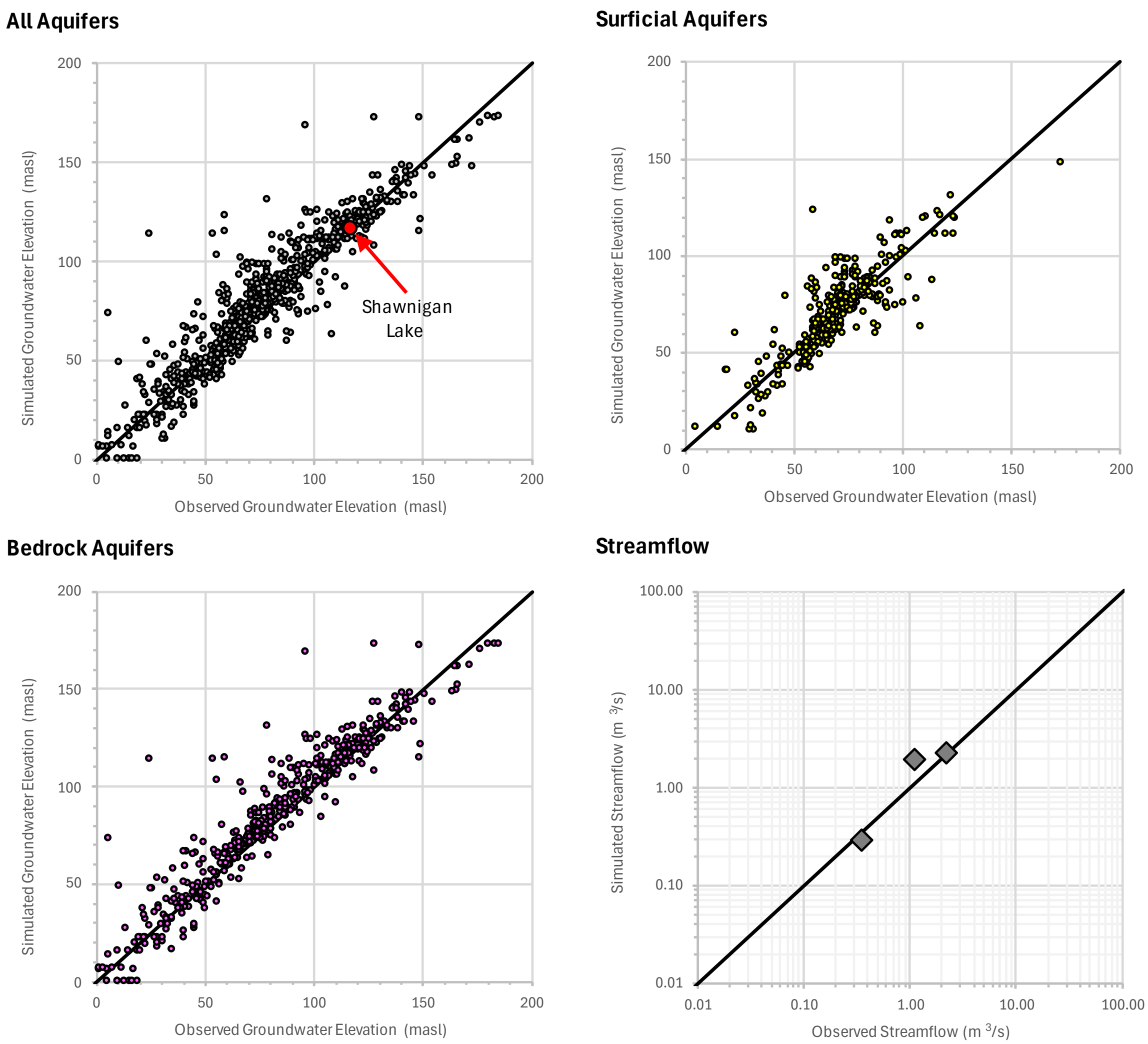

Figure 25: Simulated vs. observed long-term average groundwater elevation and streamflow.

Statistic	All Aquifers	Bedrock Aquifers	Surficial Aquifers	Streamflow
Count	822	467	355	3
Mean Residual	2.4 m	3.8 m	0.6 m	0.2 m^3/s
Maximum Residual	98.8 m	98.8 m	63.6 m	1.2 m^3/s
Minimum Residual	-45.4 m	-34.3 m	-45.1 m	-0.1 m^3/s
Root Mean Squared Error	13.0 m	14.1 m	11.3 m	Not Calculated
Normalized Root Mean Square Error	6.5%	7.1%	6.7%	Not Calculated
Coefficient of Determination	0.92	0.93	0.86	Not Calculated

Table 5: Calibration statistics for long-term average conditions.

Once the numerical model reasonably reproduced long-term average conditions, it was forced with monthly normal (1991-2020) precipitation and potential evapotranspiration and qualitatively compared to monthly-average conditions. Efforts were made to incorporate groundwater pumping information from Mill Bay Waterworks District into the calibration process. However, it became apparent that calibrating to localized pumping information would require modification to the conceptualization of the hydrostratigraphy (i.e., incorporating differences in hydraulic conductivity horizontally in addition to vertically) since improving calibration in a localized area could deteriorate the calibration regionally. Given that an unknown volume of groundwater extraction occurs across the watershed, a regional scale approach to the calibration was taken. A regional scale approach was also considered suitable for simulating the regional interaction between the subsurface and streams.

A subset of groundwater and surface water monitoring locations were assessed against simulated results on a monthly-average basis as shown in Figure 26 and Figure 27. As discussed previously, many streamflow gauging locations have sparse and incomplete datasets and therefore focus was directed towards stations where data records were considered more complete. Streamflow gauging stations that had more incomplete data records were assessed qualitatively but not included in this report. Additionally, some groundwater elevations are known to be near and affected by localized pumping (the amount and specific location of which is unknown) and therefore it can be difficult to replicate those groundwater elevations with a numerical model in the absence of information on where and when that groundwater pumping is occurring. Because of this, focus was directed towards groundwater monitoring wells that were spread across the watershed and included representation for each aquifer, where available. Note that, in Figure 26 and Figure 27, simulated monthly-average water elevations and flow are presented as deviations from the simulated long-term average since observed and simulated long-term average water elevations and flow at each monitoring location are not equal. Observed monthly-average values are shown in Figure 26 and Figure 27 as grey lines for all months and years where historical data is available. Long-term monthly-average values are visualized with a box around the data point to represent uncertainty and simulated results were considered reasonable if they were approximately within that estimated range of uncertainty (i.e., were within the boxes).

Simulated Shawnigan Lake water elevation and simulated streamflow for the subset of monitoring locations is shown in Figure 26. Water elevations in Shawnigan Lake do not vary by a large amount month to month. Simulated streamflow at 08HA004 (Shawnigan Creek near Weir), 08HA033 (Shawnigan Creek near Mill Bay), and 08HA0003 (Handysen Creek near Highway 1) generally trends within the range of uncertainty, however, simulated streamflow is underpredicted in the winter months at 08HA033 (Shawnigan Creek near Mill Bay) and overpredicted in the summer months at all gauging stations. Simulating streamflow in the summer months is particularly challenging as reduced saturation in the subsurface results in numerical stability concerns and an associated increase in simulation runtime. Future efforts might attempt to improve the calibration to streamflow in the late summer months.

Simulated groundwater elevation for the subset of monitoring locations is shown in Figure 27. Although simulated groundwater elevation is beyond the estimated range of uncertainty at certain times of year, general trends are simulated at OW 470 and OW 439. OW 345 and OW 256 are not replicated well, likely due to the influence of unknown rates of groundwater pumping not been included in the numerical model. For example, Arbutus Ridge Golf Course is known to extract groundwater from Aquifer 197 and is directly adjacent to OW 345.

