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Cowichan Lake Shoreline Assessment

Cowichan Lake Inflow and Water Level Analysis

Final Report Rev. 1
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KWL Project No. 2212.078

COWICHAN RIVER WATER SUPPLY

Prepared for:
Cowichan Valley Regional District

CVRD

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Executive Summary

Appendix D of the Cowichan Lake Shoreline Assessment report summarizes the inflow and lake water level analysis completed for Cowichan Lake. The purpose of the inflow analysis was to evaluate how inflows to Cowichan Lake would change under projected climate change conditions. A lake water level analysis was then undertaken to determine how changes in inflow, along with proposed changes to the Cowichan Lake Weir, would affect the lake levels in the future.

For the inflow analysis, the University of British Columbia Watershed Model (UBCWM) was used to model the Cowichan Lake watershed. The inputs to the model included topographic and land cover parameters, as well as a continuous time series of temperature and precipitation data. The model was calibrated and verified using net inflows back calculated from observed data. To assess inflows under climate change conditions for the 2050s and 2080s, the temperature and precipitation time series from an ensemble of ten downscaled global circulation model outputs was used as input to the hydrological model. These results were used to quantify how inflows are projected to change in the future and to understand the uncertainty in the projections.

The inflow analysis results indicate that the annual average inflow to Cowichan Lake are projected to increase 2.1% by the 2050s and 8.3% by the 2080s. Most of this increase in inflow will be seen in the fall and winter months as a result of increased precipitation and higher temperatures, resulting in less precipitation falling as snow at high elevation. The model results also indicate that inflows to Cowichan Lake will decrease during the spring and summer; summer inflows are expected to decrease 30% by the 2050s and 40% by the 2080s. A reduction in summer inflows is expected due to reduced precipitation, reduced snowpack and therefore reduced spring melt runoff, and increased evaporation due to higher temperatures expected in the future.

As the increase in inflows is expected to occur in the fall, when the gates and boat lock at Cowichan Lake Weir are fully open and there is no control of lake levels and river flows, these higher inflows may not result in increased water availability. Instead, water availability in Cowichan Lake will be most impacted by the reduction in inflows expected during the spring and summer, corresponding to the control period of the lake.

In 2017, the Cowichan Water Use Plan included a recommendation to raise the existing Cowichan Lake Weir to help improve storage and water supply resiliency. Kerr Wood Leidal Associates Ltd. (KWL) used the previously developed Cowichan Lake Operational Model to simulate past and future lake water levels under the current weir scenario and the raised weir scenario. The modelled lake inflows from the UBCWM, discussed above, were used as input to the operational model.

Comparing the results for the existing condition with the proposed raised weir condition, the results show that:

- There is a relatively small increase in elevation of peak water levels (from 0.02 m at 50-year return period flood to 0.06 m increase for the mean annual flood).
- The frequency of water levels between the proposed weir elevation and the annual high water level increased with the proposed raised weir.
- The frequency of water levels between the existing and proposed weir elevations increased with the proposed raised weir.
- The frequency of water levels below the existing weir elevation decreased with the proposed weir.
- Overall, the median water level increased for the proposed raised weir.

In the future with projected decrease in spring and summer inflow, the magnitude of the incremental change in water level frequency between the current weir under current climate and the future weir under future climate is projected to reduce, moving back towards the current climate condition without the proposed weir upgrades.

1. Introduction

Kerr Wood Leidal Associates Ltd. (KWL) has been retained by the Cowichan Valley Regional District (CVRD) to carry out a shoreline assessment for Cowichan Lake as part of the Cowichan River Water Supply Project. The shoreline assessment aims to better understand potential shoreline impacts of the proposed raising of the Cowichan Lake Weir to increase lake storage. A series of technical memoranda and reports were prepared throughout the study and are included as appendices as follows:

- Appendix A: Project Approach and Methodology (KWL Technical Memorandum)
- Appendix B: Mapping, Field Work, Shoreline Characterization (KWL Technical Memorandum)
- Appendix C: 2020 Present Natural Boundary (Bazett Land Surveying Technical Memorandum)
- **Appendix D: Cowichan Lake Inflow and Water Level Analysis (KWL Report)**
- Appendix E: Cowichan Lake Wave Energy Assessment (KWL Report)
- Appendix F: Change in Natural Boundary (KWL Report)
- Appendix G: Property Impacts (KWL Report)

As part of the assessment, an inflow analysis was undertaken for Cowichan Lake and is documented in this report. The purpose of the inflow analysis was to assess changes in inflow to Cowichan Lake under projected climate change scenarios. The results of the inflow analysis provide input to a Cowichan Lake water level analysis, which is also presented in this report. Revision 1 of this report includes updated water level analysis using the final lake level vs river flow rating curve presented in the final Cowichan Lake Weir Design Report prepared by Stantec dated December 9, 2021. The previous revisions should be considered obsolete.

The inflow analysis involves the following major tasks:

1. Collection and review of background information.
2. Characterization of the Cowichan watershed and the local climate.
3. Hydrological model development and calibration.
4. Modelling Cowichan Lake inflows for past and projected future climates.

Also, as part of the study, an analysis of water levels in Cowichan Lake was undertaken. The purpose of the Lake Level Analysis was to assess how water levels in Cowichan Lake for the existing weir and proposed raised weir could change as a result of future projected climate change impacts. The water level analysis involves the following major tasks:

1. Modelling Cowichan Lake water levels (lake levels) for current and future conditions using the Cowichan Lake Operational Model.
2. Evaluate changes in lake level frequency for current and projected future conditions.

The KWL project team included:

Crystal Campbell, P.Eng., Project Manager
Craig Sutherland, P.Eng., Technical Lead
Mike Currie, P.Eng., Overall Technical Review
Alisson Seuarz, P.Eng., Modeller
David Roche, P.Eng., Hydrology and Modelling Technical Review
Jason Vine, Luis Galindo, SQL Statistics
Grace Nidjam, GIS

2. Cowichan Watershed and Climate

2.1 Watershed Overview

The Cowichan watershed, the area that drains into Cowichan Lake and Cowichan River, is located within the CVRD on southern Vancouver Island, BC (see Figure 2-1). Cowichan Lake is located at the western end of the watershed and discharges to the Cowichan River near the Town of Lake Cowichan. The Cowichan Lake watershed is 587 km^2 in area and includes several tributary streams that flow into Cowichan Lake. Cowichan Lake is the second largest on Vancouver Island, having a surface area of about 62 km^2 (including Bear Lake) and a maximum depth of 152 m. The area of Bear Lake is included in the total lake surface area as it is at the same elevation as Cowichan Lake and is hydraulically connected by a short channel which makes Bear Lake an extension of Cowichan Lake.

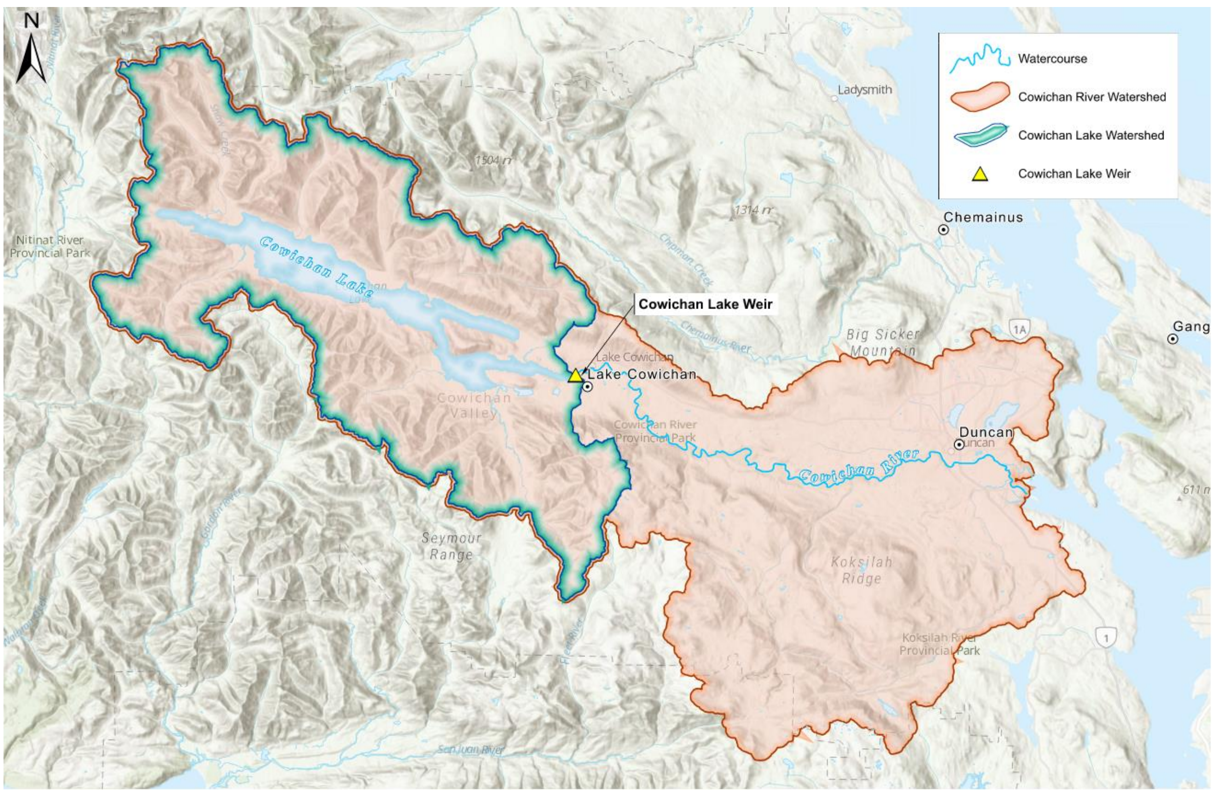

Figure 2-1: Study Area

The Cowichan Lake Weir, located at the outlet of Cowichan Lake, was constructed in the 1950s and upgraded in the 1960s. The weir is licenced to impound water for storage in the spring to supplement the Cowichan River flow in the summer. The Cowichan Lake Weir consists of a timber/sheet pile weir, a control structure, and a boat lock. The gates in the control structure are used to control the lake level and river flow during the control period from April 1 to the onset of fall rains (usually about late October). During the remainder of the year, known as the off-control period, the gates are fully open (lowered) and the boat lock is open (raised). During this period, the weir structure has no influence on the lake level or river flow due to natural flow constriction in the downstream river channel.

Downstream of Cowichan Lake, the Cowichan River flows for 47 km through the Cowichan Valley with inflow from several tributaries. The river supports many values and uses including fisheries values, first nations cultural values, industrial use at the Crofton Pulp Mill, and municipal sewage effluent dilution. Upstream of Duncan, a portion of the river flow, typically about 1.0 m^3/s, is pumped from the river for use at the Crofton Mill, while the remainder of the water in the river flows along the river channel across the Vancouver Island coastal lowlands. The Cowichan Lake Weir helps to support these values and uses by augmenting the summer flow.

The Koksilah River joins the Cowichan River just upstream of the mouth of the Cowichan River at Cowichan Bay. Although physically the Koksilah River is part of the Cowichan watershed, from a water management planning perspective the Koksilah River is considered a separate watershed as it has very different hydrological characteristics and water management issues. The total size of the Cowichan watershed, not including the Koksilah River, is 939 km^2.

As the focus of the Cowichan Lake shoreline assessment is the lake, the inflow and water level study focus on the Cowichan Lake watershed.

2.2 Watershed Characterization

The Cowichan Lake watershed is within the Vancouver Island mountains. Generally, the topography on the south side of the lake is at a lower elevation than the north side. Several of the mountain peaks above the lake exceed 1,000 m in elevation. The average lake surface is at approximately 162.6 m elevation[1]. A topographic map of the watershed is shown in Figure 2-2.

The watershed lies within the Coastal Western Hemlock (CWH) biogeoclimatic zone, with pockets of Mountain Hemlock (MH) biogeoclimatic zone above elevation 1,000 m. Most of the land in the watershed is privately owned forest land which has been actively harvested for more than 100 years. Therefore, most of the watershed consists of mature second growth or regenerating second growth forest. Stands of old growth forest are limited to the mountain tops and some of the steep sided valley slopes. The residential development within the watershed is primarily limited to the perimeter of the lake and within the villages of Youbou, Mesachie Lake, and Honeymoon Bay.

The distribution of land cover across the watershed was mapped using data provided in the BC Vegetation Resource Inventory (VRI).[2] The VRI was used to map unforested areas such as urban areas, small lakes/wetlands including Beaver Lake and Mesachie Lake, unvegetated areas (clearings/bedrock outcrops, and rivers/gravel bars), and to classify forest density as a percentage of cover. The forest density classifications are based on guidance provided in the BC Land cover classification scheme (Ministry of Sustainable Resource Management, 2002). Table 2-1 indicates the forest density classifications and shows the percentage of land cover types in the watershed. Figure 2-3 shows the distribution of land cover types across the watershed.

[1] Average recorded lake level elevation (CGVD2013) for period from 1981-2010.

[2] BC Vegetation Resource Inventory, Ministry of Farming, Natural Resources and Industry, 2018. https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-inventory

Table 2-1: Distribution of Land Cover Types in Cowichan Lake Watershed

Land Cover Type	Area (Sq. km)	% of Total Area
Densely Forested (>60% tree and shrub cover)	78.1	13%
Moderately Forested (26% to 60% tree and shrub cover)	328	56%
Sparsely Forested (<25% tree and shrub cover)	88.6	15%
Urban	0.9	0.2%
Clear (Bedrock Outcrops, Clearings, Gravel Bars, etc.)	1.0	0.2%
Impervious (Small Lakes, Wetlands, etc.)	27.9	4.8%
Cowichan Lake/Bear Lake Combined Area	62.4	11%
Total	**578**	
Note: Land cover based on BC Vegetation Resource Inventory based 2018 aerial photography.		

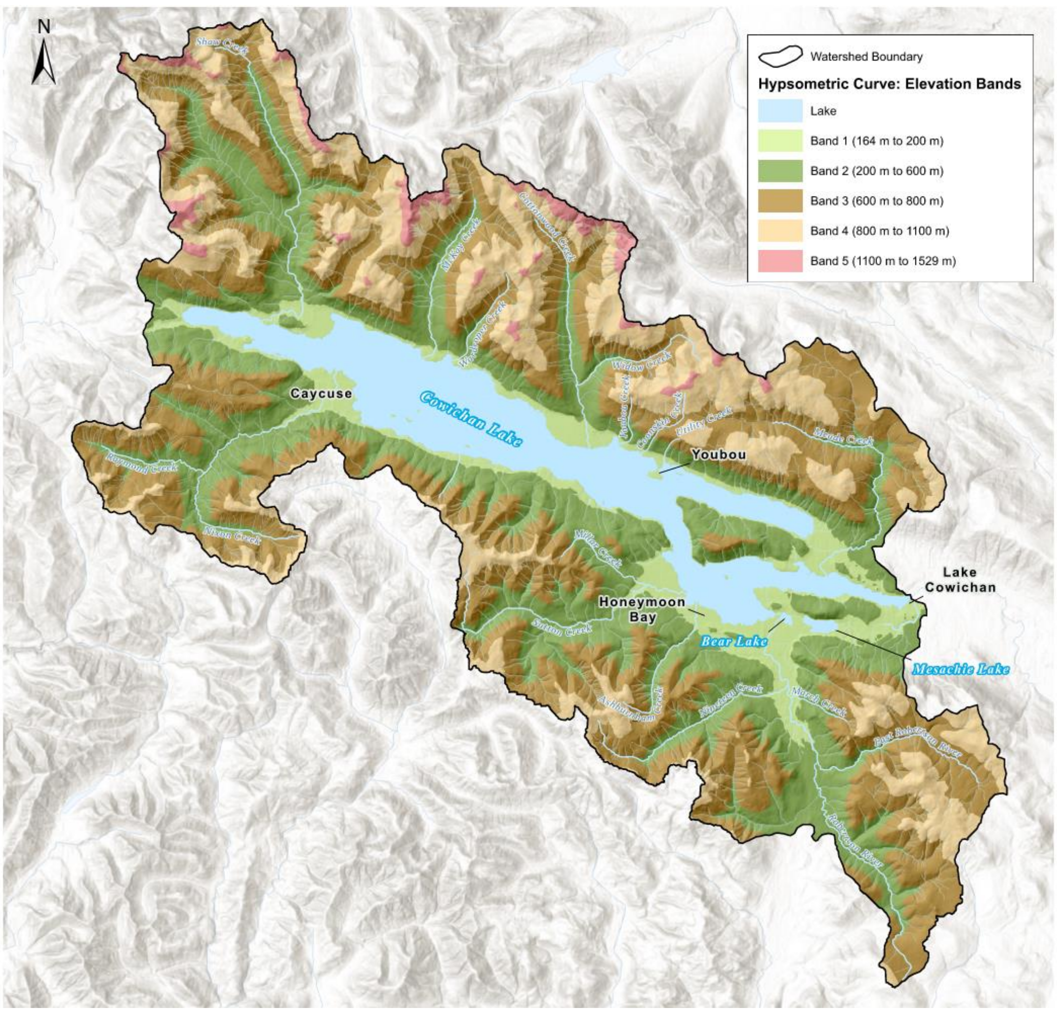

Figure 2-2: Watershed Topography

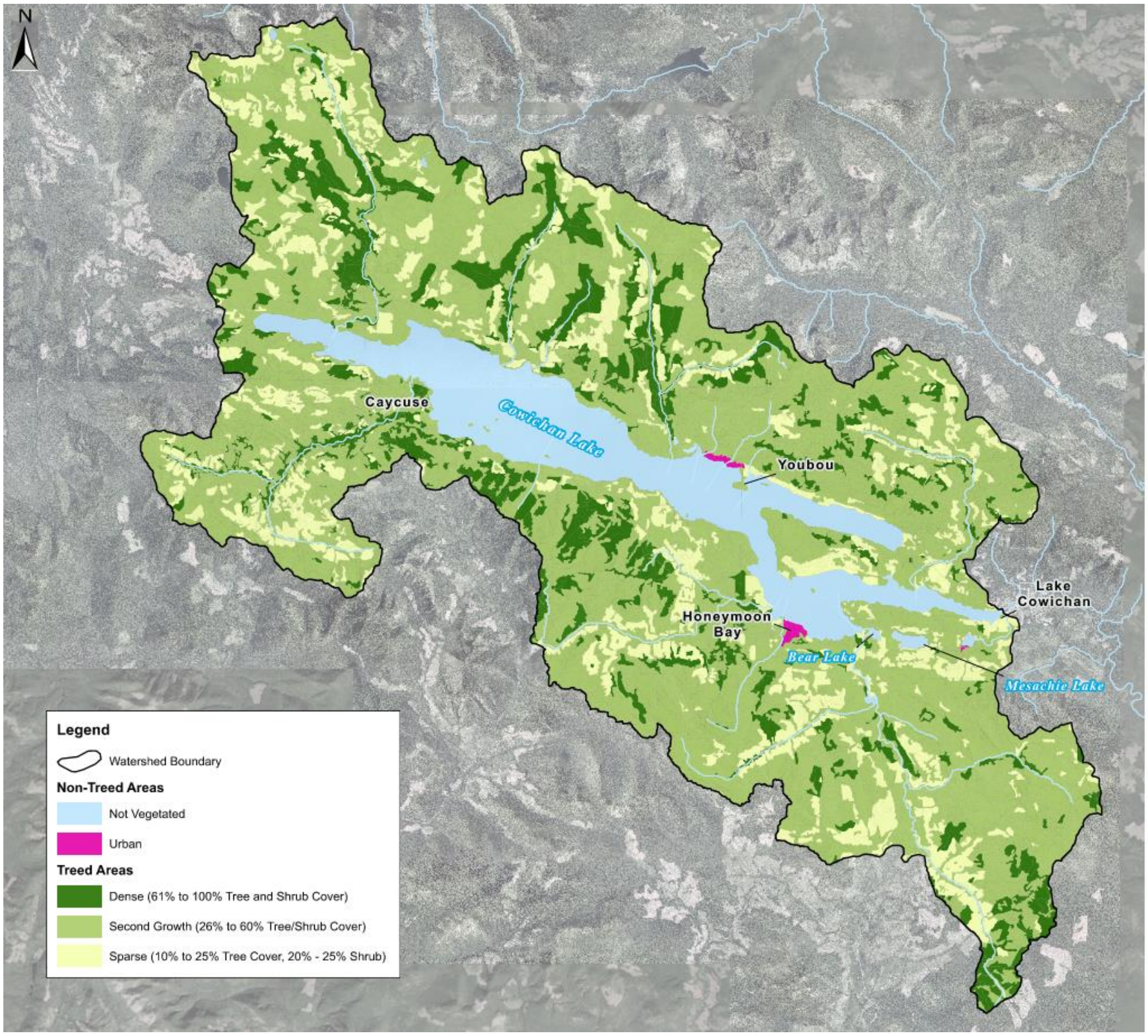

Figure 2-3: Watershed Land Cover

The Cowichan Lake watershed is underlain by geological formations typical of the Vancouver Island mountains including volcanic and sedimentary rocks of the Sicker Group, which mostly underly the area to the north of the lake; marine and volcanic deposits of the Bonanza Group, which mostly underly the area to the south of the lake; and conglomerate and sandstones of the Nanaimo Group, which are located at lower elevations near the lake (Massey & Friday, 1986). The surficial soils overlying the geology generally consists of a thin layer of moderately to well draining colluvium on the mountain slopes, with rapidly draining alluvial deposits where the tributary streams flow into the lake (Halstead, 1964). There are several bedrock outcrops at higher elevation in the watershed. A map showing the surficial soils in the watershed is shown in Figure 2-4.

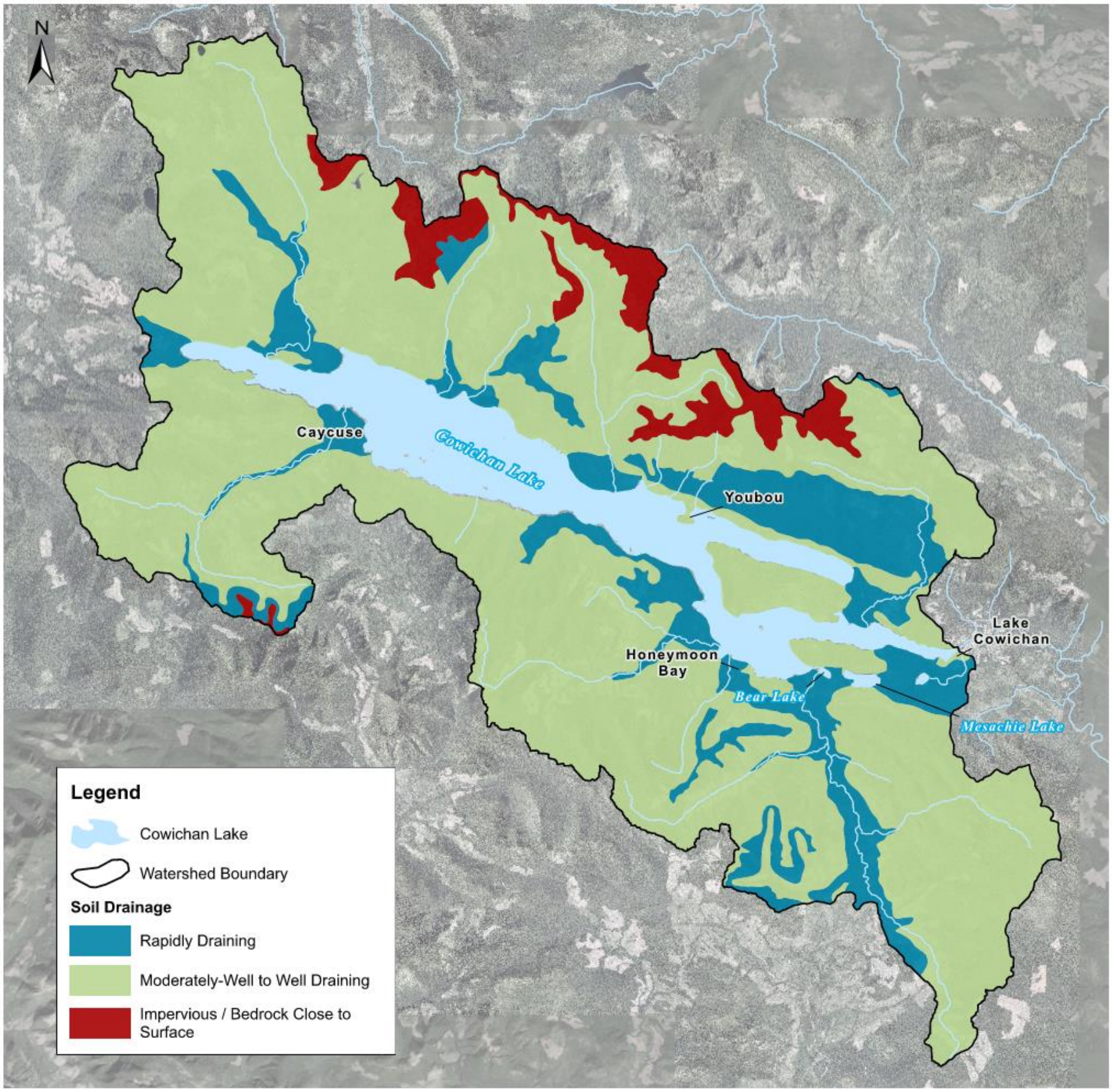

Figure 2-4: Watershed Soils

2.3 Climate

The climate of the Cowichan Valley is similar to other parts of east coast of Vancouver Island, with a cool wet season between October to March and a warm dry season from April to September. Climate normals (1981 to 2010) for the Cowichan Lake Forestry Climate Station (1012040) near the Town of Lake Cowichan indicate average monthly temperatures ranging from 17.8°C in August to 2.5°C in December. However, given that Lake Cowichan is located in the valley bottom, the higher elevations in the watershed will have colder temperatures.

The available recorded temperatures for the period from 2016 to 2020 at the Heather Mountain Snow Pillow, located at elevation 1,190 m, indicate average monthly temperature ranging from 13.8°C in August to -1.7°C in December. Temperatures are below freezing at Heather Mountain Snow Pillow 55 days per year on average over the period of record. A map of winter and summer temperature across the watershed are shown in Figure 2-5 and Figure 2-6, respectively.

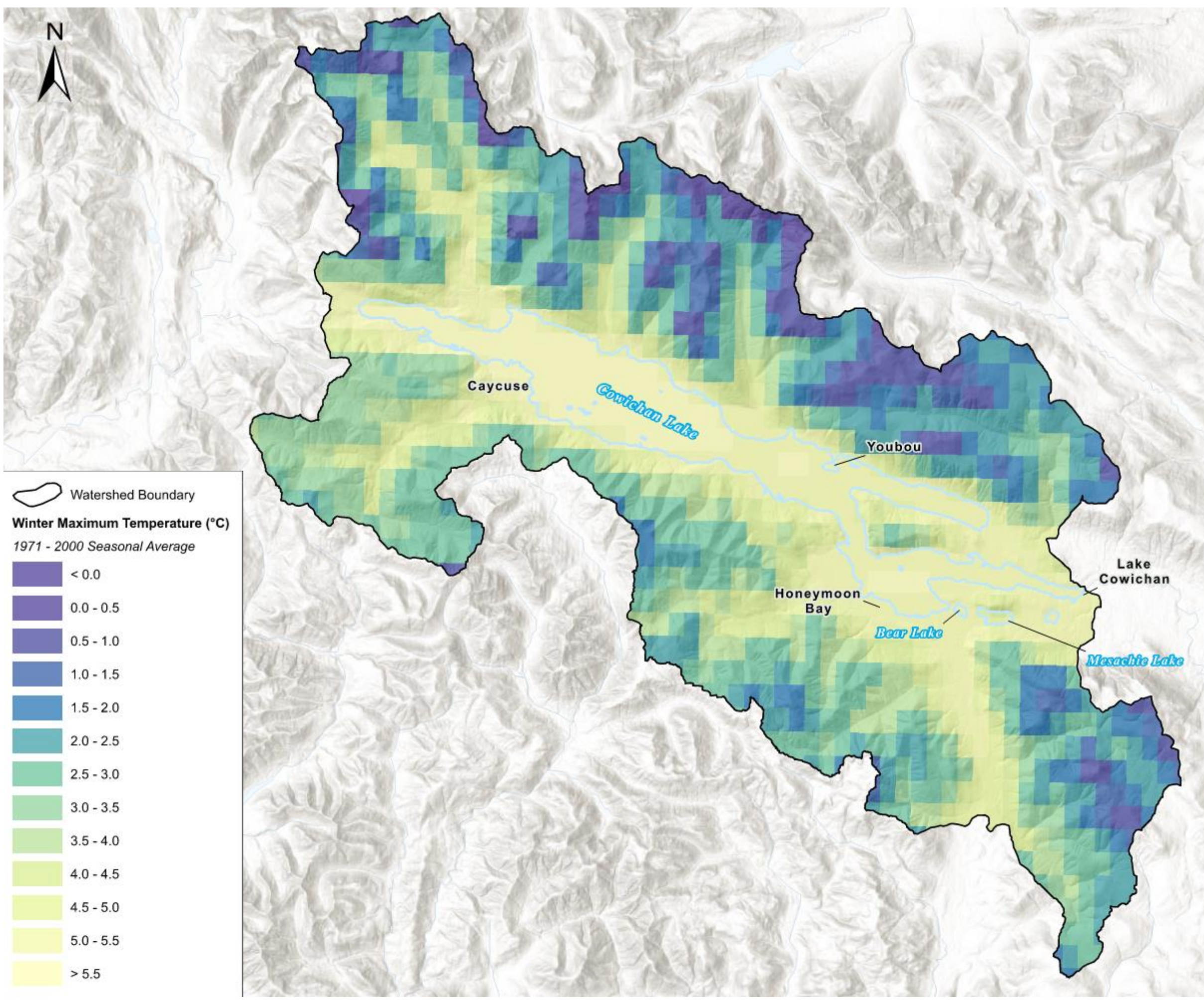

Figure 2-5: Average Winter Daily Maximum Temperature

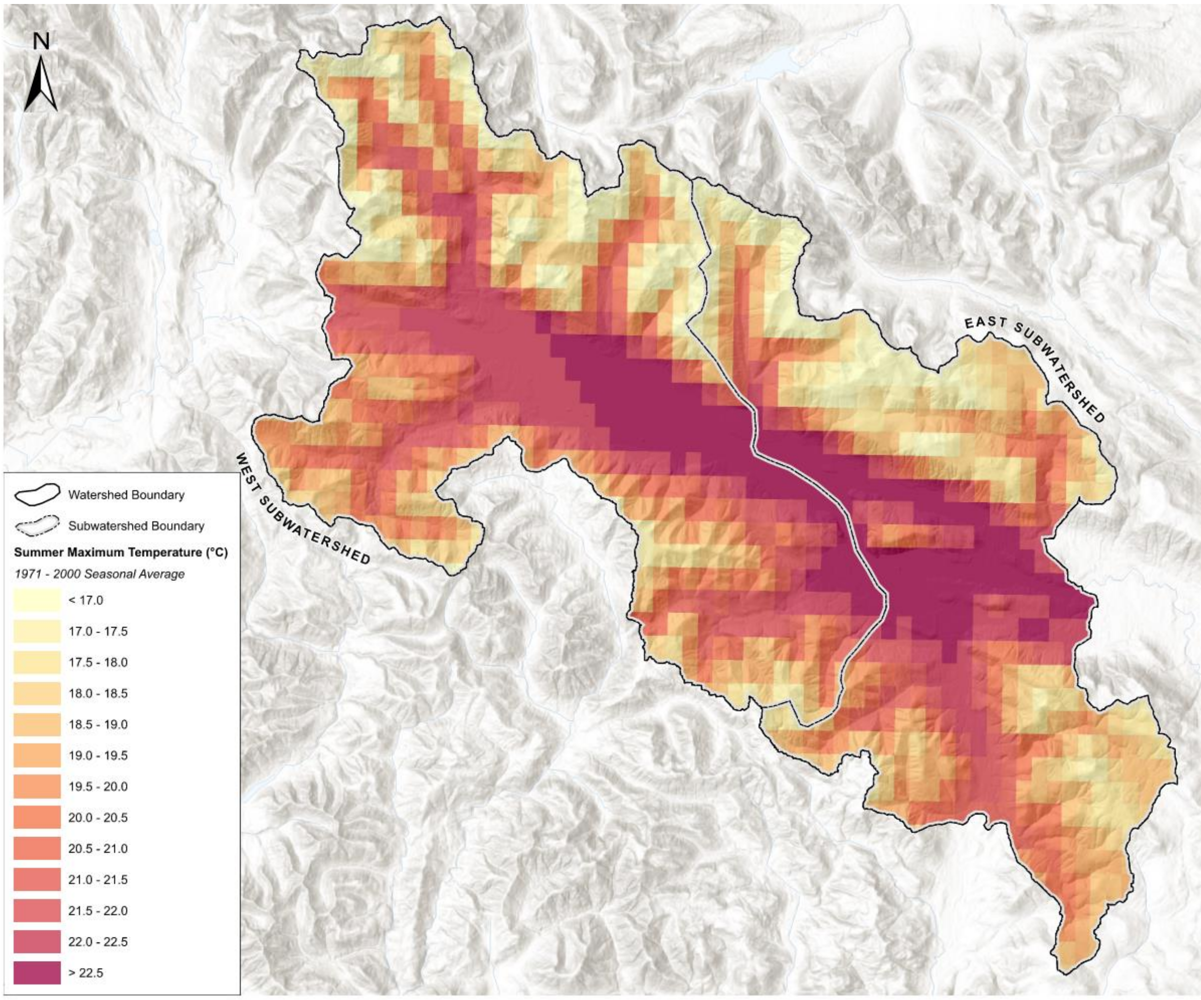

Figure 2-6: Average Summer Daily Maximum Temperature

The amount of precipitation varies considerably across the watershed because of the rain shadow effect of the Vancouver Island Mountains. The previously recorded total annual average precipitation for the 30-year period from 1981 to 2010 ranges from 1,153 mm near Duncan (Climate Station 1015628 North Cowichan) to 2,207 mm near Lake Cowichan (Climate Station 1012040 Cowichan Lake Forestry). Total annual precipitation in the mountains surrounding the lake is estimated to be greater than 3,000 mm. In the mountains, a portion of the precipitation falls as snow with snowpack accumulating in the highest portions of the watershed exceeding 1,000 mm of snow water equivalent in some years. A map showing the distribution of total annual precipitation across the watershed is shown in Figure 2-7.

There is a large seasonal variation in precipitation in the watershed. About 75% of the total annual precipitation falls over the six-month period from October to March with the remaining 25% falling over the drier period from April to September.

The mean annual discharge recorded at the Cowichan River at Lake Cowichan (08HB002) hydrometric station over the 1981 to 2010 climate normal period is 44.7 m^3/s. The seasonal variation in precipitation results in large fluctuation in river flow and lake level. At Lake Cowichan, average monthly flow in the

Cowichan River ranges from 7 m^3/s in summer to 125 m^3/s in November. Winter storms can result in very high discharge in the river. The highest flood discharge recorded at Cowichan River at Lake Cowichan is 326 m^3/s.

It should be noted that the period from 1981 to 2010 has been selected to present past climate conditions at Cowichan Lake as it is the most recent period with overlapping climate normal period data and gridded meteorological data used in model calibration and verification (discussed further in Section 4.4).