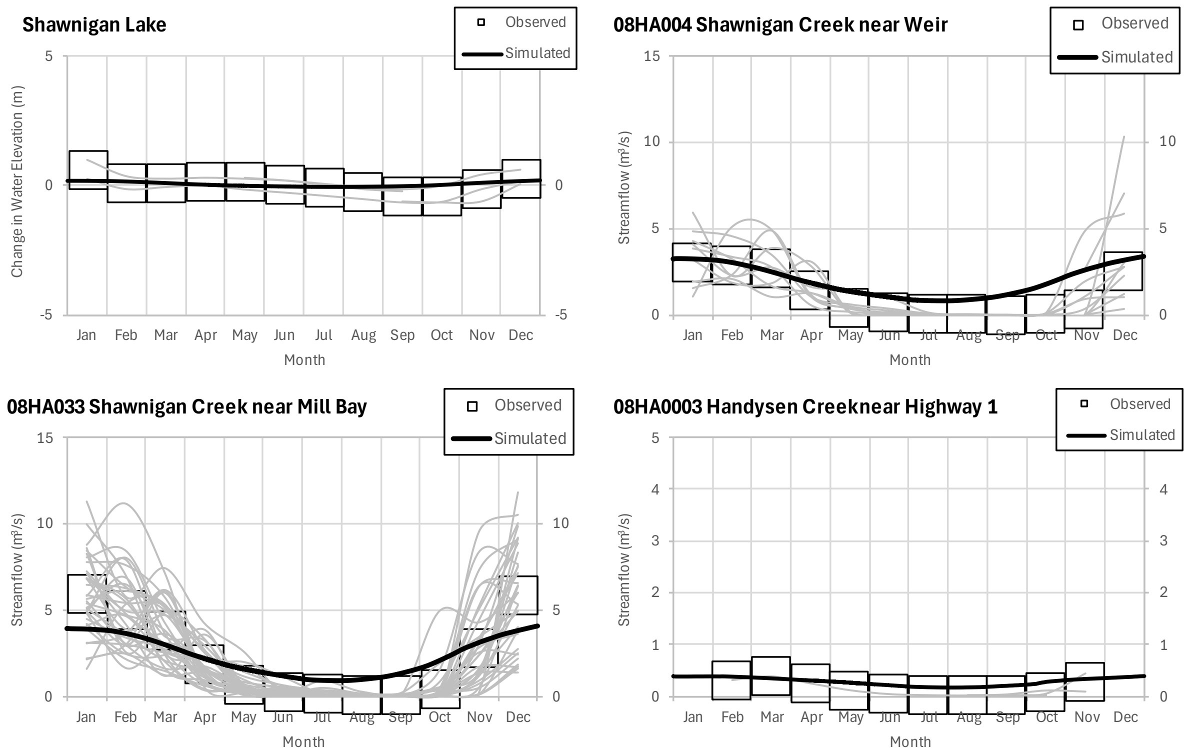

Figure 26: Simulated vs. observed monthly-average Shawnigan Lake water elevation and streamflow.

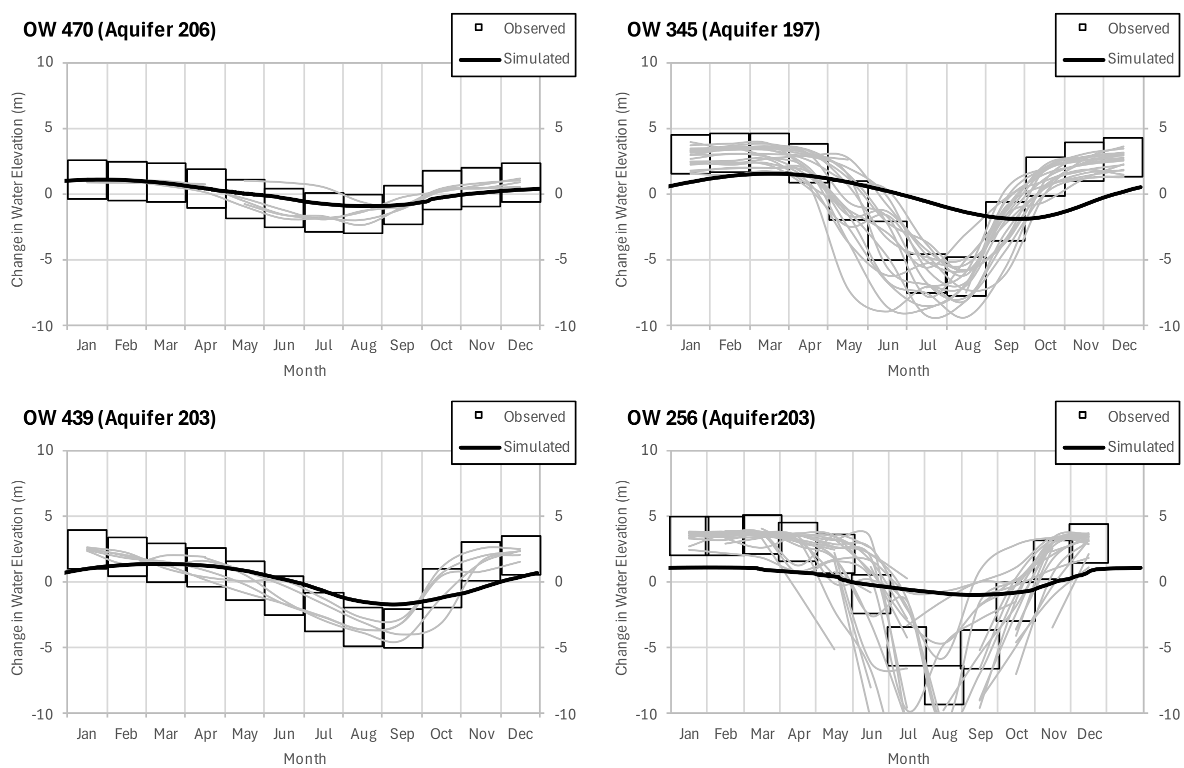

Figure 27: Simulated vs. observed monthly-average groundwater elevation.

Resulting from the preliminary calibration process, hydraulic conductivity and specific storage for hydrostratigraphic units are summarized in Table 6. Note that calibrated values of hydraulic conductivity and specific storage more closely resemble those summarized by WWAL (2018).

Hydrostratigraphic Unit	**K_h [m/s]**	**K_v [m/s]**	**Ss [1/m]**
Confining Units	5.0×10^{-7}	5.0×10^{-8}	1.0×10^{-4}
Aquifers	2.0×10^{-4}	2.0×10^{-5}	1.0×10^{-3}
Colluvium	1.0×10^{-5}	1.0×10^{-6}	1.0×10^{-4}
Weathered Bedrock	1.0×10^{-5}	1.0×10^{-5}	5.0×10^{-5}
Bedrock A	1.0×10^{-6}	1.0×10^{-6}	1.0×10^{-5}
Bedrock B	8.0×10^{-7}	8.0×10^{-7}	1.0×10^{-5}
Bedrock C	6.0×10^{-7}	6.0×10^{-7}	1.0×10^{-5}
Bedrock D	4.0×10^{-7}	4.0×10^{-7}	1.0×10^{-5}
Bedrock E	2.0×10^{-7}	2.0×10^{-7}	1.0×10^{-5}
Bedrock F	1.0×10^{-7}	1.0×10^{-7}	5.0×10^{-6}

Table 6: Calibrated hydraulic parameters.

Also resulting from the preliminary calibration process, Manning's n, LAI, and rooting depth are summarized in Table 7.

Land Cover Class	**Manning's n [$sm^{-1/3}$]**	**Leaf Area Index []**	**Rooting Depth [m]**
Water	0.02	0	0
Exposed Land	0.03	0	0
Herbs	0.04	0.5	2.6
Shrubs	0.05	1.6	5.1
Treed - Broadleaf	0.10	3.9	2.9
Treed - Mixed	0.12	3.0	3.4
Treed - Coniferous	0.15	2.7	3.9

Table 7: Calibrated land cover parameters.

4.6 Water Balance

The simulated annual water balance for the watershed is shown in Table 8. Approximately 171.3 million m^3 of water is added annually to the watershed in the form of precipitation onto the land surface. More than 90% of that water leaves the watershed by way of streamflow and evapotranspiration. Outflow directly to Saanich Inlet via groundwater flow and overland flow comprise a small percentage of the annual water balance.

Component		Percent of Annual Water Balance
INFLOW		
Precipitation	171.3 million m^3	100%
OUTFLOW		
Streamflow	85.3 million m^3	49.8%
[Runoff]	*[66.2 million m^3]*	*[38.6%]*
[Baseflow]	*[19.1 million m^3]*	*[11.2%]*
Evapotranspiration	74.7 million m^3	43.6%
Groundwater Outflow	8.7 million m^3	5.1%
Overland Outflow	2.6 million m^3	1.5%
MASS BALANCE		
Total Inflow	171.26 million m^3	-
Total Outflow	171.32 million m^3	-
Percent Error	0.03%	-

Table 8: Simulated annual water balance.

The simulated monthly-average water balance for the watershed is shown in Figure 28. Precipitation is shown to vary considerably throughout the year, with large volumes in the winter months that decrease to small volumes in the summer months. Streamflow (i.e., the sum of runoff and baseflow) is influenced by precipitation and is largest in the winter months and decreases in the summer months. Baseflow contributions to streamflow (as a percentage of total streamflow) increase from approximately 17% in the winter months (January) to 36% in the summer months (July). Water volumes lost to evapotranspiration are largest in the summer months when air and land temperatures are high and decrease in the winter months when air and land temperatures are low. Note that outflow directly to Saanich Inlet via groundwater flow and overland flow are not shown in Figure 28 as these components of the monthly-average water balance are relatively small at approximately 0.7 million m^3/month (8.7 million m^3/year) and 0.2 million m^3/month (2.6 million m^3/year), respectively.

Precipitation minus the sum of streamflow, evapotranspiration, and outflow directly to Saanich Inlet via groundwater flow and overland flow represents the net volume of water added to storage, which is positive in the winter months (i.e., an increase of storage in lakes, streams, and subsurface aquifers) but negative in the summer months (i.e., a decrease of storage in lakes, streams, and subsurface aquifers). The simulated monthly-average water balance suggests that February is when the hydrologic system switches from net positive (sum of inflows is greater than sum of outflows) to net negative (sum of inflows is less than sum of outflows) while September is when it switches back.