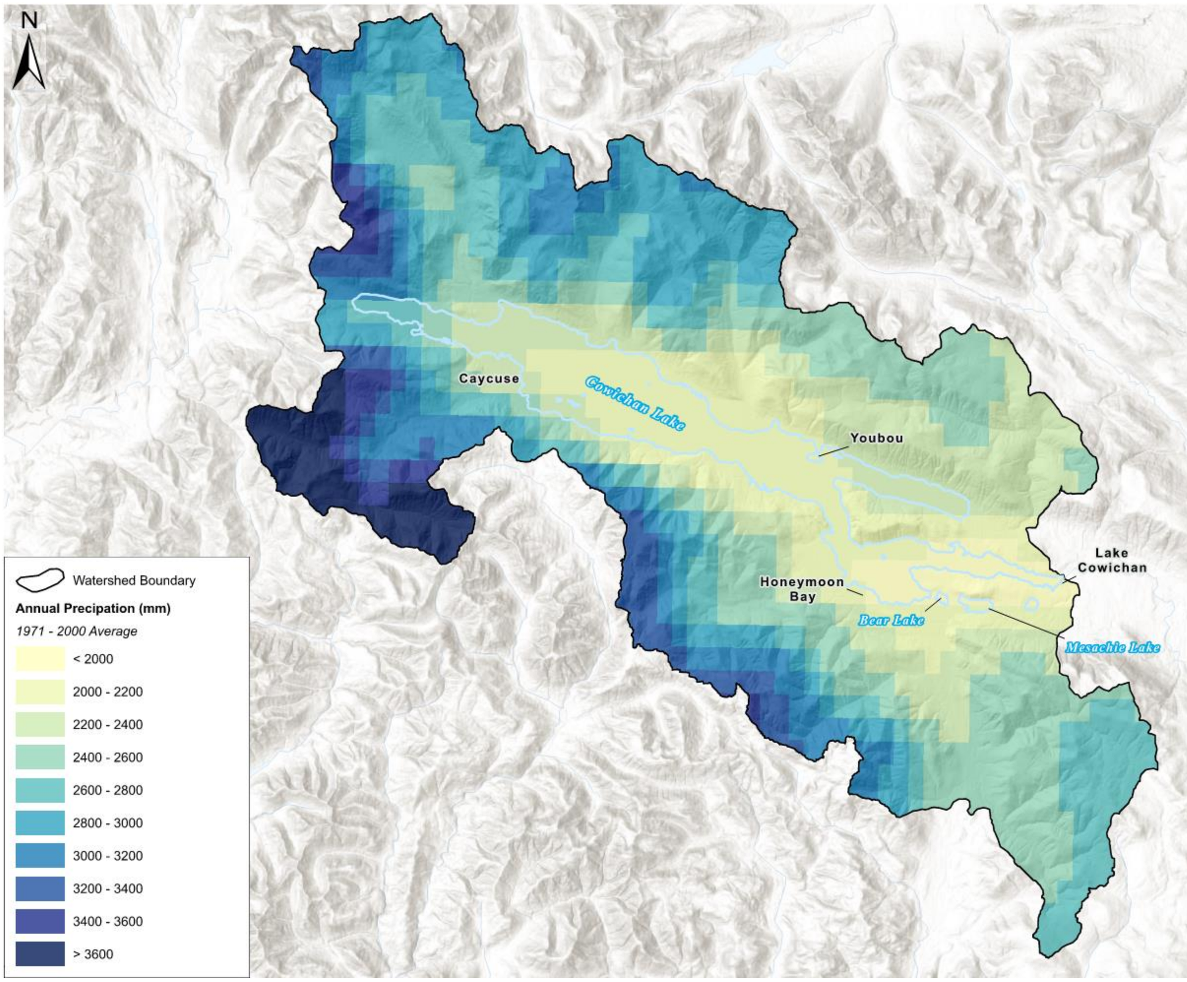

Figure 2-7: Average Annual Precipitation

2.4 Cowichan Lake Inflow

The flows recorded at the Cowichan River at Lake Cowichan hydrometric station are influenced by operation of the Cowichan Lake Weir and control gates. To better understand the quantity and timing of inflow to Cowichan Lake without the influence of operation of the weir, the inflow to the lake was calculated assuming conservation of mass, with the volume of water flowing into the lake being equal to the volume of water flowing out of the lake plus the change in storage volume in the lake.

Using this approach, the inflow to the lake was calculated using daily river flow data (08HB002) to calculate the daily volume of outflow from the lake and daily lake water level data (08HA008) to calculate the change in volume based on the product of the daily change in lake level and the surface area of the lake.

Monthly inflow to Cowichan Lake is shown in Figure 2-8 which also shows monthly average precipitation across the watershed for comparison. The graph shows volume as an equivalent depth over the watershed area for comparison between inflow and precipitation.

As shown in Figure 2-8, the seasonal variation in inflow to Cowichan Lake roughly follows the monthly distribution of precipitation. The only exception to this is in the spring when average inflow to the lake is slightly higher than the monthly precipitation. This is due to the contribution of snowmelt to the lake inflow in the spring and indicates that snowmelt plays an important role in supporting inflow to the lake during the spring. The increased spring inflow due to snowmelt means that flow in the Cowichan River can be sustained at a higher level in spring without the need to supplement flow from storage from Cowichan Lake. Therefore, storage in Cowichan Lake can be 'saved' to supplement flow in the Cowichan River in the summer. However, the future impact of snowmelt on inflow is likely to be impacted by climate change.

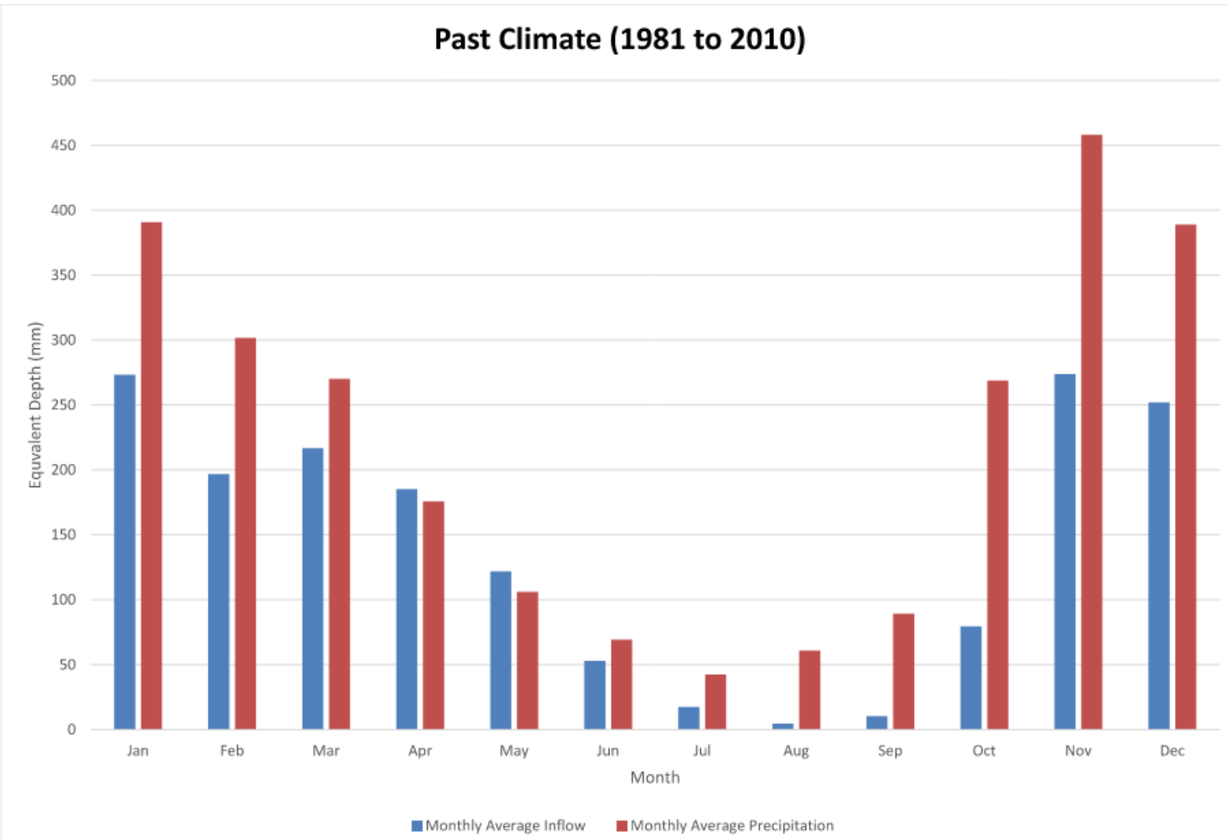

Figure 2-8: Comparison of Monthly Average Cowichan Lake Inflow with Precipitation

2.5 Climate Change

Analysis of inflow records for Cowichan Lake indicate that summer inflow (July to September) to the lake has dropped by about 33% since the 1960s (Chapman, 2011). Including data up to 2020 indicates that this trend is continuing and is likely to continue based on projected changes in climate in the region (see Figure 2-9).

The Pacific Climate Impact Consortium has carried out downscaling of climate models for the CVRD which provides projections of future climate for the region (CVRD, 2017). The results of the ensemble of downscaled GCM projections indicate that average daytime high temperatures across the region could increase by +2.7°C and +4.5°C by the 2050s and 2080s, respectively. On an annual basis, the total precipitation in the region is expected to increase by about 5% and 11% by the 2050s and 2080s, respectively. However, the increase in precipitation is projected to be in fall, winter, and spring while summer precipitation is projected to decrease by 17% and 26% by 2050s and 2080s, respectively. The projected changes presented are based on changes from the 1971 to 2000 baseline period.

The changes in average temperature and precipitation provide an indication of the magnitude of the anticipated changes. However, the output from downscaled GCMs has also been used to better understand extremes which indicate that as the climate warms in the future:

1. The number of days above 25°C changes from an average of 16 days per year in the past to 39 days per year in the 2050s, and 59 days by the 2080s.
2. The number of days when daytime high temperature remains below zero (ice days) is expected to change from about 6 days on average to no ice days by the 2080s, except at very high elevation (above 1,000 m).
3. Dry periods could increase from an average of 20 days in the past to 26 days in the 2050s, and 29 days in the 2080s. The likelihood of having extremely long periods of try weather similar to summer of 2022 (~80 days) is also projected to increase.

These projected changes could have significant impacts on water supply for Cowichan Lake due to decrease in snowpack and earlier snowmelt due to increased temperature, longer summer dry spells, and less summer precipitation to replenish the lake during summer. The average annual precipitation is expected to increase in future. However, the projections indicate that most of the precipitation will come in the form of higher intensity extreme precipitation, with the 5% wettest days increasing by about 31% by the 2050s, and 56% by the 2080s. These storms are most likely to occur in late fall/winter during the period when Cowichan weir is not controlling the lake level.

This study uses hydrological modelling to better quantify how these projected changes in climate will change quantity and timing of inflow to Cowichan Lake.

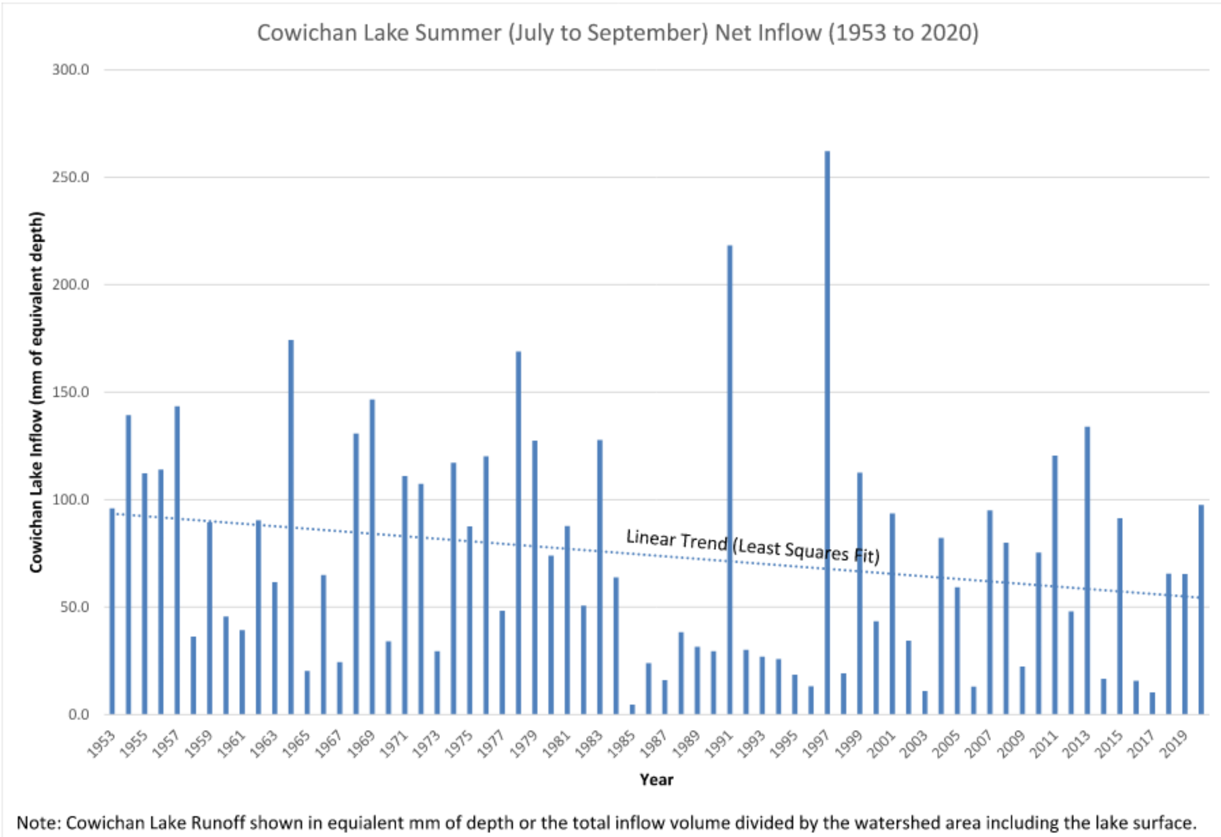

Figure 2-9: Trend in Historical Summer Inflow to Cowichan Lake

3. Modelling Approach and Model Selection

3.1 Modelling Approach

The purpose of the hydrologic modelling is to assess how climate change may affect inflow to Cowichan Lake, and thus impact Cowichan Lake water levels because of operation of the existing and proposed Cowichan Lake Weir.

The modelling was completed in steps as follows:

1. Collection of spatially distributed (gridded) meteorological data based on historical records and downscaled Global Circulation Model (GCM) time series for past and projected future climate conditions.
2. Development of hydrological model used to represent watershed hydrological processes and convert climate inputs into Cowichan Lake inflow.
3. Calibration and verification of hydrological model, which included comparing model results using gridded historical metrological data set to recorded inflow to Cowichan Lake to confirm how well the model represents runoff processes and the uncertainty in model results.
4. Run calibrated hydrological model of Cowichan Lake watershed using downscaled GCM timeseries for past and future climate conditions to assess how inflow to Cowichan Lake is projected to change from past climate to future climate conditions.
5. Use inflow time-series from hydrological model as input to the Cowichan Lake Weir Operational Model to simulate how Cowichan Lake water levels and Cowichan River discharges are projected to change from past climate to future climate conditions for existing weir and proposed raised weir operation.

3.2 Model Selection

For the hydrologic modelling component KWL applied the University of British Columbia Watershed Model (UBCWM), a conceptual semi-distributed continuous-simulation hydrologic model (Quick & Pipes, 1977). The UBCWM is routinely applied by BC Hydro for inflow forecasting throughout the province and has been found to out-perform more complex models in BC's mountainous environment.

Consideration was given to the application of a fully distributed, physically based model such as MIKE SHE or the Variable Infiltration Capacity (VIC) model. However, recent studies (e.g., Fleming et al., 2010) have found that fully distributed models are typically not supported by available data for BC watersheds. Conversely, simplified lumped models, such as the Hydrologic Simulation Program Fortran (HSPF), cannot adequately simulate important influences of mountainous terrain on hydrological processes. These include changes in temperature and precipitation with increasing elevation which influences both phase of precipitation (rain vs. snow) and snowmelt processes. The semi-distributed approach used in the UBCWM offers a balance between data requirements, hydrologic process representation, and modelling efficiency.

4. Hydrological Model Development and Calibration

4.1 UBC Watershed Model

UBCWM was originally developed at the University of British Columbia for forecasting watershed behaviour in mountainous areas. UBCWM is the principal hydrological modelling tool applied by BC Hydro for dam safety analyses, facilities design, reservoir inflow forecasting, and operations planning.

UBCWM requires a description of the watershed, which can usually be obtained from available topographic and land cover data. The watershed is divided into elevation bands based on the shape of the hypsometric (area-elevation relationship) curve. Topographic data is then used to determine properties such as area, aspect, and mid-point elevation for each band. Spatial land cover information is used to estimate additional properties such as impermeable area and the percentage of forest cover.

Snowmelt in the UBCWM is based on a thermal energy budget method, which is dependent on convective heat transfer from a warm air mass, net radiant heat transfer from sunlight and latent heat changes. As recorded net radiation is not often available, the UBCWM uses daily temperature range as a proxy for estimating the daily radiant energy input and the minimum daily temperature to estimate latent heat.

Given input time series consisting of maximum and minimum temperatures and precipitation data, the program estimates catchment outflow resulting from rainfall and snowmelt. The program can apply either explicit or implicit algorithms to distribute the input data across the elevation bands. Additionally, the program provides an internal accounting of snowpack depth, soil moisture budget, sub-surface storage, and surface and sub-surface components of runoff.

For this study, the full emulation of the UBCWM within the Raven Hydrological Framework (Raven) has been used for hydrological simulation. The Raven model has been developed to allow hydrological simulation using a variety of hydrological modelling processes including the UBCWM (Craig, et al., 2020). Raven is funded, supported, and used by a number of agencies including Alberta Environment and Parks, Artic Net, BC Hydro, the City of Calgary, Environment and Climate Change Canada, Geoscience BC, National Research Council, Natural Resources Canada, Ontario Power Generation, TransAlta, and others. Therefore, on-going support is likely to be available for the Raven modelling platform in the future.

4.2 Model Development

The UBCWM captures the change in temperature and precipitation by elevation by subdividing the watershed into elevation bands. The range of the elevation bands have been selected considering the distribution of watershed area across each band. A copy of the watershed area vs elevation (hypsometric) curve is included in Figure 4-1, which also shows the elevation bands selected for modelling. Table 4-1 provides the watershed areas and average elevations of each of the elevation bands.

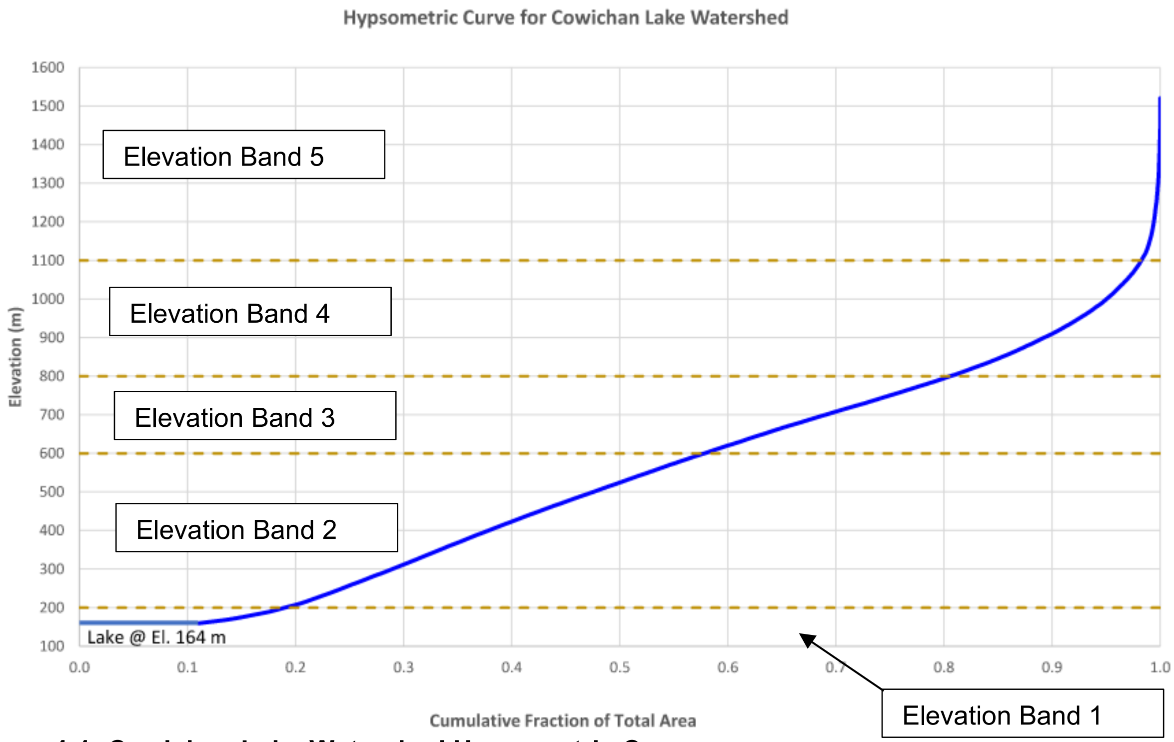

Figure 4-1: Cowichan Lake Watershed Hypsometric Curve

Table 4-1: Distribution of Land Cover Types in Cowichan Lake Watershed

Elevation Band ID	Elevation Range	Area (km^2)	% of Total Watershed Area
1	164 - 200	104	18%
2	200 - 600	230	39%
3	600 - 800	134	23%
4	800 - 1,100	109	19%
5	1,100 - 1,529	12	2%

As shown in Figure 2-8, precipitation in the watershed varies by elevation but also decreases from west to east across the watershed. Therefore, to capture the east to west variation in precipitation across the watershed, the Cowichan Lake Watershed has been divided into two subbasins. The boundary of the subbasins was selected along height of land between tributary streams to Cowichan Lake which roughly divides the watershed into two halves. Only the watershed area flowing into the lake has been subdivided; the lake surface area has been considered as a separate single subbasin for the purposes of modelling.

Raven uses the concept of Hydrological Response Units (HRU) to describe the physical character of the watershed. Each HRU consists of a unique combination of aspect, land cover, and soil type within each elevation band for each sub watershed. Using GIS spatial analysis tools and the underlying watershed mapping data sets, the watershed was divided into 178 HRUs and the surface area for each HRU was calculated.

As noted above, aspect was used as a parameter to characterize the watershed as it plays an important role in snowmelt for areas that are open with little forest cover. Given that net radiation from the sun plays an important role in snowmelt, those open areas of the watershed that are south facing would melt faster than those areas that are north facing. To account for this, the UBCWM lumps open areas into two groups, north facing aspects from NW (315 degrees) to NE (45 degrees), and all other aspects (East, South, and West). The north facing aspect areas account for approximately 48% of the watershed area, while the remaining 52% of the watershed has east, south, and west aspects.

4.3 Model Input

The UBCWM requires daily time series of maximum temperature, minimum temperature, and precipitation as climate inputs to generate daily watershed runoff. Most of the climate stations and all the long duration climate stations are in the eastern portion of the watershed (see Figure 4-2). Given the precipitation gradient from west to east across the watershed, and the influence of topography on precipitation and temperature, these stations are not likely representative of the watershed as a whole. Therefore, two spatially distributed (gridded) climate data sets have been used in the study for modelling.

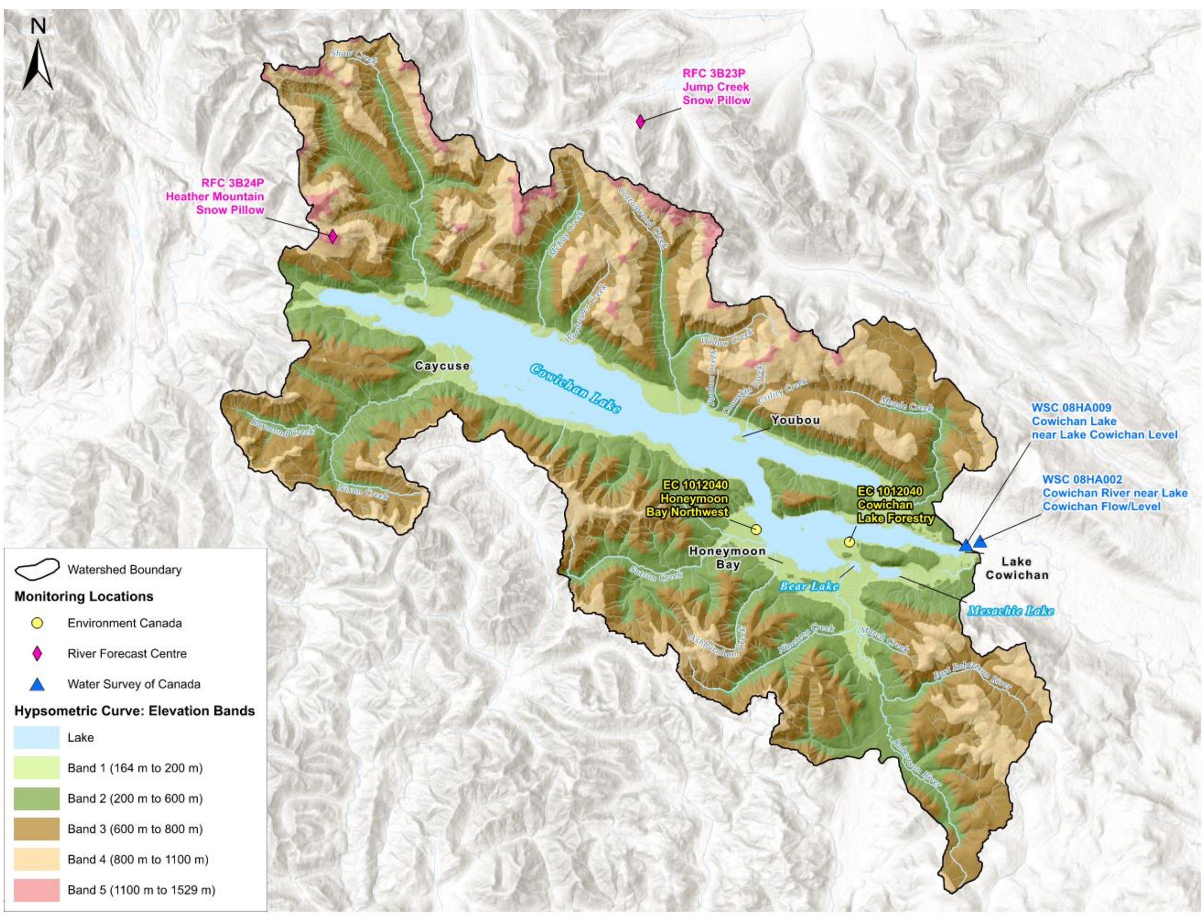

Figure 4-2: Locations of Climate and Hydrometric Stations used for Inflow Study

For model calibration and verification, the 1945 to 2012 PNWNAmet gridded meteorological dataset based on recorded climate data for the period from 1971 to 2012 was used[3]. This gridded meteorological data set has been derived by spatially interpolating metrological data recorded at regional climate stations accounting for topographical effects on temperature and precipitation (Wener, et al., 2018). It was important to use a dataset based on recorded climate conditions such that the metrological dataset and the recorded inflow data are temporally consistent for purposes of model calibration and verification.

Modeling inflow to Cowichan Lake under past and future projected climate conditions was based on downscaled global circulation model (GCM) output from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor, Stouffer, & Meehl, 2012). The downscaled GMC datasets have been downloaded from the Pacific Climate Impacts Consortium (PCIC)[4] for the ensemble of twelve GCM models which cover the widest range of climate projections for Western North America (Cannon A. J., 2015).

The downscaled GCM datasets are based on the Representative Concentration Pathway (RCP) RCP 8.5, representing the projected greenhouse gas concentrations under future business as usual conditions (projected 3 degrees to 4 degrees increase in global average temperature) (IPCC AR5 WG1, 2013). At the time of this study, RCP 8.5 was the most appropriate RCP for adaptation planning and has been used by PCIC in its Plan2Adapt tool[5].

For both the meteorological dataset and downscaled GCM datasets, time series of daily maximum temperature, daily minimum temperature, and precipitation were developed for each elevation band within the western sub-watershed, eastern sub-watershed, and for the lake areas. The time series for each elevation band was developed by first resampling the PNWNAMet meteorological dataset down to the same grid size as the downscaled GCM raster data prepared by PCIC for the CVRD[6]. GIS spatial analysis tools were then used to calculate the average maximum temperature, minimum temperature, and precipitation for each elevation band. The ratio of the average annual maximum temperature, average annual minimum temperature, and annual average precipitation calculated from the PNWNAMet meteorological dataset and the downscaled GCM data for the 1971 to 2000 period was used to adjust the PNWNAMet meteorological dataset for each elevation band to account for the higher resolution results.

To verify the gridded climate data, comparisons have been made between recorded data from Jump Creek Automatic Snow Pillow (ASP) station located in the adjoining watershed north of Cowichan Lake, climate data from Honeymoon Bay, and the adjusted daily PNWNAMet meteorological dataset calculated for elevation band 5 and elevation band 1, respectively. Although there is now an ASP at Heather Mountain within the Cowichan watershed, it was installed in 2015 and therefore, does not have a coincident record with the PNWNAMet meteorological dataset.

[3] PCIC, University of Victoria (2015), Daily Gridded Meterological Datasets, PNWNAMet, https://data.pacificclimate.org/portal/gridded_observations/map/ Accessed Februar7 2021.

[4] PCIC, University of Victoria (2019), Statistically Downscaled Climate Scenarios, BCCAQv2, https://data.pacificclimate.org/portal/downscaled_gcms/map/ Accessed February 2021.

[5] PCIC, University of Victoria (2020), Plan2Adapt Tool, https://services.pacificclimate.org/plan2adapt/app/

[6] CVRD, A Changing Climate – Climate Projections for Cowichan Valley Regional District, (2017) GIS-Raster Maps, https://www.cvrd.bc.ca/DocumentCenter/View/81963 Accessed February 2021

A comparison of the daily maximum temperatures recorded at the Jump Creek Automatic Snow Pillow (ASP) station with the daily maximum temperature time-series data based on the adjusted PNWNAMet meteorological dataset for elevation band 5 is shown in Figure 4-3. This shows that the gridded temperature data used for calibration matches well with recorded data. The root mean square error between the gridded temperature dataset and the recorded data at Jump Creek ASP is +/- 3.1°C which is reasonable given the uncertainty associated with interpolation of climate data within mountainous terrain with limited climate stations.

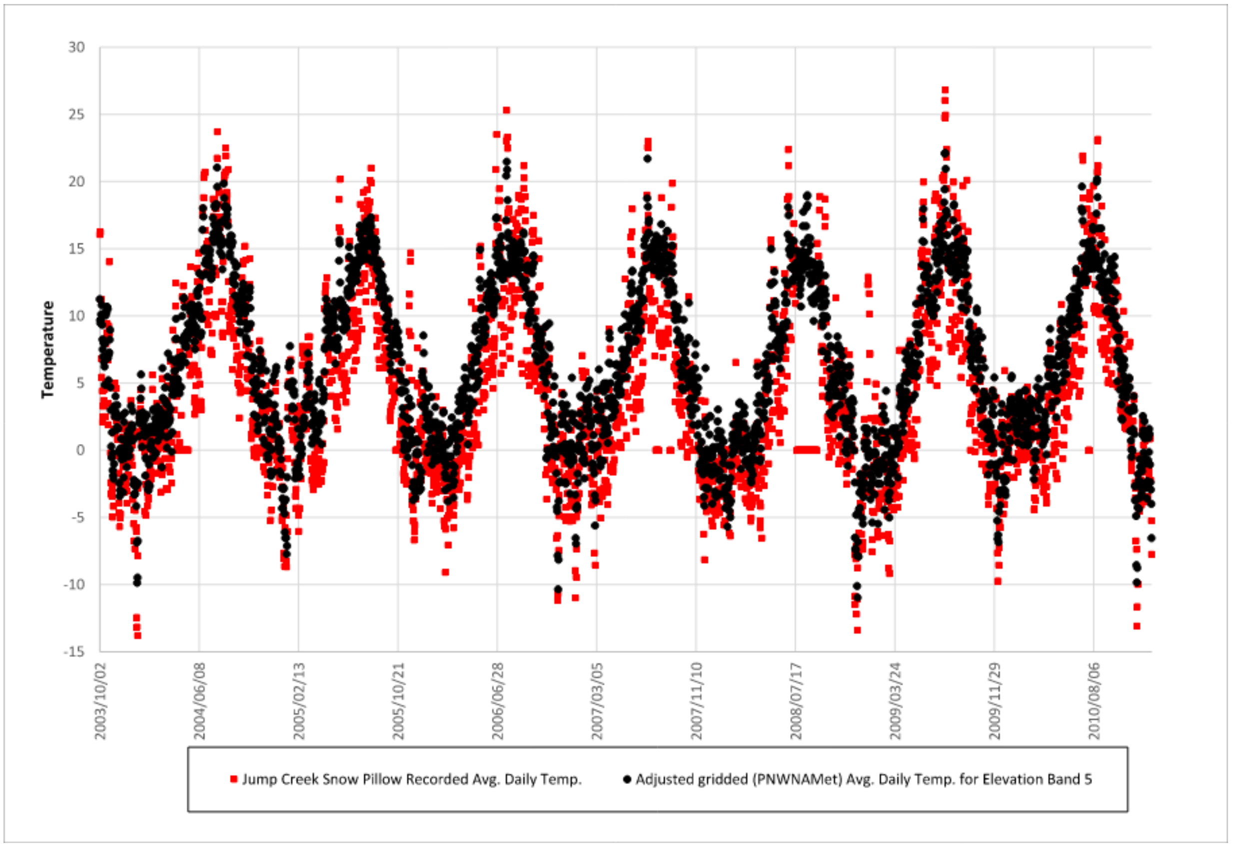

Figure 4-3: Comparison of Adjusted Gridded Temperature and Recorded Temperature

A comparison of the total normalized annual precipitation between the records at the Jump Creek ASP, Honeymoon Bay climate station, and the adjusted PNWNAMet metrological dataset is shown in Figure 4-4. The data has been normalized by dividing the total annual precipitation for each water year by the average total annual precipitation over the duration of the period of record for the station. This provides an indication of the relative magnitude of the annual precipitation, with values greater than 1.0 being wetter than average and values less than 1.0 being drier than average. Using the water year, the period from October through September the following year, as the basis for comparison reduces the influence of year-to-year storage in the watershed, as September is the month most likely to have the least amount of water storage in the watershed.

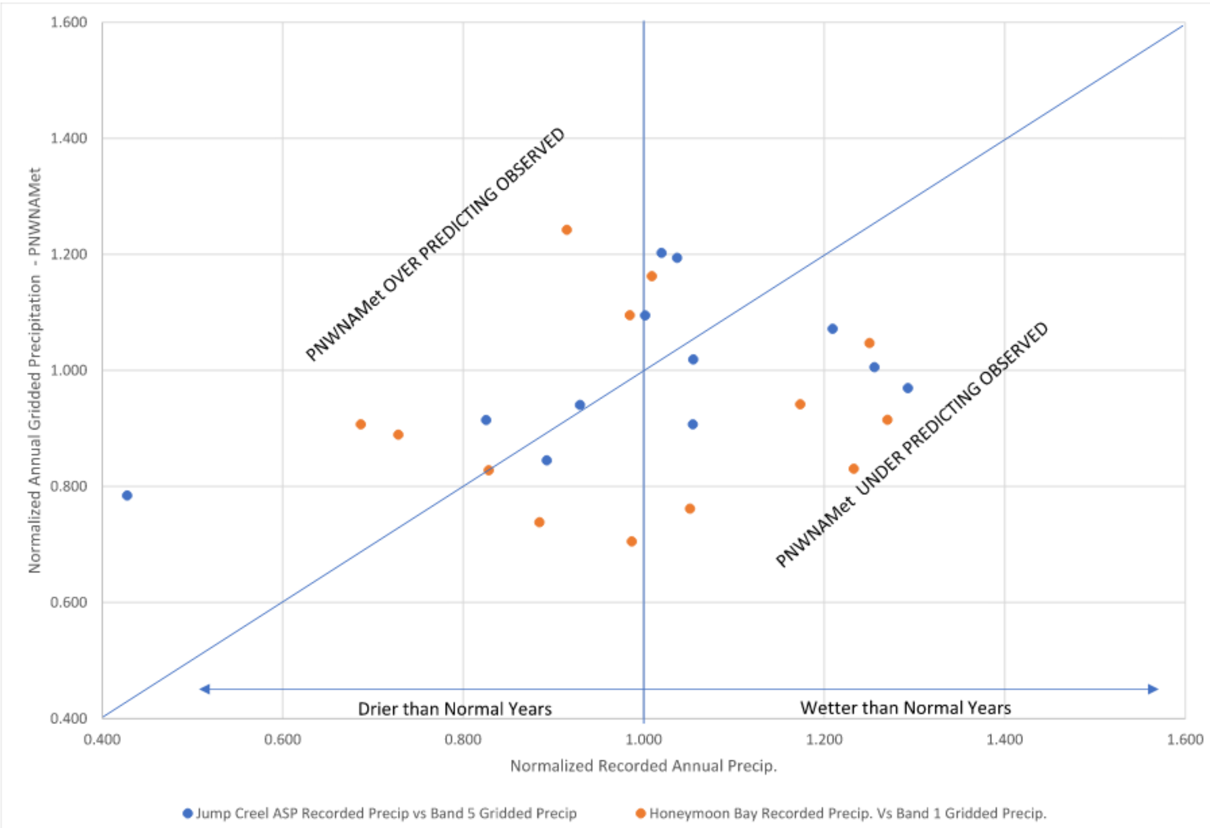

Figure 4-4: Comparison of Normalized Gridded Precip. and Normalized Recorded Precip.