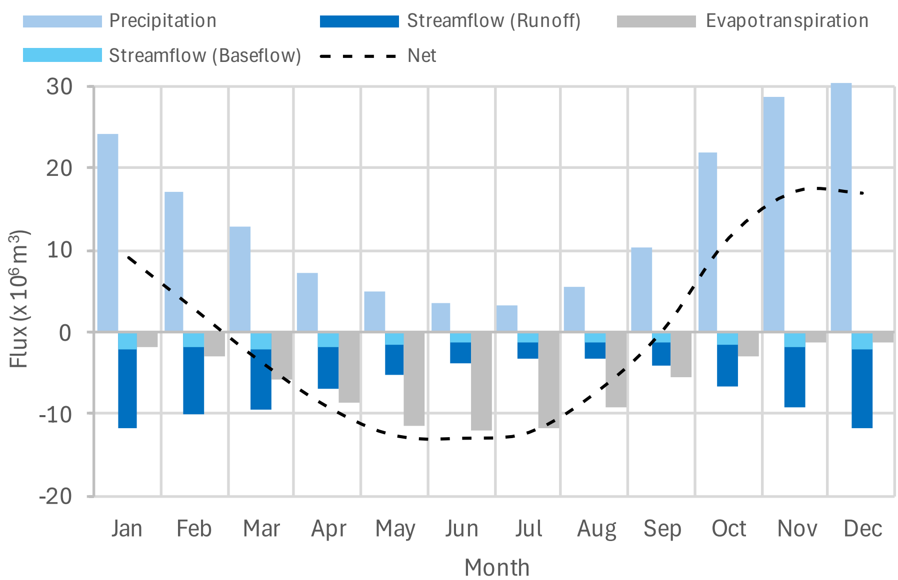

Figure 28: Simulated monthly-average water balance: inflows and outflows.

The net volume of water added to storage (as shown in Figure 28 by the dashed black line) can be apportioned to storage within the overland flow domain (i.e., lakes), the channel flow domain (i.e., streams), and the porous media domain (i.e., subsurface aquifers). Simulated monthly-average storage fluxes are shown in Figure 29 and suggest that changes in subsurface storage are the dominant mechanism to absorb and release surplus water at the watershed scale, with minor changes in storage on the land surface in lakes and/or streams. Positive storage fluxes in the winter months indicate that subsurface aquifers are being replenished while negative storage fluxes in the summer months indicate that subsurface aquifers are being depleted. Dashed black lines in Figure 28 and Figure 29 are near-coincident (i.e., mass is conserved in the water balance) while the sum of storage over the course of the year is near-zero (i.e., the simulation has reached a dynamic equilibrium).

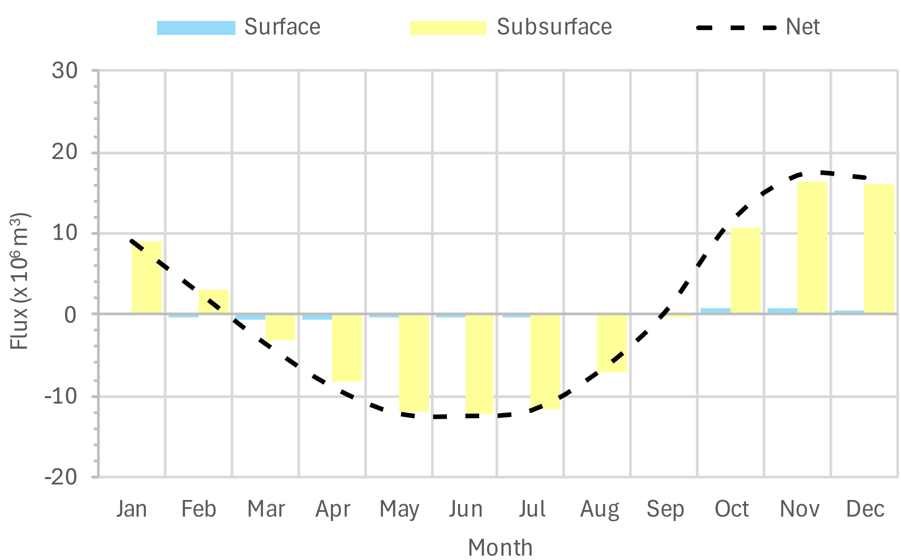

Figure 29: Simulated monthly-average water balance: storage.

Evapotranspiration (i.e., actual evapotranspiration) as shown in Figure 28 is separated into its sub-components and compared to potential evapotranspiration as shown in Figure 30. As expected, evapotranspiration is largest in the summer months when incoming solar radiation is at a maximum (air and land temperatures are high) and decreases in the winter months when incoming solar radiation is at a minimum (air and land temperatures are low). Potential evapotranspiration acts as an upper limit to actual evapotranspiration and the relative percentage of potential evapotranspiration that is actually evapotranspired varies through the year and is limited by water availability. Actual evapotranspiration, (as a percentage of potential evapotranspiration) is generally lower in the summer months compared to the winter months. The magnitude of potential evapotranspiration also decreases considerably from the summer months to the winter months. Furthermore, most evapotranspiration is simulated to originate from a combination of evaporation and transpiration in the subsurface with a smaller amount from areas of open water on the land surface, such as Shawnigan Lake.

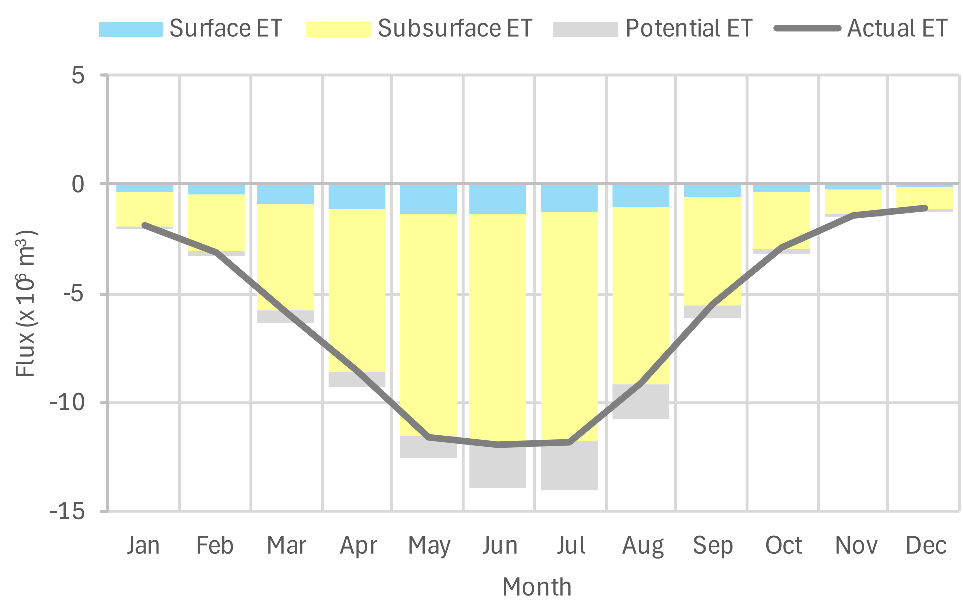

Figure 30: Simulated monthly-average water balance: evapotranspiration.

4.7 Hydraulic Connection

ParaView (Ahrens et al., 2005; Ayachit, 2015) and Surfer (Golden Software, 2023) were used to process, visualize, and create animations of spatially-distributed output from the numerical model, including hydraulic connection between the subsurface and streams. Simulated monthly-average exchange between the subsurface and streams is shown in Figure 31.

Exchange between the subsurface and streams is classified as positive (i.e., when a stream receives water from the subsurface), negative (i.e., when a stream contributes water to the subsurface), and neutral (i.e., when the magnitude in either direction is near-zero or weak). Note that Figure 31 shows the exchange between the subsurface and streams and does not incorporate exchange between the land surface and streams (i.e., overland flow contributions to streamflow are not included). As a result, positive or negative exchange between the subsurface and streams does not necessarily correspond to gaining and losing stream reaches, respectively.

As shown in Figure 31, hydraulic connection between the subsurface and streams varies both spatially across the watershed and with time. High elevation streams receive water from the subsurface throughout the year while low elevation streams are more variable and may either receive or contribute water to the subsurface. Streams in small sub-watersheds that drain directly into Saanich Inlet are generally neutral or contribute water to the subsurface throughout the year. Simulated exchange between the subsurface and streams suggests that the magnitude of hydraulic connection in the central (urban) portion of the watershed (lower Shawnigan Creek and Handysen Creek) can change direction depending on the time of year. Simulated results suggest that some stream reaches that receive water from the subsurface in the winter months (when groundwater levels are high) contribute water to the subsurface in the summer months (when groundwater levels are low).