In addition, normalizing the data can also provide indication if the adjusted PNWNAMet meteorological dataset is overestimating or underestimating the total annual precipitation for any given year. The diagonal line on Figure 4-4 represents years where the relative magnitude of the total annual precipitation is the same between the adjusted PNWNAMet meteorological dataset and the climate record. Any data points above the diagonal line represent a year where the adjusted PNWNAMet meteorological dataset overestimates the recorded precipitation while points below the diagonal line represent years where the adjusted PNWNAMet meteorological dataset underestimates the recorded precipitation. As shown in Figure 4-4, the adjusted PNWNAMet meteorological dataset tends to overestimate precipitation in drier years by 13% on average and underestimate wetter years by 10% on average compared to observed records.

Previous work by KWL has found similar biases with the PNWNAMet meteorological dataset in other mountainous areas of Vancouver Island, and it is likely a result of the limitations of the underlying interpolation in mountainous terrain with limited climate records. Even though there are limitations with the data set with regard to precipitation, the PNWNAMet meteorological dataset is considered to be the best metrological dataset available for hydrological model calibration and verification purposes.

4.4 UBCWM Model Calibration and Verification

After development of the UBCWM and input of watershed character parameters, the UBCWM model was run using maximum daily temperature, minimum daily temperature, and daily precipitation from the adjusted PNWNAMet meteorological dataset for the period from 1975 to 2010. The UBCWM results were then compared to back calculated net inflow records for the periods of 1998 to 2010 and 1985 to 1997 for model calibration and model verification, respectively. Two twelve-year periods where selected as they cover the most recent period of data available for the PNWNAMet meteorological dataset and allow for 10 years of model “spin up” between 1975 and 1984 to limit the influence of the assumed initial watershed conditions on model calibration and verification results.

The parameters in the model, including the threshold temperatures to determine the phase of precipitation (snow vs rain), the evapotranspiration parameters, the soil moisture storage, and the fast, medium, and slow runoff response factors, were adjusted until optimum fit between the model results and recorded lake inflows was found for the calibration period. The model results using the same calibrated parameters were then compared with the verification period to check if parameters are valid during other periods outside the calibration period. The selection of calibration parameters was carried out in a stepwise approach, first adjusting parameters which impact overall water balance on annual basis, then checking and adjusting parameters which influence the timing of runoff within the year.

A comparison of the modelled and observed total annual runoff on a water year basis is summarized in Table 4-2 (on the next page). For each water year, the relative error between the modelled results and the observed results is presented; the winter, spring, summer and fall relative errors are also presented for each water year. The comparison indicates that the model represents the water balance well on a long-term basis, with 0% difference between modelled and recorded inflows for the calibration period and 2% difference for the verification period. On an annual basis, the average relative error between model results and recorded inflow is +/-7% and +/- 6% for the calibration and verification periods, respectively. The largest positive relative error in annual volumes for the calibration and verification periods are 21% and 15%, respectively. The largest negative relative error in annual volumes for the calibration and verification period are -9% and -8%, respectively.

A review of the relative % error in annual volumes for the calibration and verification periods indicates that years with smaller annual inflow volumes tend to have positive % error while years with larger annual inflow volumes tend to have negative % error. This indicates that the model is overpredicting inflows (positive relative error) during drier years and underpredicting inflows (negative relative error) during wet years.

The results also indicate that the model tends to underpredict winter volumes and overpredict summer volumes. For the calibration period, the average winter error was -12%, while the spring, summer, and fall volume errors were 12%, 8% and 11%, respectively. The seasonal volume errors for the verification period are -12%, 14%, 20% and 28% for winter, spring, summer, and fall, respectively.

The reasons for the biases between the modelled flows and observed flows will be discussed further in Section 4.5.

Table 4-2: Cowichan Lake Inflow Model Calibration and Verification Results

			Total Volume (Million m^3)														
			Water Year (all)			Water Year (Winter)			Water Year (Spring)			Water Year (Summer)			Water Year (Fall)		
Period	Water Year	Nash-Sutcliffe Efficiency	Modelled	Observed	Rel Error %	Modelled	Observed	Rel Error %	Modelled	Observed	Rel Error %	Modelled	Observed	Rel Error %	Modelled	Observed	Rel Error %
Verification Period	1985	0.45	1,064	928	15%	195	233	-16%	421	276	53%	54	33	65%	394	387	2%
	1986	0.63	1,198	1,132	6%	473	535	-12%	412	347	19%	59	51	16%	254	199	27%
	1987	0.70	1,197	1,258	-5%	588	636	-8%	334	353	-5%	49	69	-29%	226	199	14%
	1988	0.59	1,092	1,052	4%	459	466	-1%	405	413	-2%	61	86	-29%	167	87	93%
	1989	0.57	1,167	1,041	12%	359	379	-5%	396	345	15%	67	42	60%	346	276	25%
	1990	0.47	1,185	1,117	6%	423	510	-17%	372	290	28%	93	95	-2%	297	221	34%
	1991	0.60	1,560	1,612	-3%	619	695	-11%	314	210	49%	116	104	11%	512	603	-15%
	1992	0.79	1,227	1,194	3%	727	803	-9%	192	160	20%	36	27	33%	272	204	33%
	1993	0.48	1,026	930	10%	198	263	-25%	489	412	19%	78	66	18%	261	189	38%
	1994	0.78	1,044	1,088	-4%	510	578	-12%	359	386	-7%	54	58	-6%	120	66	81%
	1995	0.76	1,310	1,314	0%	738	804	-8%	291	289	1%	58	24	138%	223	196	13%
	1996	0.62	1,509	1,637	-8%	631	745	-15%	329	352	-7%	45	40	11%	504	499	1%
	1997	0.32	1,609	1,671	-4%	513	593	-14%	595	601	-1%	132	177	-25%	369	300	23%
Calibration Period	1998	0.80	1,367	1,380	-1%	683	712	-4%	230	207	11%	45	38	20%	409	424	-3%
	1999	0.46	1,782	1,805	-1%	719	820	-12%	551	439	25%	90	184	-51%	421	363	16%
	2000	0.41	1,296	1,182	10%	463	460	1%	382	327	17%	82	93	-12%	369	301	22%
	2001	0.46	833	884	-6%	311	363	-14%	251	278	-10%	67	70	-3%	203	173	17%
	2002	0.64	1,338	1,367	-2%	586	673	-13%	403	345	17%	48	66	-28%	302	283	7%
	2003	0.75	1,189	1,301	-9%	497	594	-16%	424	445	-5%	39	31	23%	228	231	-1%
	2004	0.63	1,288	1,203	7%	483	532	-9%	264	207	28%	62	33	84%	479	430	11%
	2005	0.58	1,250	1,217	3%	526	549	-4%	335	354	-5%	60	55	8%	329	258	28%
	2006	0.65	1,258	1,328	-5%	596	736	-19%	309	299	3%	48	44	9%	306	248	23%
	2007	0.58	1,576	1,733	-9%	653	699	-7%	483	495	-2%	68	74	-9%	371	465	-20%
	2008	0.22	1,225	1,263	-3%	334	510	-34%	472	314	50%	99	94	5%	320	345	-7%
	2009	0.12	1,005	832	21%	216	251	-14%	423	319	32%	51	37	36%	316	223	41%
	2010	0.64	1,400	1,654	-15%	511	623	-18%	318	409	-22%	75	73	3%	495	549	-10%
	Averages																
	verification period	0.60			2%			-11%			14%			20%			28%
	calibration period	0.53			-1%			-13%			11%			7%			10%

4.5 UBCWM Model Performance

The comparisons between modelled and observed flows show that the model can not perfectly reproduce recorded inflows to the lake, especially the annual and seasonal variations in flows This is often due to the difficulty in selecting a single set of model parameters which represent watershed conditions under both extreme (wet and dry) as well as average conditions (Huang, et al., 2020). This limitation often results in hydrological models being calibrated with focus on the conditions the model will be used for (changes in average conditions over time, drought, or flooding). Given that the hydrological model is intended to provide Cowichan Lake Inflows to assess how water levels could change across the full range of water levels, the focus of the calibration and verification was to provide best fit for average conditions and not for extremes. However, despite this limitation, the magnitude of the error between model results and recorded inflow is reasonable and within limits expected for reasonable model calibration.

In addition, the limitations of the gridded climate data, especially the precipitation, also influence how well the model can reproduce recorded data. Figure 4-5 compares the % relative error between the modelled annual volumes and annual recorded inflow volumes for the calibration and verification periods.

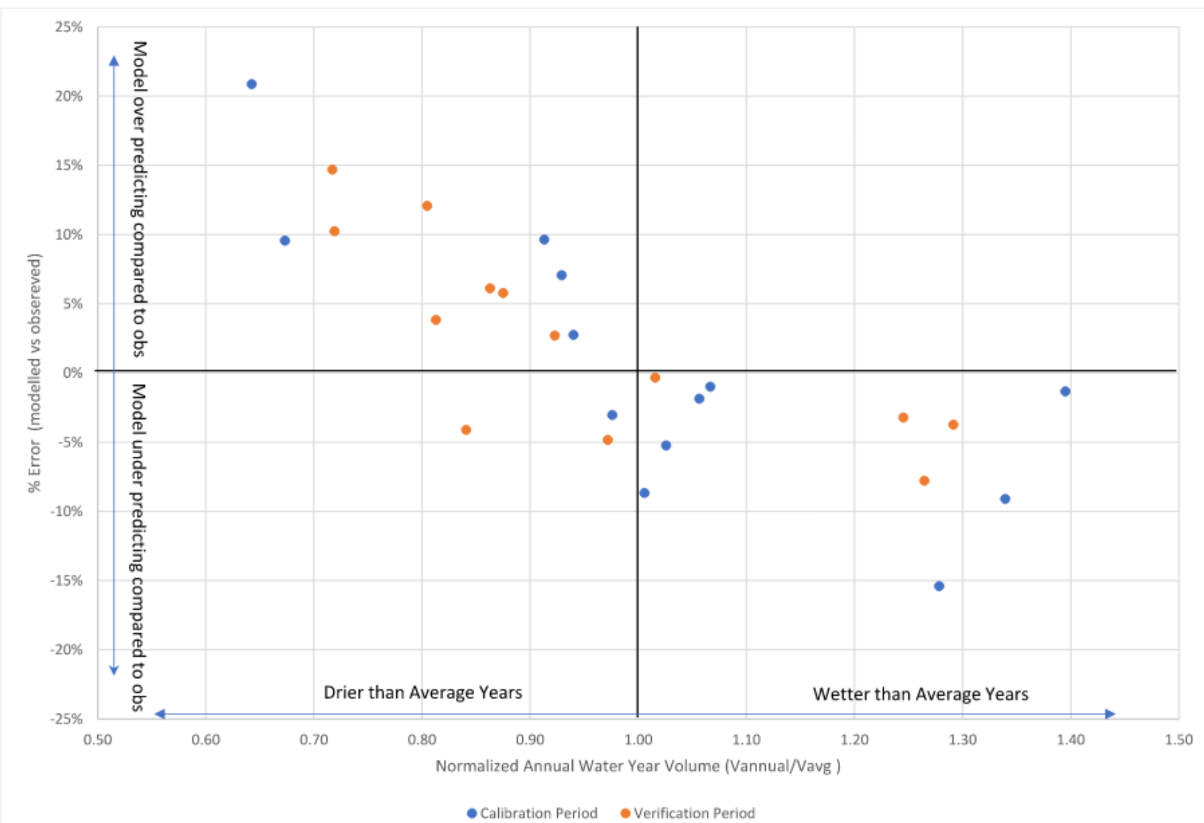

Figure 4-5: Comparison of Relative Error Between Modelled and Recorded Annual Inflow

The figures show how the model tends to over-predict annual volume, positive % error, in dry years by average of 6% and under predict annual volume, negative % error, in wet years by an average of 5.2%. As discussed previously in Section 4.3, the PNWNA data used for model calibration and verification tend to generally overpredict total annual precipitation in dry years and under predict total annual precipitation in wet years. The error between annual modelled volumes and the observed inflows is less than the average error between the PNWNA dataset and observed precipitation data for wet years and dry years.

The model provides a reasonable representation of the daily recorded flows. Figure 4-6 and Figure 4-7 show comparisons of the daily flow hydrographs from the model and the recorded inflow for the calibration and verification periods, respectively. The Nash-Sutcliffe Efficiency parameter provides an indication of the “goodness of fit” between two data sets and is used to assess the performance of hydrological models. A Nash-Sutcliffe Efficiency value of 1.0 represents a perfect fit between model results and observed data, where as a value of 0 represents a fully random comparison. The Nash Sutcliffe Efficiencies for the calibration and verification periods are 0.58 and 0.68, respectively. These values are considered to represent satisfactory to good fit between modelled and recorded values (Moriasi, et al., 2007).

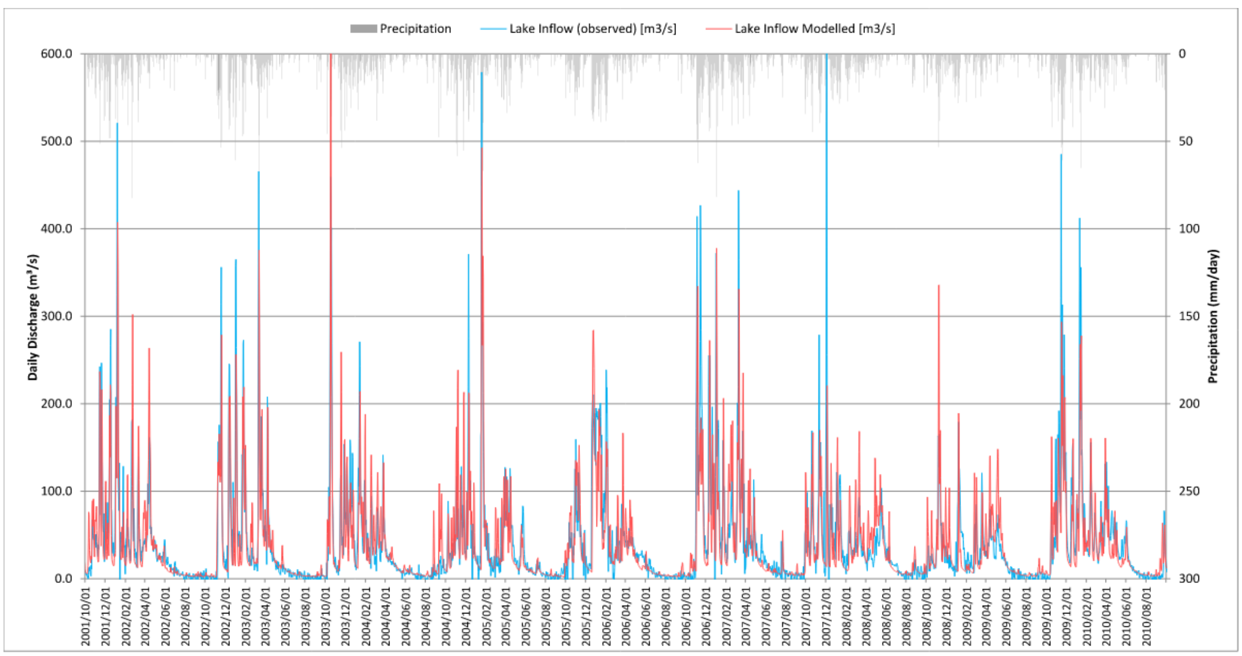

Figure 4-6: Comparison of Modelled and Observed Cowichan Lake Inflow for Calibration Period

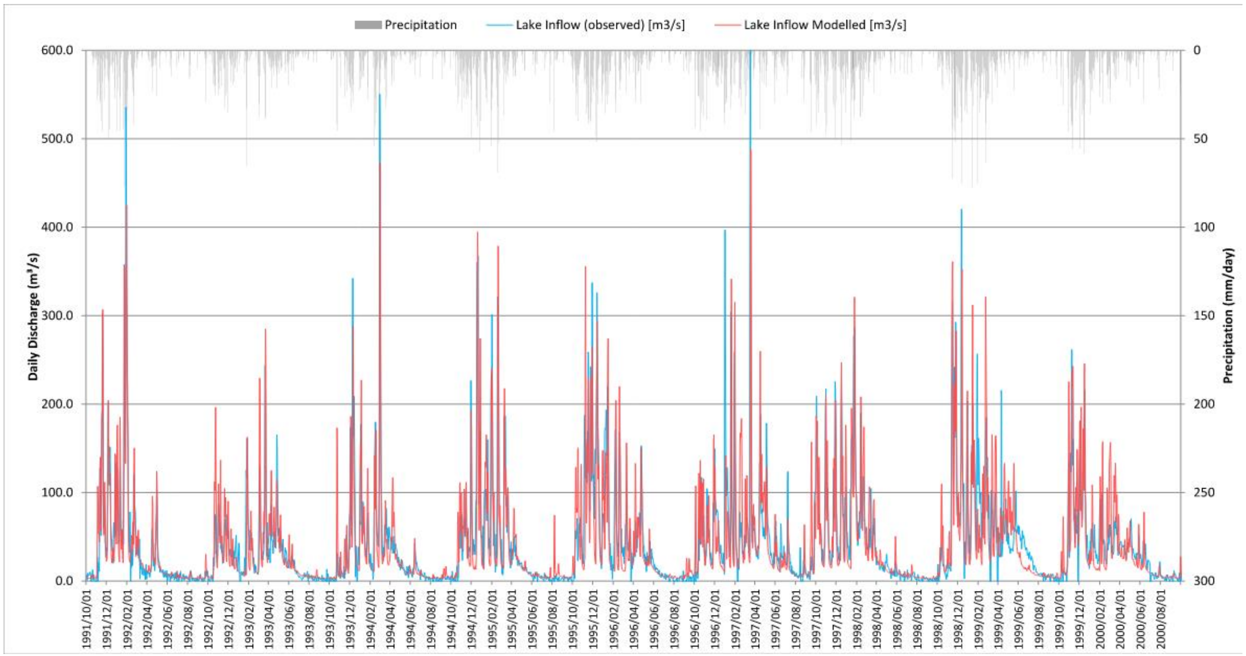

Figure 4-7: Comparison of Modelled and Observed Cowichan Lake inflow for Verification Period

Although model calibration indicates that the model may be underpredicting inflow in wet years and overpredicting inflow in dry years, this does not have significant impact on the underlying purpose of the model - to consider relative changes in inflow and water levels for both changes in the weir, and over time with climate change. Provided that results are compared within the model space (i.e., the model results for past climate are compared with model results for future climate, rather than recorded past climate with future model results) then the limitations of the fit of the model results to recorded values should not have as significant an impact.