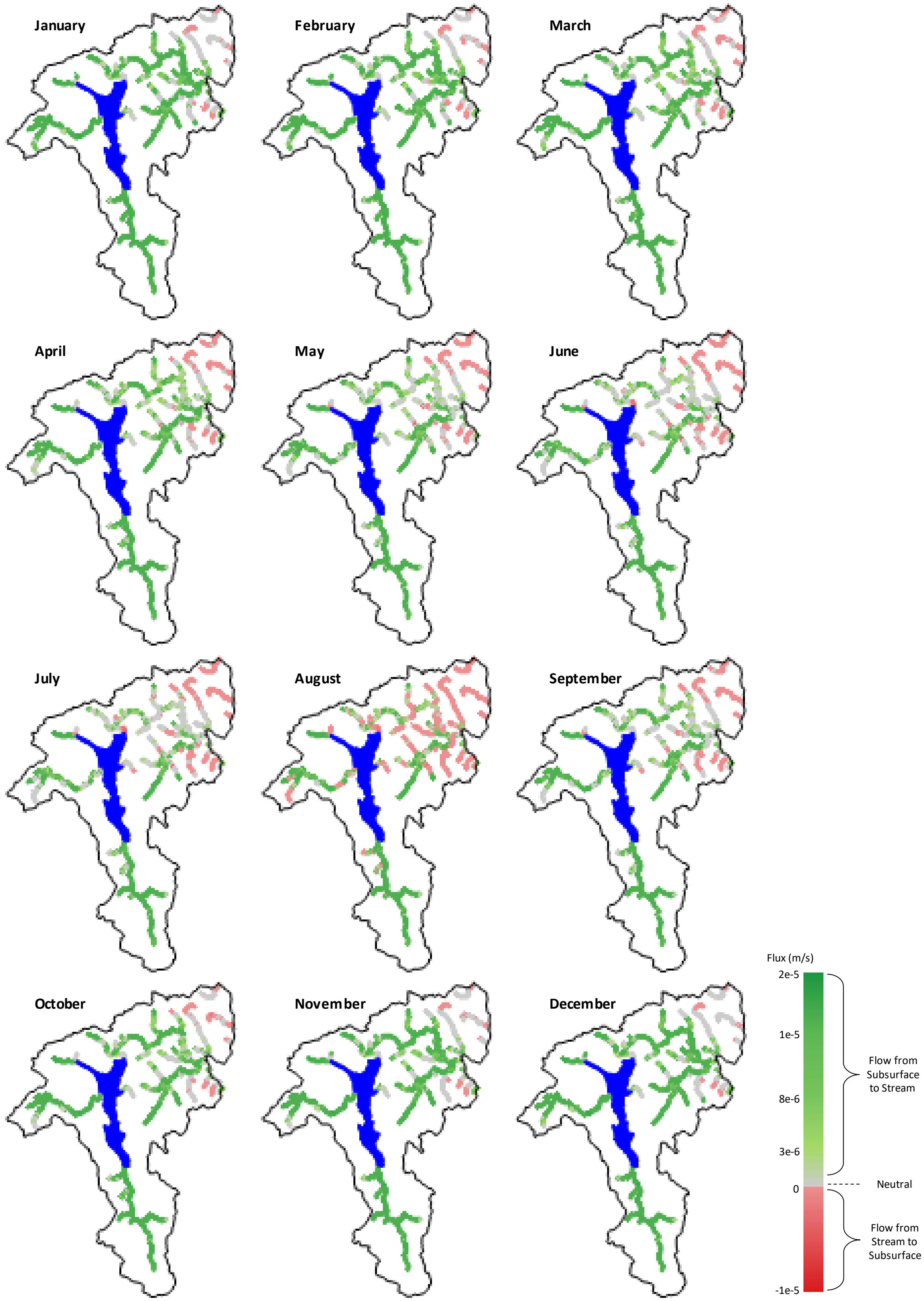

Figure 31: Simulated monthly-average subsurface – stream exchange.

5. WATER USE SCENARIOS

5.1 Water Use (Current Climate)

A water use scenario was developed to assess cumulative effects using best available water use information at the time of this report. The water use scenario incorporates groundwater use (130 groundwater pumping wells – 50 in surficial aquifers and 80 in bedrock aquifers), surface water use (187 points of diversion from Shawnigan Lake and 104 points of diversion from Shawnigan Creek, its tributaries, and surrounding streams), and discharges to ground (9 point source discharges).

Licensed surface water use, groundwater use, and discharges to ground are shown in Figure 32. Points of extraction in Figure 32 are colour-coded according to source with the shape of the points representing the purpose of the use. Dominant purposes include waterworks, irrigation, lawn, fairway and garden (i.e., watering), and domestic. Surface water and groundwater use is unknown and was assumed to be 100% of the allocated amount, with irrigation and lawn, fairway and garden (i.e., watering) use active during the months of May through September. All other uses, including domestic and waterworks, were assumed to be 100% of the allocated amount throughout the year. This is a conservative assumption as most licensees likely do not extract their full allotment at all times of the year and that extraction is likely not fully consumptive as a portion of use is likely lost to runoff and infiltration to the subsurface. Note that domestic groundwater use was not simulated because it is not licensed.

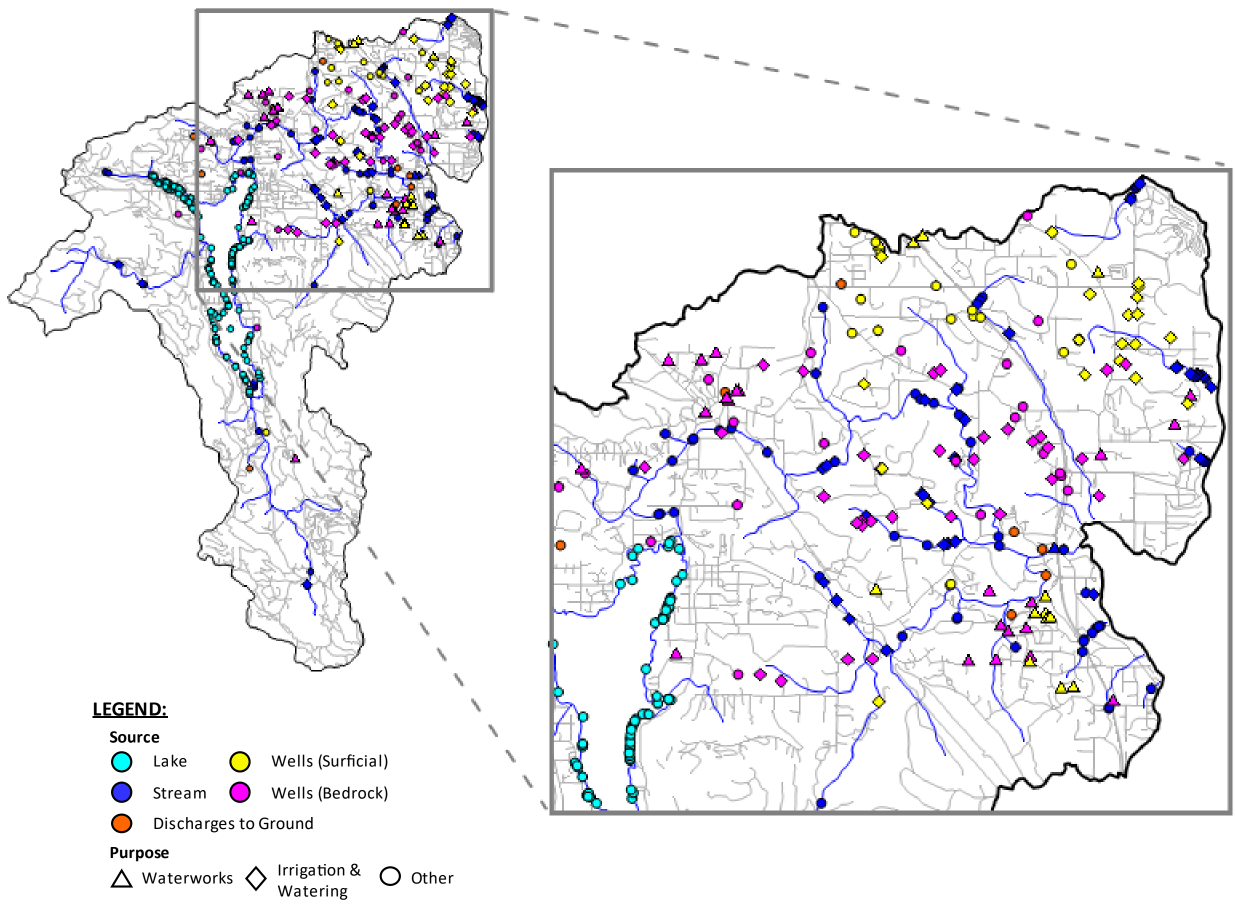

Figure 32: Licensed water use by source and purpose.

Annual surface water and groundwater use by source and purpose is summarized in Table 9. Approximately 5.0 million m^3 of water is extracted from the watershed across all sources and purposes, with approximately 3.1 million m^3 of water extracted from groundwater and 1.9 million m^3 of water extracted from surface water features.

Purpose	Lake (million m^3)	Streams (million m^3)	Aquifers (million m^3)	Total (million m^3)
Waterworks	-	0.41	1.58	**2.00**
Irrigation	-	0.59	1.03	**1.62**
Lawn, Fairway & Garden	-	0.00041	0.14	**0.14**
Domestic	0.17	0.06	-	**0.23**
Other	0.17	0.50	0.38	**1.04**
Total (million m^3)	**0.34**	**1.57**	**3.12**	**5.03**

Table 9: Annual licensed water use by source and purpose.