One of the key changes to the hydrology in the watershed under climate change conditions is expected to result from changes in the magnitude of snowpack and the timing of snowmelt runoff. This is due to increase winter temperatures resulting in less days below freezing, even at higher elevation, resulting in precipitation falling as rain rather than snow. In addition, temperatures in future will tend to be below freezing for shorter periods of time resulting in less accumulation of snowpack.

Given the importance of the snowpack accumulation and melt process in assessing climate change impacts for the Cowichan Lake watershed, a comparison of the modelled snow water equivalent (SWE), a measure of the amount of water in the snowpack, to recorded SWE in and near the watershed has been carried out.

The SWE records from the Heather Mountain manual snow course, Jump Creek ASP, and the SWE model results for elevation Band 5 from the western sub-watershed have been used for comparison (see Figure 4-8). The results indicate a reasonable fit between the modelled and recorded SWE from the Heather Mountain snow course. The model tends to under predict SWE at Jump Creek. However, previous studies comparing SWE from Heather Mountain and Jump Creek indicated that Jump Creek data tends to over predict SWE conditions in the Cowichan Lake watershed (Chapman, 2011).

Although the comparison between SWE at Jump Creek and modelled SWE does not match regarding magnitude of the peak, the timing of the onset of runoff is similar between the modelled and recorded data. These comparisons provide good indication that the model is accumulating the appropriate amount of snowpack in the watershed and is providing a reasonable representation of snowmelt runoff processes in the watershed.

When comparing the modelled and recorded volumes, hydrograph shape, and modelled SWE, the calibrated UBCWM was considered suitable for modelling change in inflows to Cowichan Lake from past to future climate conditions.

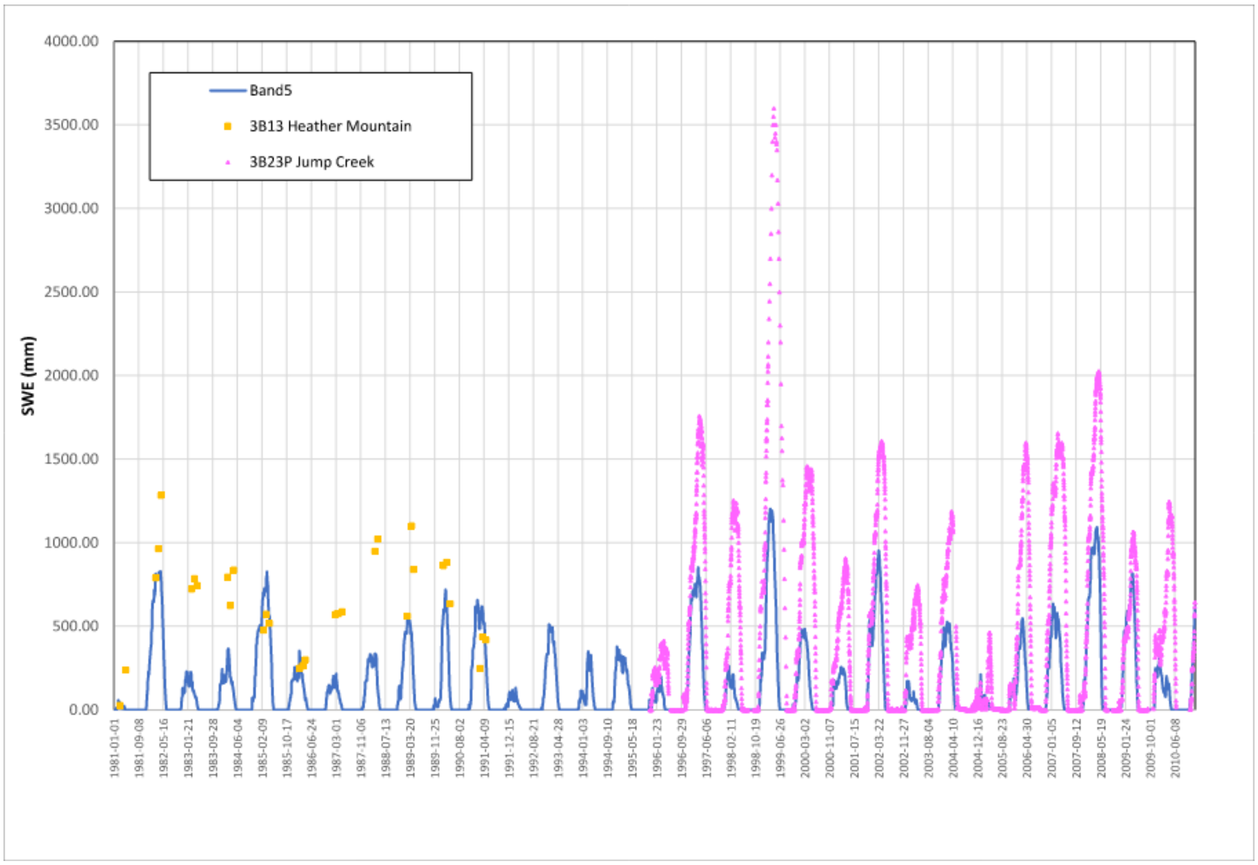

Figure 4-8: Comparison of Modelled and Recorded Snow Water Equivalent

5. Changes in Cowichan Lake Watershed Hydrology

5.1 Approach to Considering Climate Change

The calibrated and verified UBCWM hydrological model was used to simulate hydrological processes in the Cowichan Lake watershed under past and future climate conditions using an ensemble of twelve downscaled GCM model time series. As discussed previously in Section 4, the ensemble of downscaled GCM datasets cover the period from 1975 to 2099. The UBCWM model has been run over the entire period using the daily precipitation, maximum temperature, and minimum temperature for each elevation band within the western sub-watershed and the eastern sub-watershed. The climate time series for each elevation band has been adjusted using the same ratios as those derived for the PNWNAMet dataset. The UBCWM model output consists of the runoff into the lake from the watershed only, therefore direct precipitation and evaporation on the lake surface has been accounted for separately using MS-Excel.

To compare how climate change is projected to impact the hydrology of Cowichan Lake, the time period for the downscaled GCM has been divided into three 30-year subperiods, including the past climate (1981 to 2010), the 2050s climate (2030 to 2059), and the 2080s climate (2070 to 2099). The 30-year periods are based on the standard 30-year period used to calculate climate normal and is a suitable length to derive statistics for a specified climate condition (WMO, 2017).

5.2 Future Land Cover Conditions in the Watershed

Under future climate conditions, the hydrological modelling assumes no change in the proportions of land cover in the watershed. Essentially, the percentage of the watershed that is harvested and regenerating is assumed on average to be the same in the future as it was recorded in the VRI in 2018. This is a reasonable assumption for the purpose of modelling inflows for projecting future changes in lake levels due to the long-time frames (30 years) used for averaging model results.

One limitation to assuming consistent land cover now and into the future is the potential for hydrological changes due to wildfire. A review of literature on this topic indicates there is no clear evidence linking all wildfires to measurable changes in hydrological response (Robinne, Hallema, Baldon, & Buttle, 2020). However, one study focused on wildfire impacts on water supply watersheds in continental North America indicates that the impact may be related to the extent of wildfire, the severity of the fire, and timing of large storm events after the occurrence of wildfire (Hallema, et al., 2018).

Finally, the assumption of consistent land cover over time does not consider potential changes in vegetation cover as a result of climate change. For instance, reduction in Mountain Hemlock biogeoclimatic zone area as temperatures increase at higher elevations in the watershed. Although these changes will result in changes in the hydrology, they are anticipated to be relatively small driver of change compared to changes in climatic variables such as temperature and precipitation on the magnitude and timing of inflow to Cowichan Lake.

For the purposes of this modelling exercise, the range of future land cover conditions over space and time were assumed to be the same as the historical conditions used for model calibration and verification from 1982 to 2010. This is a reasonable assumption, in that, although land cover changes year to year, on average over the long term, the make up of watershed land cover is consistent. One exception to this would be wildfire impacts, which have not been accounted. The impacts of wildfire on the Cowichan Lake watershed, and the associated risks to water supply and quality, could be assessed in a future study.

5.3 Projected Change in Inflow to Cowichan Lake

A summary of the inflow model results, including direct precipitation and evaporation from the lake surface, for the ensemble of models is shown in Table 5-1. Figure 5-1 shows the minimum, 25th percentile, average, 75th percentile and maximum seasonal inflows to Cowichan Lake based on the ensemble of the twelve downscaled GCM models for 2050s and 2080s, respectively.

Table 5-1: Summary of Projected Changes in Seasonal Average Inflow to Cowichan Lake

Season	Average Daily Inflow to Cowichan Lake (m^3/s)			% Change in Inflow	
	Past Climate (1981 to 2010)	2050s Climate	2080s Climate	Past to 2050s Climate	Past to 2080s Climate
Winter (JFM)	63.5	62.8	69.2	-1.4%	8.4%
Spring (AMJ)	22.6	19.5	18.7	-15.7%	-18.2%
Summer (JAS)	5.9	4.2	3.6	-30.7%	-40.4%
Fall (OND)	57.6	66.4	70.7	14.5%	21.6%
Annual	37.3	38.1	40.4	2.1%	8.3%

Note: Inflow projections based hydrological model results using climate input from the ensemble of 12 downscaled GMC models from the CMIP5 provided by PCIC using RCP 8.5. The averages shown is the average of all twelve models and include direct precipitation and evaporation on the lake surface.

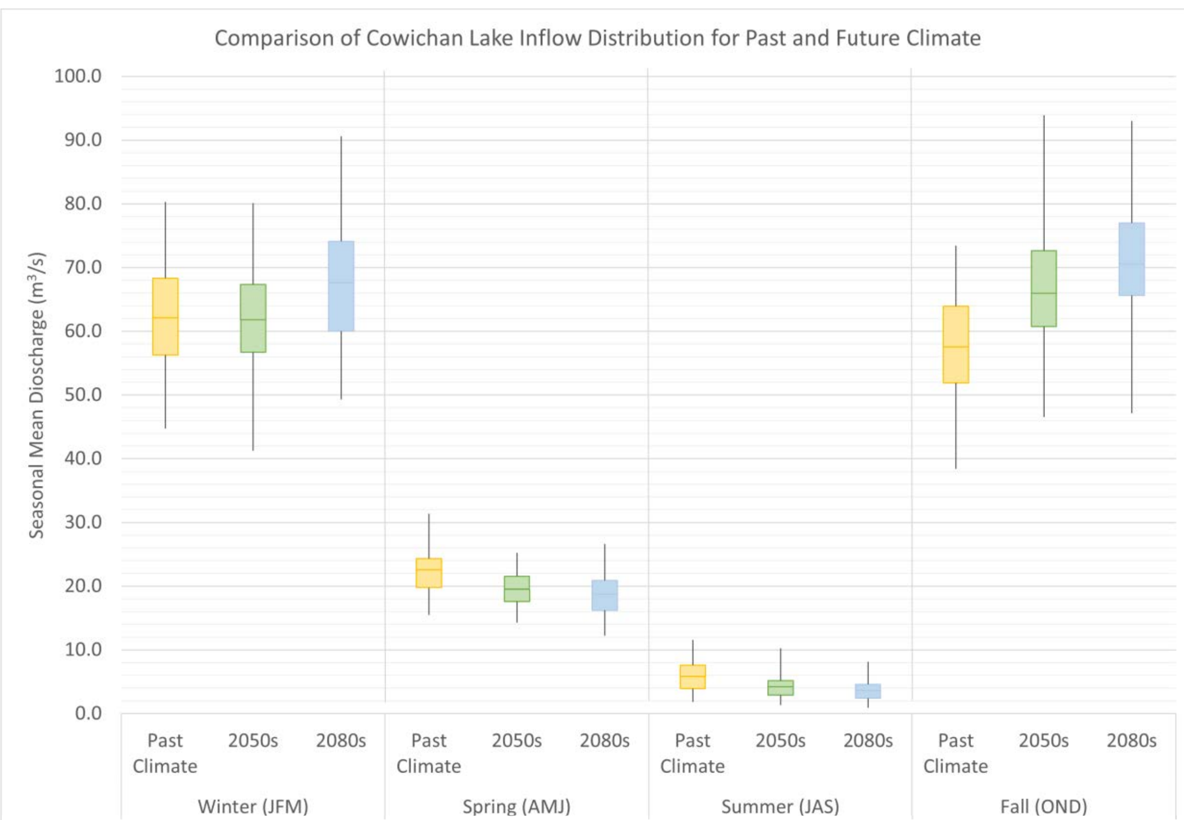

Figure 5-1: Modelled Current Climate and Projected Future Climate Inflows to Cowichan Lake

The annual average inflow to Cowichan Lake is projected to slightly increase in the future, 2.1% by the 2050s and 8.3% by the 2080s, which corresponds to the projected increase in annual precipitation. As seen in Table 5-1, Figure 5-1, and Figure 5-2, the majority of the increase occurs in the fall and winter, as a result of the increase in precipitation during fall and winter storms and increased runoff due to more precipitation falling as rain than snow in the watershed. However, these changes occur during the "off control" period when the gates and boat lock at Cowichan Lake Weir are fully open and there is no control of lake levels and river flows. During the control period in the spring and summer, the average inflow to Cowichan Lake is projected to decrease by 30.7% and 40.4% by the 2050s and the 2080s, respectively. These are similar changes to those observed in the historical record since the 1960s. These projected changes in inflow will have the most impact on water availability in Cowichan Lake for supporting Cowichan River flow during spring and summer.

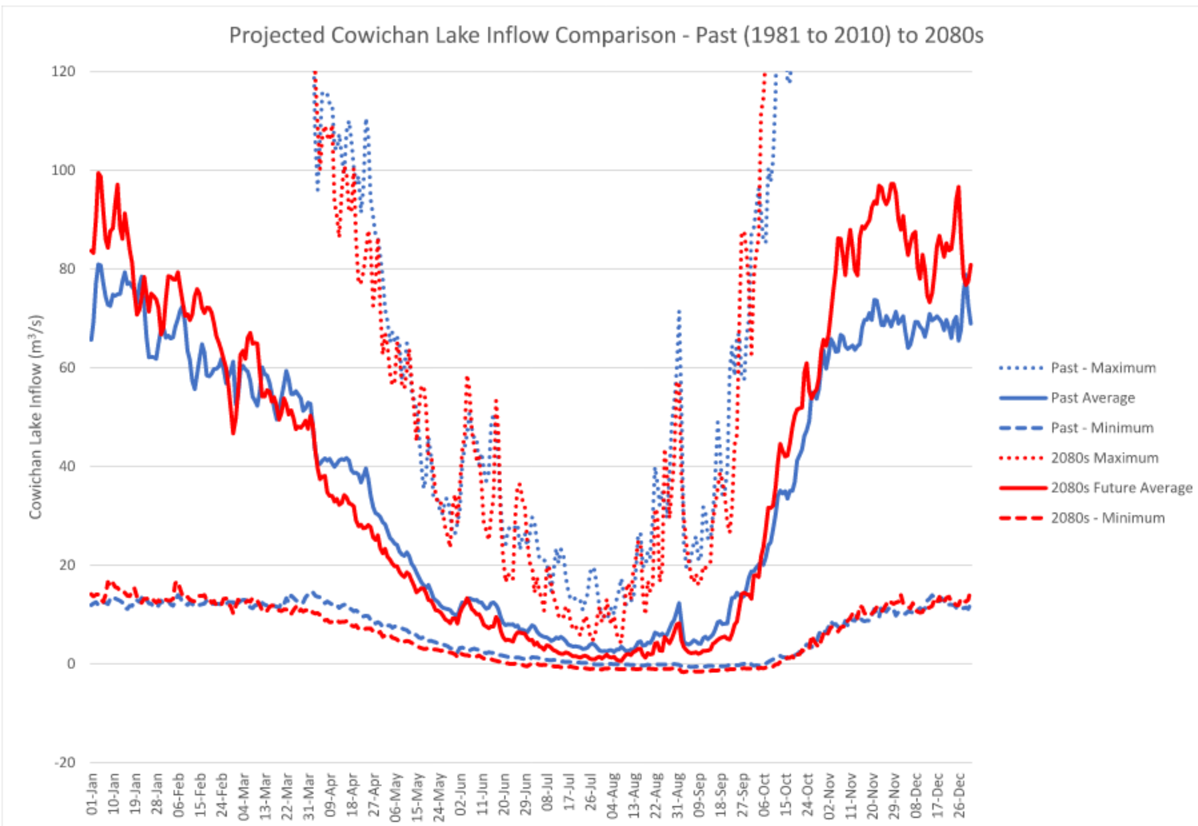

Figure 5-2: Projected Cowichan Lake Inflows for 2080s

5.4 Why is Summer Inflow Changing?

As discussed previously, the reduction in spring and summer Cowichan Lake inflow is most influenced by:

1. Reduced summer precipitation and longer dry spells.
2. Reduction in snowpack and spring snow melt contribution.
3. Increase in evaporation from the lake.

The changes in summer precipitation and dry spells have been discussed previously in Section 2.5. However, the UBCWM hydrological model results give us a better understanding of changes in snowpack and evaporation from the lake, as discussed below.

Snowpack

The UBCWM models accumulation and melt of snowpack within each of the elevation bands. The projected change in SWE is shown in Table 5-2.

Table 5-2: Change in Modelled SWE (mm) from Past and Projected Climate

SWE Parameter	Period of Time	
	2050s	2080s
Median Change in SWE	-80%	-97%
Range of Change in SWE	-52% to -95%	-69% to -100%
Values represent the percentage change from the past climate period (1981 to 20201) of the median and range of the average annual maximum SWE for all models in the CMIP5 downscaled GCM ensemble.		

These results indicate the sensitivity of the snowpack to projected increasing temperatures in the watershed. As temperatures rise, the number of days that the temperatures fall below zero diminishes, even at high elevation. Therefore, more precipitation in the future will fall as rain rather than as snow. As presented earlier, this results in reduced spring inflows as less water is available in the snowpack to supply the lake in the form of snowmelt.