Water use was implemented in the numerical model as follows:

- Groundwater use was incorporated by applying well boundary conditions in the well domain. Pumping wells were incorporated into the numerical mesh with approximately 2 m resolution around their precise location (see Figure 23). Pumping wells were assigned to aquifers based on Provincial mapping and, in the case of the bedrock aquifer, were screened across multiple numerical layers to allow for hydraulic connection within the well. Pump elevations were assumed at the bottom of wells and automatic flow reduction was activated where needed to reduce pumping to maximum sustainable rates at wells that became dry (i.e., if the water elevation in the pumping well decreased below the elevation of the pump).
- Surface water use was incorporated by applying specified flux boundary conditions in the overland flow domain. Points of diversion from surface water features (i.e., lakes and streams) were not incorporated into the numerical mesh with precise locations but were instead mapped to the nearest node. For example, points of diversion coordinates from streams often did not precisely match the DEM-derived stream network and were adjusted accordingly.
- Discharges to ground were incorporated by applying specified flux boundary conditions in the overland flow domain. Discharges to ground include known releases of water from water treatment facilities and other commercial or industrial processes. Points of discharge to ground were not incorporated into the numerical mesh with precise locations but were instead mapped to the nearest node.

The simulated annual water balance for the watershed in the water use (current climate) scenario is shown in Table 10. Note that changes are shown relative to the simulated annual water balance from the numerical model that does not incorporate water use (Table 8).

In this scenario, approximately 171.3 million m^3 of water is added annually to the watershed in the form of precipitation onto the land surface. More than 90% of that water continues to leave the watershed by way of streamflow and evapotranspiration, although volumes lost to streamflow and outflow directly to Saanich Inlet via groundwater flow and overland flow have decreased. Note that simulated water use in Table 10 is less than that shown in Table 9 as a result of automatic flow reduction during the simulation, meaning that pumping rates at wells that become dry are reduced to a maximum sustainable rate.

Combined surface water and groundwater use represents less than 3% of the simulated annual water balance. At first glance this does not seem significant, but it is important to note that monthly-average precipitation is approximately 3.0 million m^3 in the summer months (see Figure 28) when surface water and groundwater use are anticipated to be largest. Assuming that irrigation and lawn, fairway and garden use are evenly distributed across the months of May through September, surface water and groundwater use could be upwards of 10% to 20% of monthly precipitation in the summer months as shown in Figure 33. Note that a complete monthly-average water balance figure for the water use (current climate) scenario is not provided since components of the water balance are similar to that already shown in Figure 28. The new component of the water balance applied in the numerical model for this scenario (i.e., water use) is shown in Figure 33.

Component		**Percent of Annual Water Balance**	**Change in Magnitude from Calibrated Numerical Model**
INFLOW			
Precipitation	171.3 million m^3	99.7%	No Change
Discharges to Ground	0.6 million m^3	0.3%	-
OUTFLOW			
Streamflow	82.4 million m^3	48.0%	-3.4%
[Runoff]	*[64.0 million m^3]*	*[37.3%]*	*[-3.3%]*
[Baseflow]	*[18.4 million m^3]*	*[10.7%]*	*[-3.7%]*
Evapotranspiration	74.7 million m^3	43.6%	Negligible Change
Groundwater Outflow	7.8 million m^3	4.5%	-10.3%
Overland Outflow	2.3 million m^3	1.3%	-11.5%
Water Use	4.3 million m^3	2.5%	-
MASS BALANCE			
Total Inflow	171.9 million m^3	-	-
Total Outflow	171.5 million m^3	-	-
Percent Error	0.23%	-	-

Table 10: Simulated annual water balance in the water use (current climate) scenario.

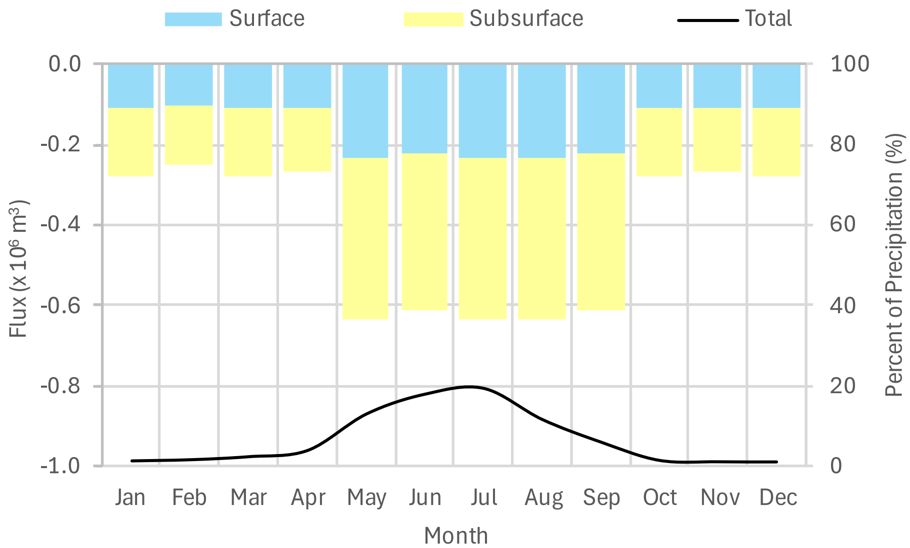

Figure 33: Monthly water use applied in the water use (current climate) scenario.

Simulated changes to monthly-average exchange between the subsurface and streams once water use has been incorporated are shown in Figure 34. Note that this figure shows incremental change from Figure 31 and does not show the actual magnitude of monthly-average exchange between the subsurface and streams. Changes to the exchange between the subsurface and streams are classified as positive (i.e., an increase towards exchange directed from the subsurface to a stream), negative (i.e., an increase towards exchange directed from a stream to the subsurface), and negligible (when the magnitude of change is near-zero).

Incorporating water use tends to result in negative changes to the exchange between the subsurface and streams. This could indicate either an increased magnitude of exchange for stream reaches that are already directed from a stream to the subsurface (i.e., an increased water loss) or a decreased magnitude of exchange for stream reaches that are directed in the opposite direction (i.e., a reduced water gain). Negative changes to the exchange between the subsurface and streams are prevalent along the mainstems of Shawnigan Creek and Hollings Creek where groundwater use is largest. Note that in some areas of the watershed, positive changes to the exchange between the subsurface and streams are shown. These locations correlate with locations of discharges to ground.

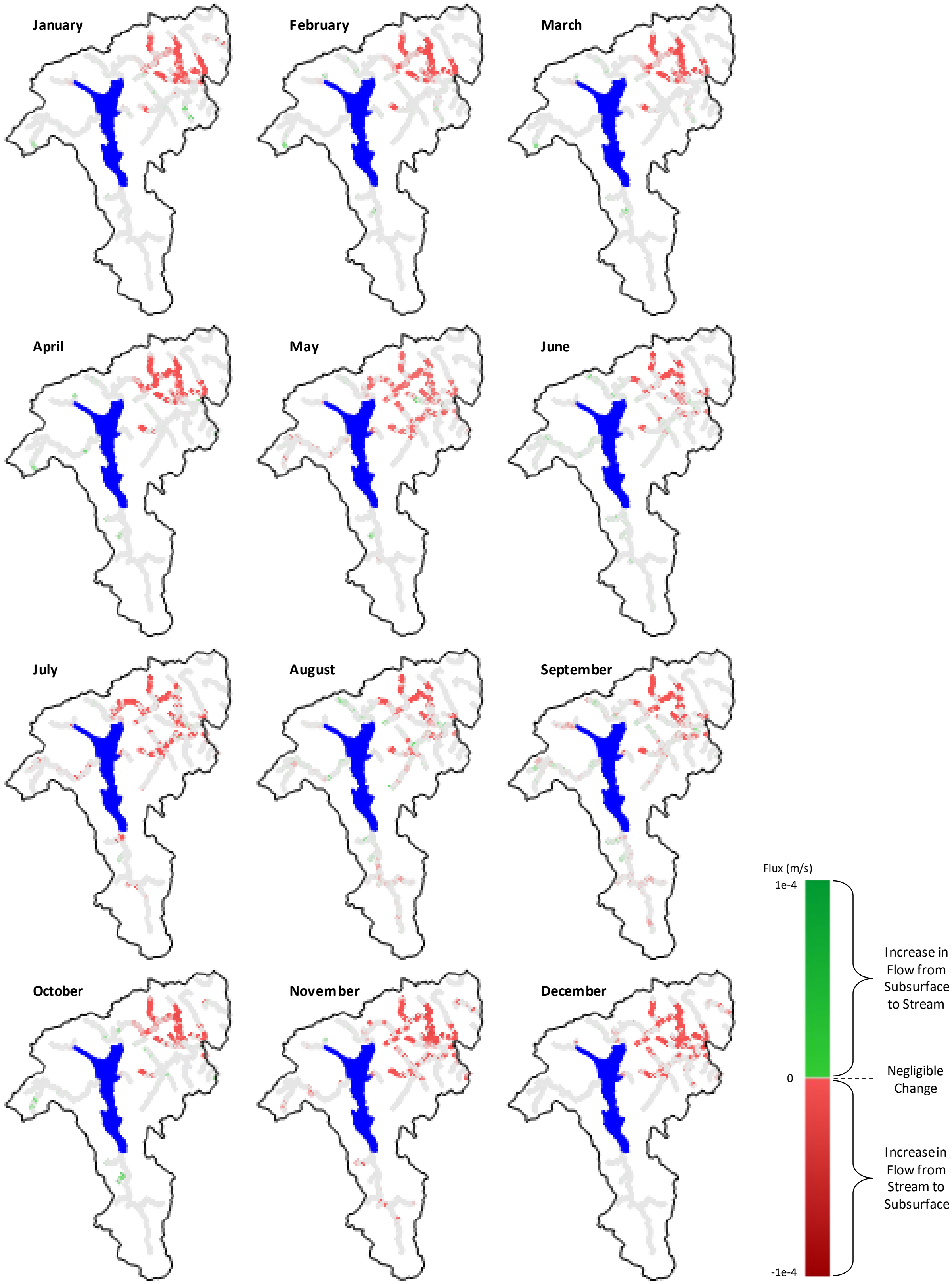

Figure 34: Simulated change to monthly-average subsurface – stream exchange in the water use (current climate) scenario.