Evaporation

The modelled seasonal average evaporation from Cowichan Lake is shown in Table 5-3. The values are shown as an equivalent flow rate for comparison with inflow values. The results indicate that projected increasing summer temperatures result in increases in spring and summer evaporation by 14% and 24% by the 2050s and the 2080s, respectively. This projected increase in evaporation is responsible for roughly 20% in the projected change in summer inflows.

Table 5-3: Projected Changes in Seasonal Average Evaporation from Cowichan Lake

Season	Average Daily Evaporation from Cowichan Lake (m^3/s)			% Change	
	Past Climate (1981 to 2010)	2050s Climate	2080s Climate	Past to 2050s Climate	Past to 2080s Climate
Winter (JFM)	0.3	0.4	0.5	35%	64%
Spring (AMJ)	1.5	1.7	1.8	14%	24%
Summer (JAS)	2.0	2.3	2.5	14%	24%
Fall (OND)	0.8	1.0	1.1	23%	39%
Note: Evaporation projections based hydrological model results using climate input from the ensemble of 12 downscaled GMC models from the CMIP5 provided by PCIC using RCP 8.5. The averages shown is the average of all twelve models.					

6. Cowichan Lake Weir and Proposed Upgrade

6.1 Existing Weir

The Cowichan Lake Weir is located at the outlet of Cowichan Lake near the Town of Lake Cowichan (see Figure 2-1). The existing weir was constructed in the 1950s under Conditional Water Licence C023085 and expanded in the 1960s under Conditional Water Licence C029542 to supply water for the Crofton Pulp Mill. The weir is 0.97 m high and is authorized to store 49,700 acre-feet (approximately 60 million m^3) of water in Cowichan Lake. The existing lake surface area is approximately 62 km^2.

The weir includes a timber crib weir structure, a control structure consisting of four overshot floodgates used to control lake level and flow in the Cowichan River, and a boat lock to allow navigation between the lake and the river. Under the water licences, the weir can be controlled from April 1 to November 5 each year. The lake level is to be controlled at or below the 2013 modified rule curve defined in the licences. The licence requires that the weir be operated to maintain a minimum flow of 250 cfs (approximately 7.0 m^3/s) in the Cowichan River downstream of the weir.

A photo of the existing weir is provided below in Photo 6-1.

Photo 6-1: Existing Weir (Source: *Cowichan Watershed Board*)

The typical operation of the Cowichan Lake Weir over the year is summarized as follows.

1. The lake is typically full (above the weir crest) during the winter (November - March), with uncontrolled outflow in proportion to the seasonal rainfall.
2. The lake level is maintained near the weir crest elevation during spring (after April 1) and early summer, provided sufficient inflow to support flows in the Cowichan River.
3. The lake drops below the weir crest level in late summer to supply minimum Cowichan River flows in the absence of rainfall.
4. The lake gradually fills again in the fall with increasing rainfall.

Lake level and flow in the Cowichan River is guided by the 2013 Cowichan Lake Rule Curve (KWL, 2012) and the 2008 Cowichan Lake Operating Protocols (Vessey, 2008).

6.2 Datum

The elevations reported in this study will be presented in Canadian Geodetic Vertical Datum 2013 (CGVD2013) recently adopted in the last year. Much of the previous Cowichan Lake work references the CGVD28 datum (adopted in 1935). There is a difference of about 20 cm between these two reference datums at Cowichan Lake. The difference is not constant and ranges from 0.197 m at the east end of the lake to 0.218 m at the northwest end. CGVD2013a datum is below CGVD28 datum, or in other words, the elevation of a common point, expressed with reference to CGVD2013a is higher than if expressed with reference to CGVD28.

6.3 Proposed Weir Raising

In 2018, a structured decision-making process was carried out to help explore future water use needs alongside a range of different potential water supply and storage options which resulted in the preparation of the Cowichan Water Use Plan (Cowichan WUP). The preferred alternative recommended in the Cowichan WUP includes an upgrade to the weir that would increase the height of the weir by 0.7 m, to a total height of 1.67 m (compared to 0.97 m for the exiting weir).

Raising the weir would involve:

- replacing the existing weir structure with a raised structure;
- upgrading the boat lock structure with new electrical/mechanical components;
- upgrading the control structure with raised gates, new electrical and mechanical components; and
- installing a new fishway.

The proposed weir raising is intended to store additional water in the spring to support flow releases in summer and early fall and to improve resiliency under projected climate change conditions. Details of the proposed raised weir are included in the Cowichan Lake Weir Final Design Report prepared by Stantec dated December 9, 2021.

6.4 Note on Weir Crest Elevation

As part of detailed design work being carried out for proposed upgrades to the Cowichan Lake Weir, a topographic survey was carried out on April 21 and April 22, 2021, to confirm the geometry of the existing weir. The results of this survey indicate that the average crest elevation of the existing weir is 162.65 m about 0.08 m higher than the elevation shown in the original record drawings and the crest elevation used in past analyses. Further details of the survey and elevation of the weir crest are summarised in the technical memo prepared by Stantec, dated June 11, 2021.

As outlined in the Cowichan Lake Weir Final Design Report (Stantec 2021), the proposed weir design assumes that the existing weir will be raised the full 0.7 m recommended by the Cowichan WUP. Therefore, the crest of the proposed weir is 163.35 m.

The modelled water level results for the existing weir and proposed weir presented in this memo account for the change in the existing weir crest elevation noted above.

6.5 Existing and Proposed Weir Rating Curve

The proposed raised Cowichan Lake Weir will alter the Cowichan Lake level versus river flow relationship, or rating curve, over a range of lake levels between the existing weir crest and the mean annual high water mark (HWM) elevation (El. 164.2 m). The proposed weir upgrades have been designed to limit impacts on extreme high-water levels in the lake which results in the lake level vs river flow rating curve for the existing weir and proposed raised weir to be the same above the mean annual HWM.

The rating curves for the existing weir and the proposed raised weir were developed for two operating conditions. The first is the operating condition with the boat lock closed which is typical on-control operating condition when the weir and gates are controlling water levels through spring and summer.

The second condition is with the boat lock open which is the assumed operating condition for the off control period when the weir and gates are not controlling water level or flows during later fall and winter.

The rating curves for the two operating conditions for the existing weir and proposed weir were developed using a HEC-RAS computational hydraulic model and was carried out by Stantec as part of the Cowichan Lake Weir Design Project. A comparison of the rating curves for the existing weir and proposed raised weir with and without the boat lock open are provided in Figure 6-1.

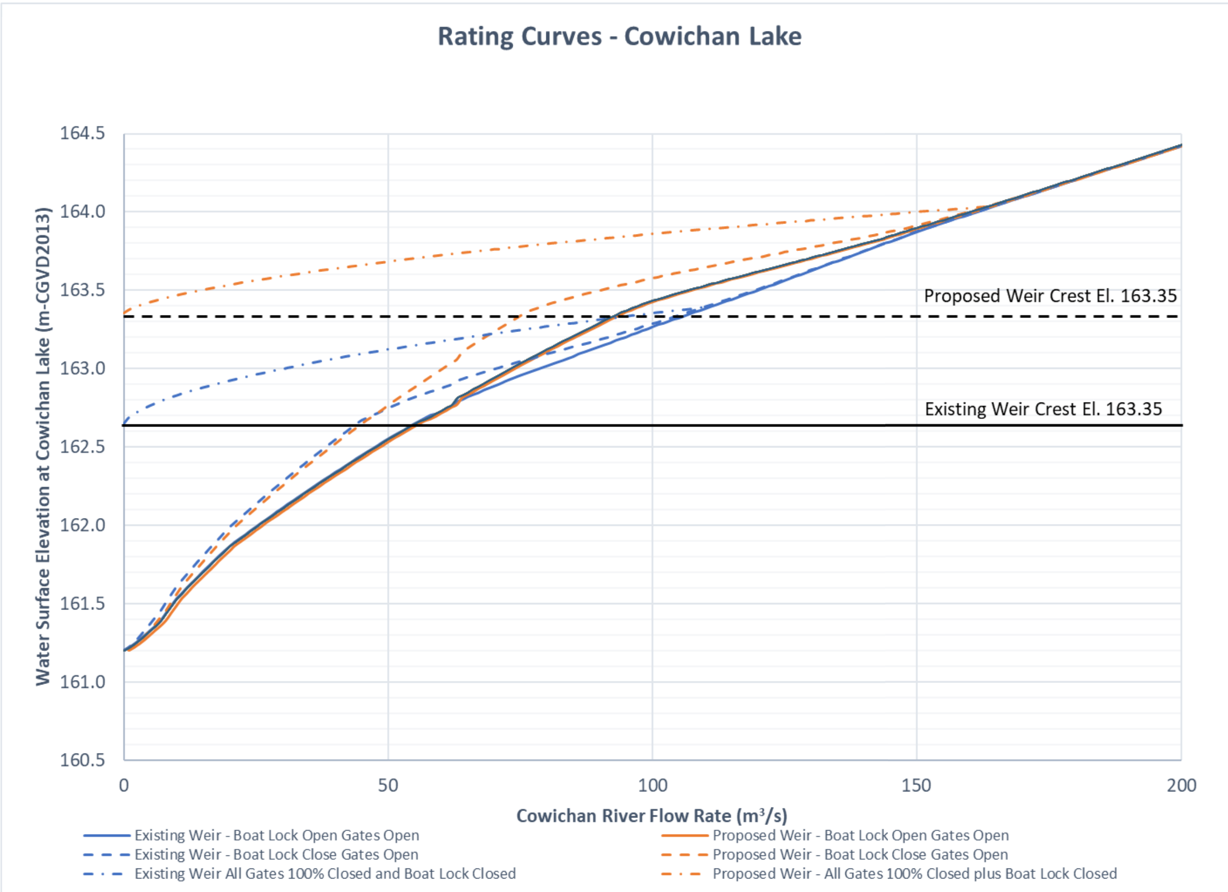

Figure 6-1: Lake Level vs. River Flow Rating Curves for Existing and Proposed Raised Weir

7. Lake Level Analysis

7.1 Cowichan Lake Operational Model

The Cowichan Lake Operational Model simulates how the weir, as well as operation of the gates and boat lock at the outlet of Cowichan Lake, affects lake level and river discharge throughout the year. The operational model was previously used in water management studies for Cowichan Lake, including the Cowichan WUP. The model can be used to assess how lake level and river flow change because of:

- changes in weir operation and prescribed outflow schedule;
- increasing storage by either raising the weir structure and/or pumping; and
- projected future changes in inflow to the lake.

The model simulates lake level and river discharge using water balance calculation with daily timestep based on a simple mass balance equation:

$$I - O = \Delta S / \Delta t$$

Where Δt is the model time step, I is the average net-inflow over Δt, O is the average outflow over Δt, ΔS is the change in storage in the lake over Δt.

7.2 Application of Cowichan Lake Operational Model

The model input is either historical back-calculated inflow using recorded lake level and river discharge or projected inflow using output from the UBCWM hydrological model. The operational model output is lake level and river flow which are a function of:

- either the control of the gates at the Cowichan Lake Weir during the operation period; or
- the uncontrolled lake level discharge relationship in the channel downstream of the weir during the period when the gates at the Cowichan Lake Weir are not operating.

Change in water storage in the lake is calculated as the change in lake level multiplied by the lake surface area. Note that for the purposes of the operational model, the lake surface area is assumed to be constant over the range of the modelled lake levels.

A schematic of the model logic is included in Figure 7-1 and further details about the model can be found in the Cowichan Lake Operational Model Technical Memorandum, prepared by KWL as part of the Cowichan WUP project in 2017 (included in Appendix D-1).

The Cowichan Lake Operational Model was run for two scenarios to simulate water levels for the existing weir and the proposed raised weir. The assumed operating rules for the two scenarios are:

1. Existing weir with current operating guidelines in accordance with the 2013 Cowichan Lake Rule Curve and the 2008 Cowichan Lake Operation Protocols (considered the status quo).
2. Proposed raised weir operated using the proposed operation protocols recommended in the 2017 Cowichan WUP.

The model selects the appropriate operating condition rating curve to use during different periods of the year. The on-control period starts when water levels drop below the existing weir crest after April 1 in accordance with the requirements of the Water Licence for Cowichan Lake Weir and the 2008 Cowichan Lake Operating Protocols. For the operating condition with the proposed weir, the on-control period starts when the water levels drop below the proposed raised weir crest after March 1 in accordance with the operational recommendations in the Cowichan WUP.

Ending the control period is an operational decision that varies from year to year depending on reservoir conditions and weather forecasts. For the purposes of modelling, both the existing and proposed weir operating conditions, it is assumed that the off-control period ends when the lake level rises above the existing or proposed weir crest after October 1 or on November 7, which ever comes first. The actual operation of the existing weir usually involves moving to the off-control period before the lake level reaches the weir crest which results in more flow being released into the river as the lake level rises. Therefore, the assumptions in the model are assumed to be conservative and may result in slightly higher initial peak water levels in fall compared to observed conditions.

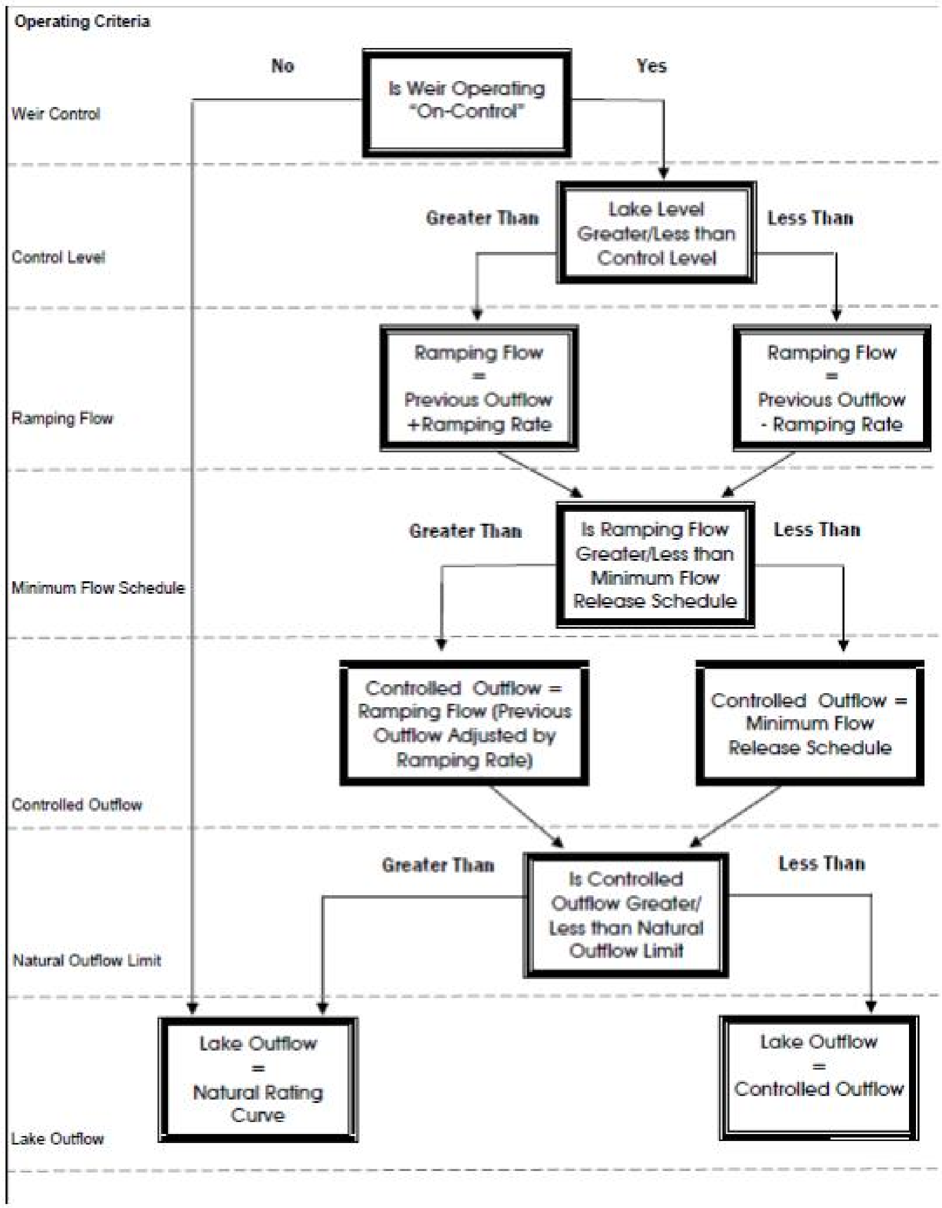

Figure 7-1: Cowichan Lake Weir Operational Model Logic Diagram

The water level scenarios use an ensemble of modelled inflows to Cowichan Lake based on climate projections from ten downscaled Global Circulation Models (GCM) prepared by PCIC (discussed previously in Section 5.1). The ensemble of models helps understand the range of projected inflows and thus the range and uncertainty in projected changes in lake level and river flow. However, in order to carry out the analysis of projected impacts to the shoreline of Cowichan Lake as a result of changes in lake level, a single time-series is required. Using the average of the projected lake level across all the models in the ensemble would remove the internal consistency of the model approach (i.e., taking the average of the model ensemble results would combine years where snowmelt is projected with other years where snowmelt was not projected for instance); the average also does not provide a good indication of the inter-annual variability in inflows and thus lake levels.

Therefore, a modelled lake level time series based on inflows projected from a single GCM model was selected for assessing changes in lake levels as a result of climate change. The single lake level time series was selected by comparing the results of the various GCM projections with the ensemble and selecting a lake level time series which provided reasonable variability within the projected range of ensemble model results and had values near the average. Based on this review, the lake level time series from the Cowichan Lake Operational Model based on inflows projected using the CanESM2-r1 GCM model was selected. As a comparison to the other GCMs in the ensemble, the CanESM2-r1 GCM model is ranked the second highest representative GCM model for the Western North America region (Cannon A. J., 2015).

The selected lake level time series is presented Figure 7-2 and Figure 7-3 in and for the existing weir condition and proposed raised weir condition, respectively. The figures show how the lake level regime is projected to change as a result of changes in inflow due to climate change for past climate, 2050s climate, and 2080s climate. The figures also include the range of lake level results based on the full ensemble of GCM projections. This comparison indicates that the selected lake level time series falls within the uncertainty range of the future projected lake levels and that the selected time-series is near the average of the ensemble of projected lake levels based on all the full ensemble of GCM models.