5.2 Water Use (Future Climate)

The numerical model described in the previous section was further modified by incorporating future climate projections from ClimateBC. ClimateBC has selected and reported an ensemble of future climate projections from General Circulation Models (GCMs) of the Coupled Model Intercomparison Project (CMIP6). Emissions scenarios, Shared Socioeconomic Pathways (SSPs), include SSP126, SSP245, SSP460, SSP370, and SSP585. The 13-GCM ensemble SSP585 future climate projection for the 2071-2100 climate normal period (Mahony et al., 2022) was selected for this project as it is anticipated to be the most conservative future climate projection available on ClimateBC. Monthly normal end-of-century (2071-2100) precipitation is shown in Figure 35 and potential evapotranspiration is shown in Figure 36. Comparing to the 1991-2020 climate normals, there is generally increased precipitation, potential evapotranspiration, and variability over the course of a year in the end-of-century (2071-2100) climate normals.

The water use (future climate) scenario was implemented by simply forcing the numerical model with end-of-century (2071-2100) precipitation and potential evapotranspiration instead of 1991-2020 climate normal data. The simulated annual water balance for the watershed in the water use (future climate) scenario is shown in Table 11. Note that changes are shown relative to the simulated annual water balance for the water use (current climate) scenario (Table 10).

Component		**Percent of Annual Water Balance**	**Change in Magnitude from Water Use (Current Climate) Scenario**
INFLOW			
Precipitation	183.9 million m^3	99.7%	+7.4%
Discharges to Ground	0.6 million m^3	0.3%	No Change
OUTFLOW			
Streamflow	83.7 million m^3	45.6%	+1.6%
[Runoff]	*[65.6 million m^3]*	*[35.5%]*	*[+2.5%]*
[Baseflow]	*[18.1 million m^3]*	*[10.1%]*	*[-1.6%]*
Evapotranspiration	85.3 million m^3	46.4%	+14.2%
Groundwater Outflow	7.8 million m^3	4.2%	Negligible Change
Overland Outflow	2.6 million m^3	1.4%	+13.0%
Water Use	4.3 million m^3	2.3%	No Change
MASS BALANCE			
Total Inflow	184.5 million m^3	-	-
Total Outflow	183.7 million m^3	-	-
Percent Error	0.44%	-	-

Table 11: Simulated annual water balance in the water use (future climate) scenario.

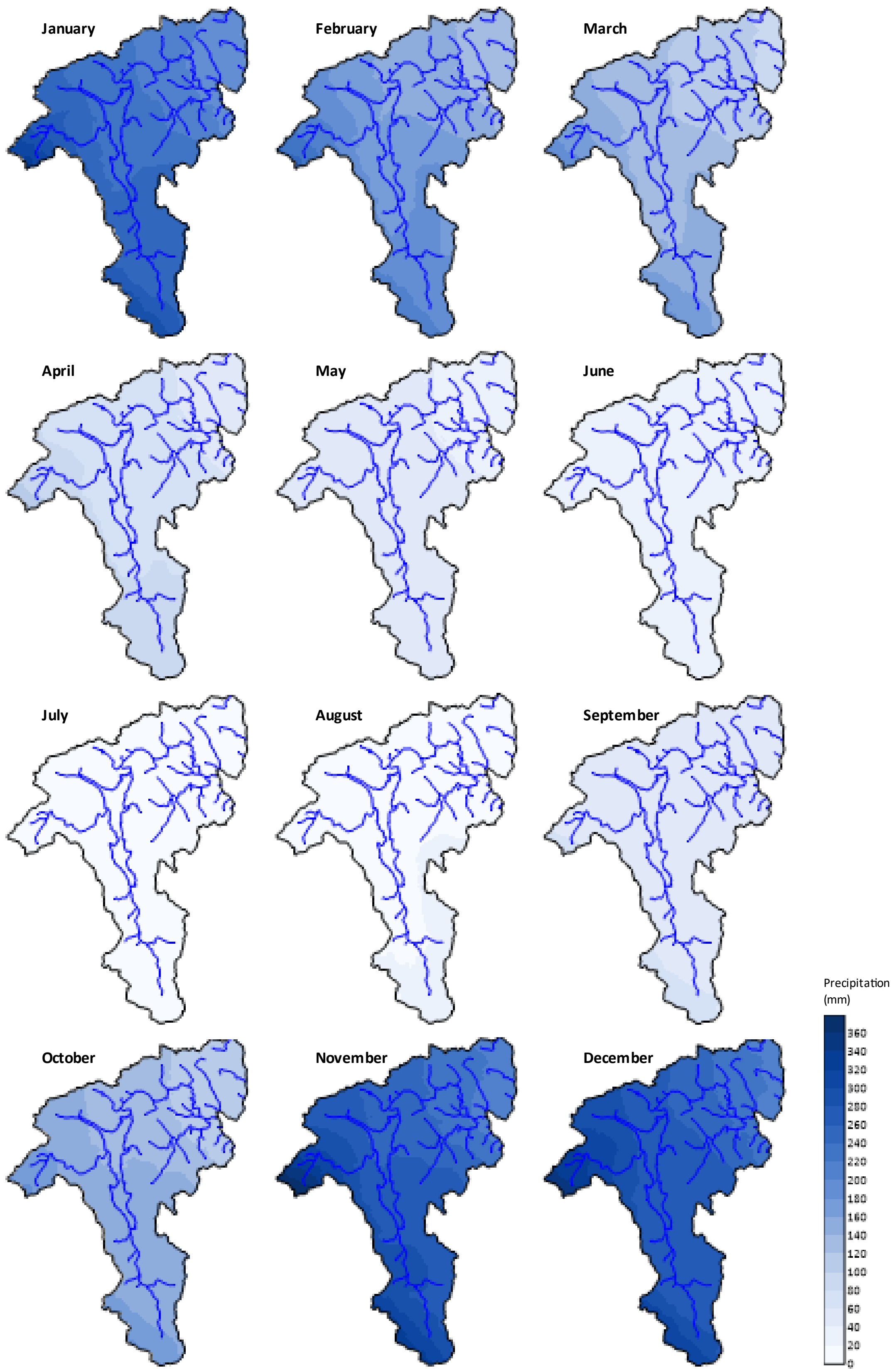

Figure 35: Monthly normal end-of-century (2071-2100) precipitation.

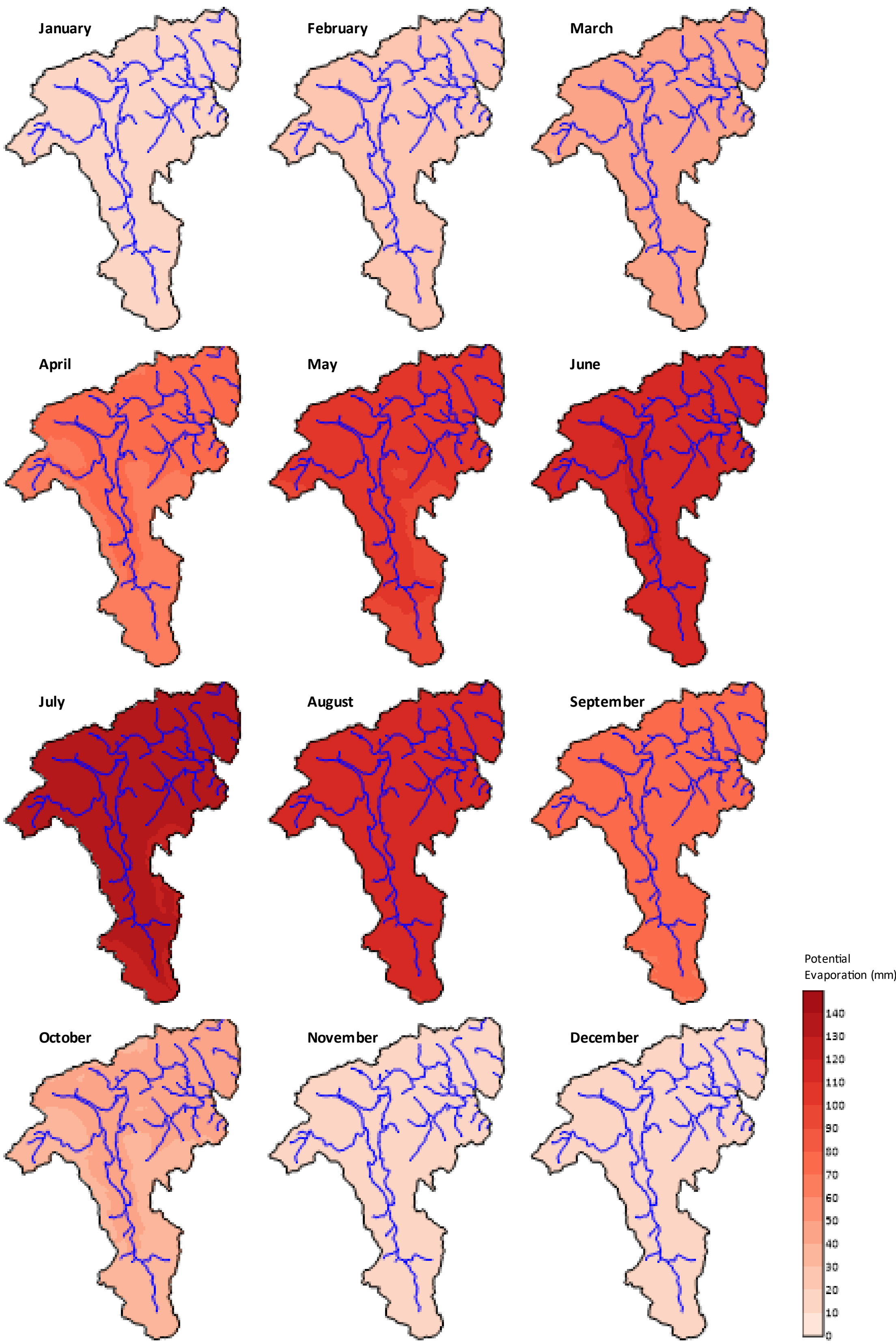

Figure 36: Monthly normal end-of-century (2071-2100) potential evapotranspiration.

In the future climate scenario, approximately 183.9 million m^3 of water is added annually to the watershed in the form of precipitation onto the land surface. This represents an increase of approximately 7.4% from the 171.3 million m^3 of precipitation using the 1991-2020 climate normals. More than 90% of that water continues to leave the watershed by way of streamflow and evapotranspiration, although volumes lost to streamflow and evapotranspiration have increased by approximately 1.6% and 14.2%, respectively. Outflow directly to Saanich Inlet via groundwater flow has remained relatively constant while outflow directly to Saanich Inlet via overland flow has increased. Note that simulated water use in Table 11 is less than that shown in Table 9 as a result of automatic flow reduction during the simulation, meaning that pumping rates at wells that become dry are reduced to a maximum sustainable rate.

Simulated changes to specific components of the monthly-average water balance for the water use (future climate) scenario are shown in Figure 37. Note that changes are shown relative to the water use (current climate) scenario. In the end-of-century (2071-2100) climate scenario, precipitation is anticipated to increase in the winter months and decrease in the summer months, resulting in greater variability across seasons. Evapotranspiration (i.e., actual evapotranspiration) is anticipated to increase in all months of the year while streamflow is anticipated to decrease in the summer months. Replenishment of subsurface aquifers in the winter months and depletion of subsurface aquifers in the summer months are anticipated to increase in magnitude and result in greater variability across seasons. Increased subsurface storage suggests that more water will infiltrate and be stored in the subsurface while decreased subsurface storage (or more negative subsurface storage) suggests that more water will exfiltrate to the land surface from the subsurface. In the end-of-century (2071-2100) climate scenario, it appears that the storage capacity of the subsurface could play an important role in modulating variability in meteorological forcing.

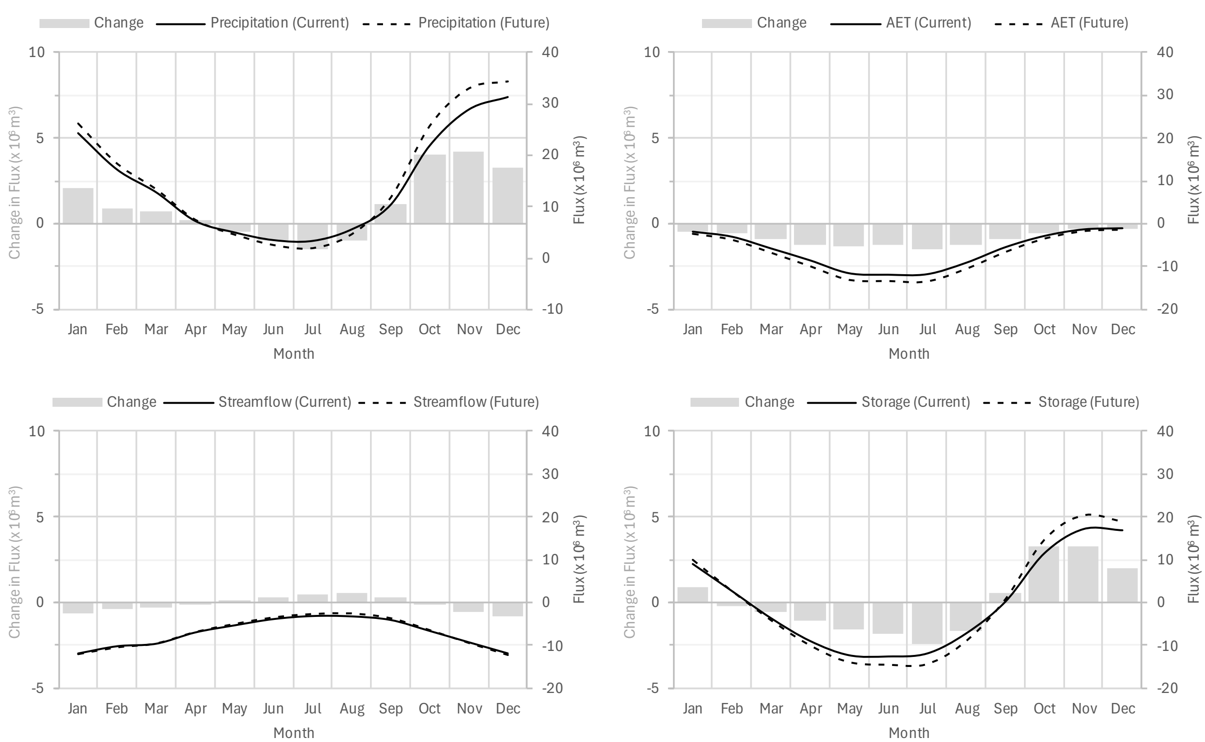

Figure 37: Simulated change to monthly-average water balance in the water use (future climate) scenario.

Simulated changes to monthly-average exchange between the subsurface and streams with water use and end-of-century (2071-2100) climate are shown in Figure 38. Note that this figure shows incremental change from the water use scenario (Figure 34) and does not show the actual magnitude of monthly-average exchange between the subsurface and streams. Changes to the exchange between the subsurface and streams are classified as positive (i.e., an increase towards exchange directed from the subsurface to a stream), negative (i.e., an increase towards exchange directed from a stream to the subsurface), and negligible (when the magnitude of change is near-zero).

Implementing end-of-century (2071-2100) climate with water use tends to result in both positive and negative changes to the exchange between the subsurface and streams. As discussed previously, negative changes could indicate either an increased magnitude of exchange for stream reaches that are already directed from a stream to the subsurface (i.e., an increased water loss) or a decreased magnitude of exchange for stream reaches that are directed in the opposite direction (i.e., a reduced water gain). Negative changes to the exchange between the subsurface and streams continue to be prevalent along the mainstems of Shawnigan Creek and Hollings Creek. However, negative changes are now generally constrained to the months of May to September, with largest negative changes in the warm and dry months of July and August. During the months of October to April, there is generally positive changes to the exchange between the subsurface and streams. It is likely that increased precipitation dictates the increased positive changes to the exchange between the subsurface and streams in the winter months while increased evapotranspiration dictates the increased negative changes to the exchange between the subsurface and streams in the summer months.

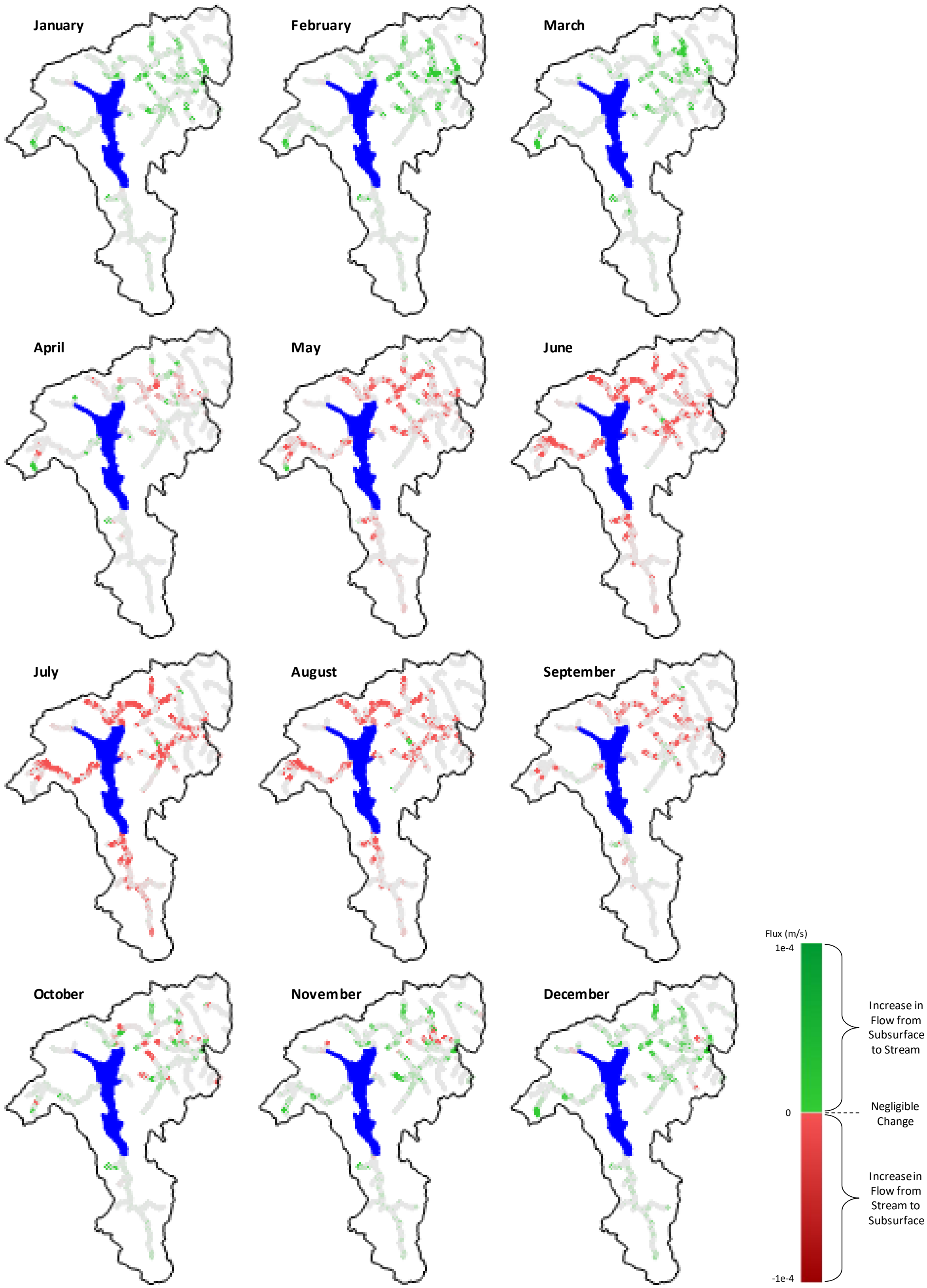

Figure 38: Simulated change to monthly-average subsurface – stream exchange in the water use (future climate) scenario.

6. LIMITATIONS

The numerical model developed herein serves as a decision support tool that provides statutory decision makers with site-specific information that can be used when considering water licence applications. However, the numerical model has the following limitations:

- GWELLS (WLRS, 2023) was the primary source for borehole lithology data and is known to contain incomplete and erroneous borehole lithology data. Professional judgement was exercised in classifying and grouping borehole lithology intervals when developing the hydrostratigraphic framework. It is acknowledged that uncertainty exists in the subsurface interpretations that may impact simulated results.
- GWELLS (WLRS, 2023) was the primary source for groundwater elevation data used in the calibration to long-term average conditions. It is acknowledged that GWELLS may not be representative of actual long-term average conditions (i.e., observations are generally reported at time of drilling) considering groundwater elevations have likely been modified by anthropogenic activity.
- Transient water elevation and flow data have been collected at multiple locations in the watershed but some data is intermittent, not current, or for only brief periods of time. This leads to uncertainty in the observed monthly-averages to which simulated monthly-averages are compared during the calibration process, and ultimately to uncertainty in the calibration and simulated predictive results.
- Bedrock was incorporated into the numerical model as a single hydrostratigraphic unit using an equivalent porous medium approach and no attempt was made to represent fractures and/or faults. Fractures and faults may act as conduits or barriers to groundwater flow. Aquifer 203 is known to be variably fractured and may contain localized groundwater flow systems that are not and cannot be represented in the numerical model.
- Monthly-average precipitation and potential evapotranspiration (1991-2020 climate normals) from ClimateBC forced the numerical model but actual precipitation and potential evapotranspiration may vary. An empirical relationship was used to estimate actual evapotranspiration from potential evapotranspiration. Precipitation was not differentiated into rainfall and snowfall – and the numerical model does not consider the impact of snow accumulation and melt. Uncertainty in this input data may impact simulated results.
- Water use was implemented in the numerical model based on licensed volumes and may not reflect actual use. Licensees may be extracting more or less than their allotted amount. An unknown volume of unauthorized use likely occurs in the watershed and the list of domestic licenses is likely incomplete. In the absence of more detailed information, irrigation and lawn, fairway and garden (i.e., watering) water use was assumed to occur only in the months of May to September, inclusive. Lastly, the Shawnigan Creek weir and engineered drainage works were not included in the numerical model and likely affect water flow.
- The numerical model was developed with a code that solves the governing flow equations for surface water and groundwater flow using a tightly-coupled approach. The code, HydroGeoSphere, is computationally intensive and specialized training is required to use both the code and required ancillary programs. An early-version graphical user interface has been developed but more complex use of the code requires a user to work with lines of code and

command prompts. As a result, under current circumstances, it may be challenging to expand use of this decision support tool to those who are not experienced numerical modellers.

Considering these limitations, the numerical model is best suited for addressing watershed-scale questions such as generating annual and monthly water balances, quantifying the exchange between aquifers and streams, and assessing cumulative effects due to water use and climate change. Detailed use of the numerical model at the well-scale is not recommended given the current level of uncertainty. The calibration should be improved in areas of interest prior to applying the numerical model at the local-scale.

7. RECOMMENDATIONS

This pilot study has illustrated an approach to support the Province of B.C.'s efforts to conjunctively manage surface water and groundwater. Local opportunities in the Shawnigan Creek watershed and broader opportunities for the Province are described below.

The following is recommended for the Shawnigan Creek watershed and numerical model developed for this study:

- The numerical model is best suited for addressing watershed-scale questions and detailed use at the well-scale is not recommended given the current level of uncertainty. The calibration and information on water use should be improved in areas of interest prior to applying the numerical model at the local-scale.
- Consider collecting additional hydrological and hydrogeological data to resolve uncertainties described in this report and incorporate that information into the numerical model as it becomes available. The numerical model (as documented in this report) has been developed using best available data at the time of this report and future studies may result in advancements that spur updates to the numerical model. Confidence in observational data will also increase with additional data collection efforts and will subsequently lead to increased confidence in the calibration and predictive results. At minimum, consider:
    - Conducting detailed, localized mapping of soil cover and land cover;
    - Continuously monitoring streamflow immediately upstream of Mill Bay;
    - Continuously monitoring surface water elevations in Shawnigan Lake;
    - Improving coverage of groundwater monitoring wells that collect continuous measurements of groundwater elevation across the watershed and in all aquifers; and
    - Estimating evapotranspiration with meteorological data to allow comparison with (and validation of) simulated volumes.
- Consider incorporating operation of the Shawnigan Creek weir and engineered drainage works into the numerical model to assess their impact on surface water and groundwater interaction, particularly in the summer months.
- Carefully consider new groundwater use applications in the Shawnigan Creek watershed that are located near stream reaches prone to subsurface – surface exchange directed from a stream towards the subsurface. New groundwater use adjacent to these stream reaches may amplify this exchange and further reduce streamflow at key times of the year when adequate streamflow is required for environmental flow needs and existing water licenses. Statutory decision makers are also advised to consider that projected future climate at the end-of-century

may result in an increased magnitude of subsurface – surface exchange directed from streams towards the subsurface in the summer months.

- Consider using the numerical model internally within the Ministry of Water, Land and Resource Stewardship to assess scenarios of future water use and to collaborate with local governments, First Nations, and stakeholders on water-sharing agreements and impact assessment of proposed future changes to land use (including urban development and any agricultural or forestry practices).

The following is recommended for the Shawnigan Creek watershed but also for broader application of the *Water Sustainability Act* and assessment of cumulative effects by the Province:

- Consider implementing requirements in current and future groundwater use licenses to report monthly usage to the Province. Considerable uncertainty exists with respect to water use as the Province has not required licensees to report usage since implementation of the WSA. Uncertainty will continue to grow should more licenses be granted without reporting requirements. Incorporating information on actual water use will increase confidence and improve the ability of decision support tools to assess cumulative effects.
- Consider implementing requirements in current and future groundwater use licenses for large volume non-domestic users to continuously monitor groundwater elevation in one or more observation wells near their extraction wells and report that data to the Province. Provincial staff can use that data to support development of decision support tools, assess impacts, and inform the decision-making process.
- Consider implementing a time-variable element to current and future non-domestic groundwater use licenses in the West Coast Region. Most rain-dominated watersheds in the region likely have a water surplus in the winter months and a water deficit in the summer months; therefore, larger volumes can be extracted in the winter months and stored for when it is needed in the summer months.
- Consider broader use of agricultural water demand models (e.g., van der Gulik et al., 2010) to improve estimates of water use for inclusion into numerical models. Agricultural water demand models have been developed to estimate current and future water use to support the Province's commitment to reserve water for agricultural lands.
- Consider developing integrated numerical models in priority watersheds in other water-stressed areas of the province to support water allocation, environmental flow needs management, and regional watershed planning (including Water Sustainability Plans). Integrated numerical models can be used to predict impacts to streamflow, surface water elevation, groundwater elevation, and other hydrological variables due to current and planned future anthropogenic activity. A gap exists between the basin-scale focus of provincial flood prediction efforts and the well-scale focus of provincial water allocation efforts. Integrated numerical models can address this gap and results can be visualized and shared with stakeholders in an open and transparent manner on web platforms.

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