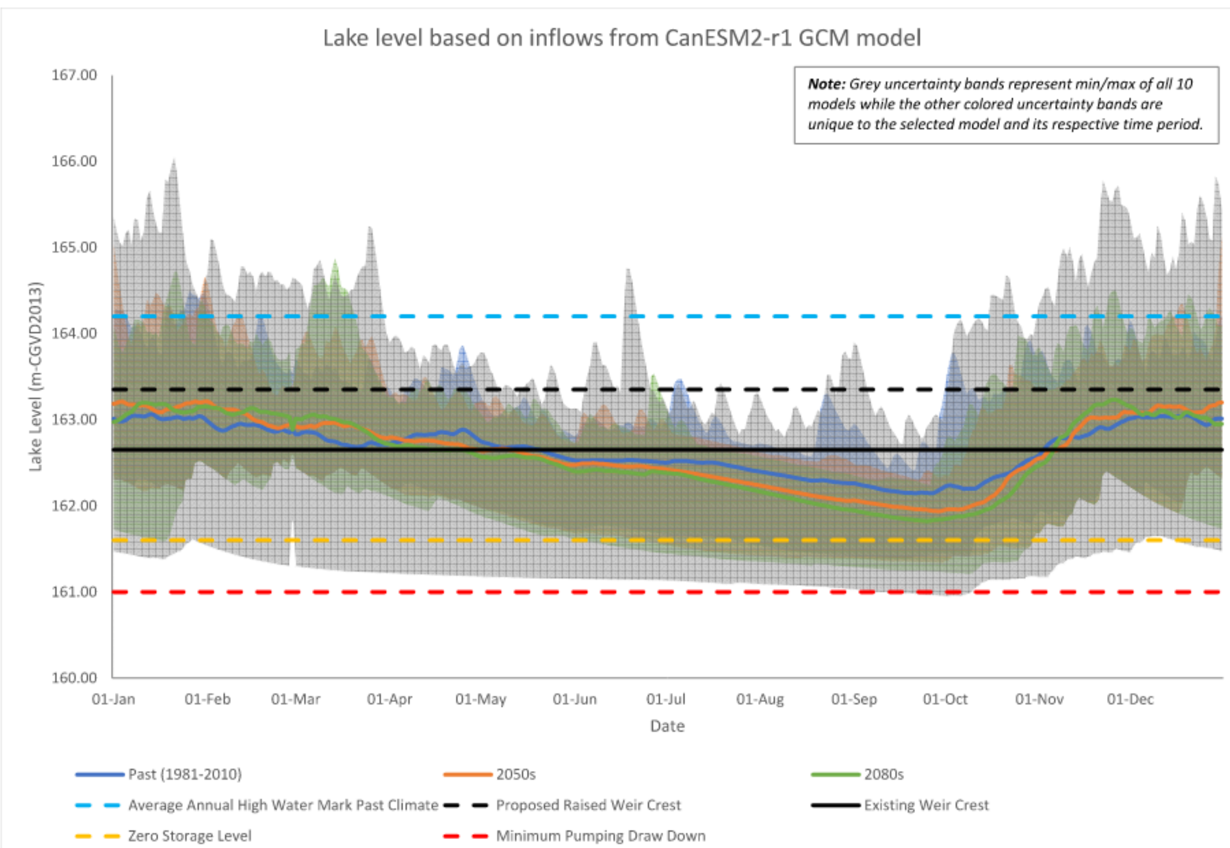

Figure 7-2: Modelled Lake Levels for Past and Future Climate Conditions with Existing Weir

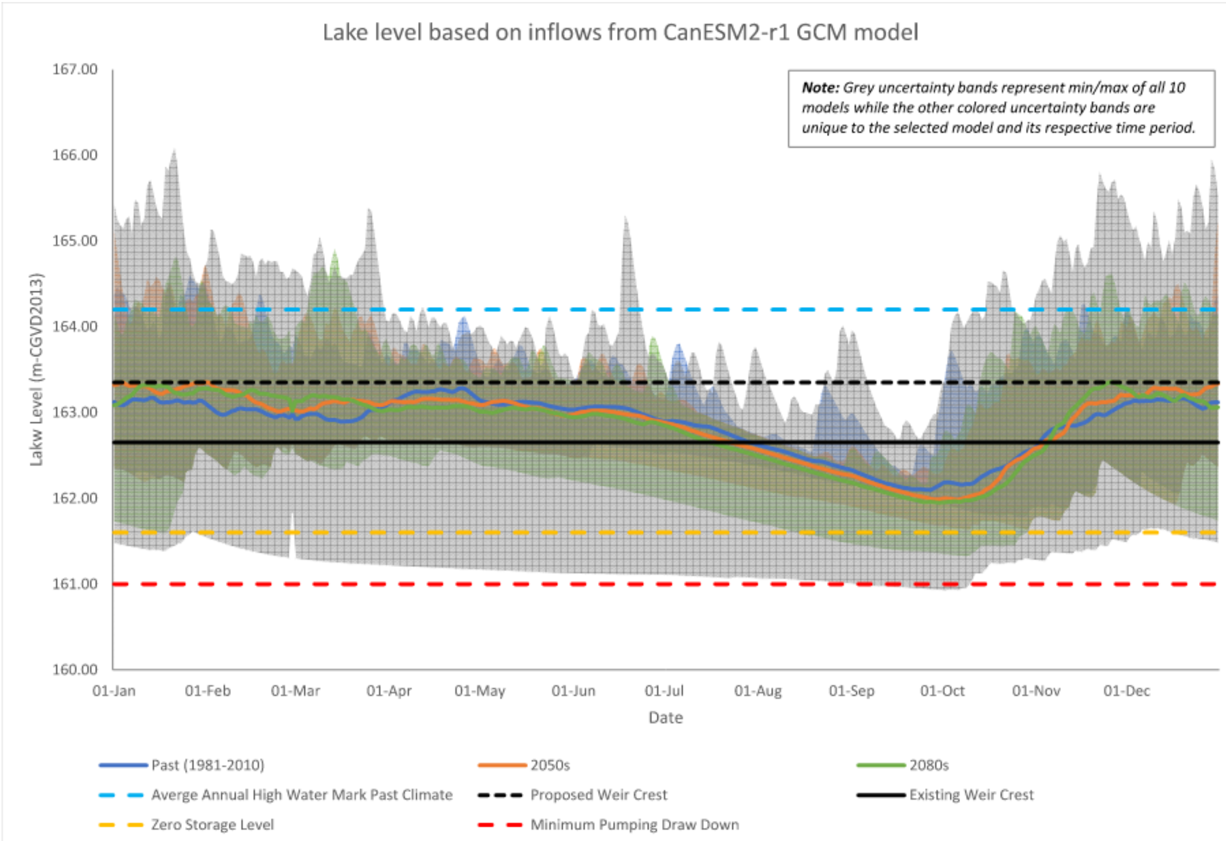

Figure 7-3: Modelled Lake Levels for Past and Future Climates with Proposed Raised Weir

8. Lake Level Frequency Comparisons

8.1 Changes in Lake Level Frequency

The results of the lake level analysis that used the CanESM2-r1 GCM model climate projections were selected to assess how lake level is projected to change as a result of the proposed raised Cowichan Lake Weir. Figure 8-1,

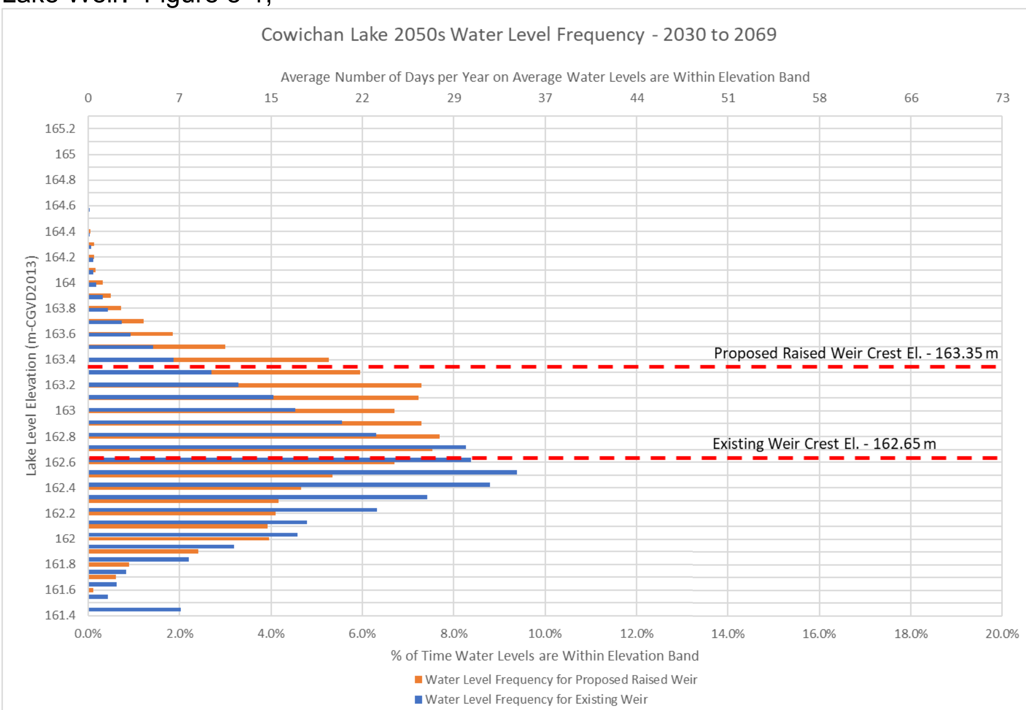

Figure **8-2**, and Figure 8-3 provide comparisons of the lake level frequency for the existing weir and the proposed raised weir under past climate (1991 to 2020), projected future climate for the 2050s (2040 to 2069), and projected future climate for the 2080s (2070 to 2099), respectively. The comparison of lake levels under past climate conditions uses recorded lake levels for the existing weir and modelled lake levels using recorded inflows for the proposed weir. The comparison of lake levels under future climate conditions is based on modelled lake levels using projected inflows to Cowichan Lake.

The figures show the length of time (as a percentage of the year and as an average number of days per year) that lake levels fall within a range of 0.2 m increments of elevation. This shows how the lake level frequency is projected to change with the proposed upgrades to the weir, as well as over time.

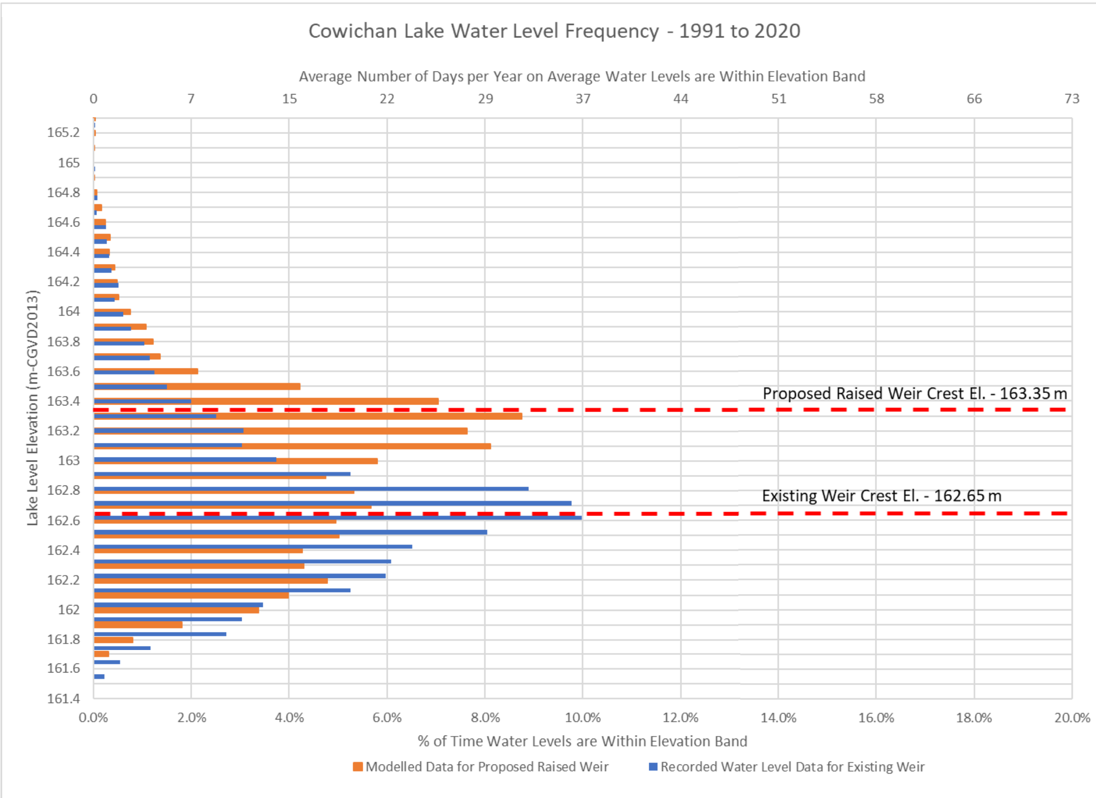

Figure 8-1: Lake Level Frequency for Existing and Raised Weir Scenarios (1991 to 2020)

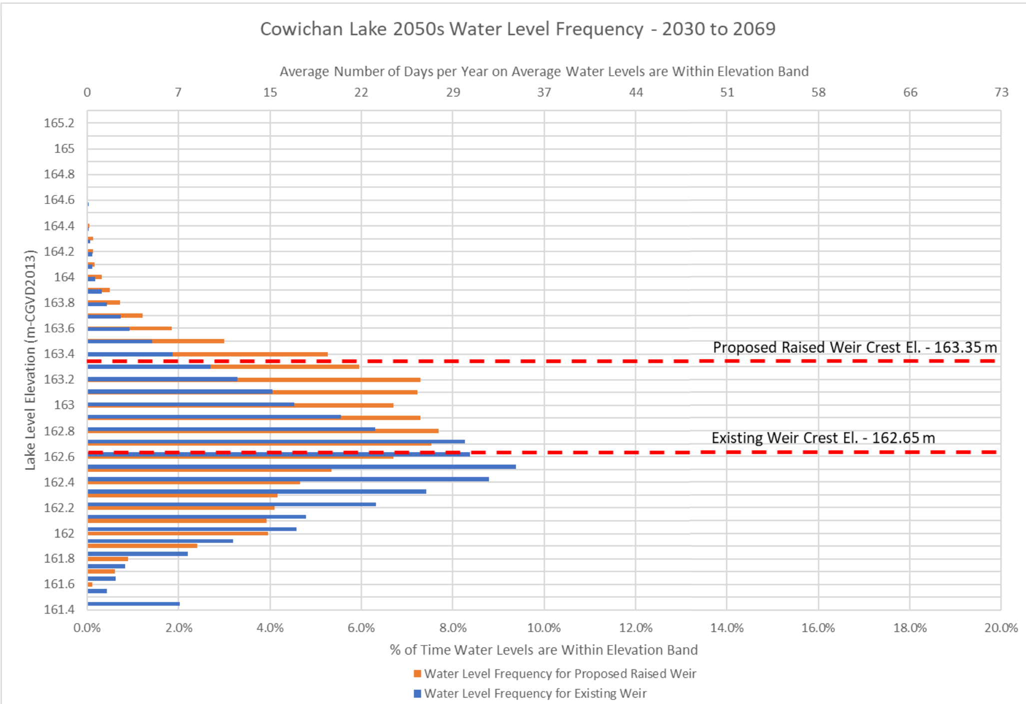

Figure 8-2: Lake Level Frequency Under Projected 2050s Climate Conditions

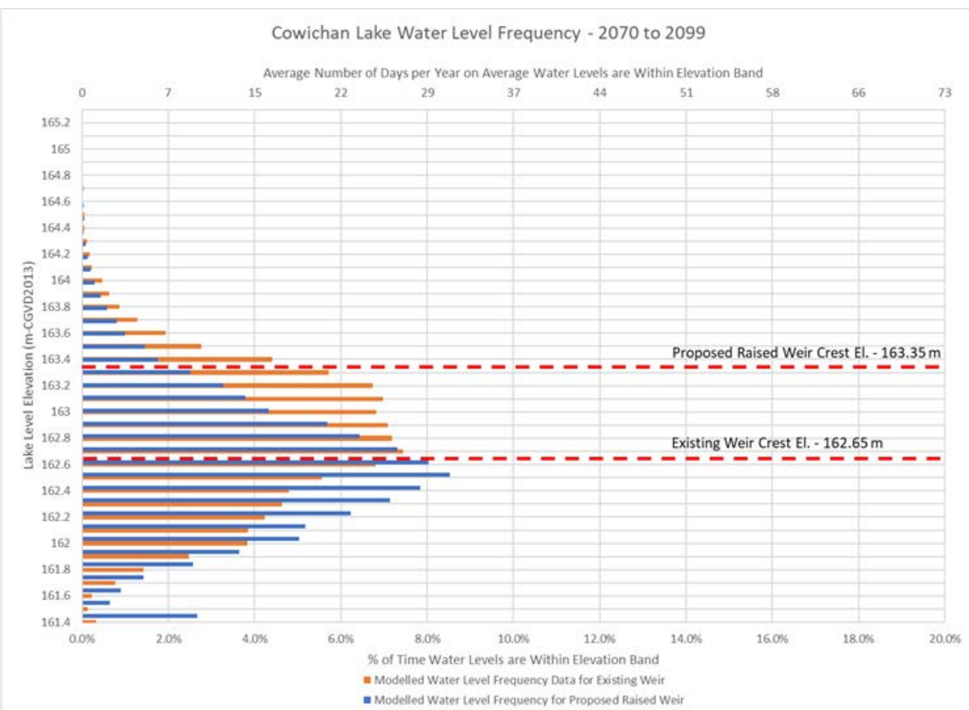

Figure 8-3: Lake Level Frequency for Existing and Raised Weir Scenarios for 2080s

In addition to changes in lake level frequencies for the entire year, summary statistics have been prepared to compare changes in frequencies of lake levels over the four seasons. Figure 8-4, Figure 8-5, and Figure 8-6 provide whisker plots showing the range of lake levels, including the 25th percentile, median, and 75th percentile, for the existing and proposed weir conditions over the four seasons for the past climate, 2050s, and 2080s respectively.

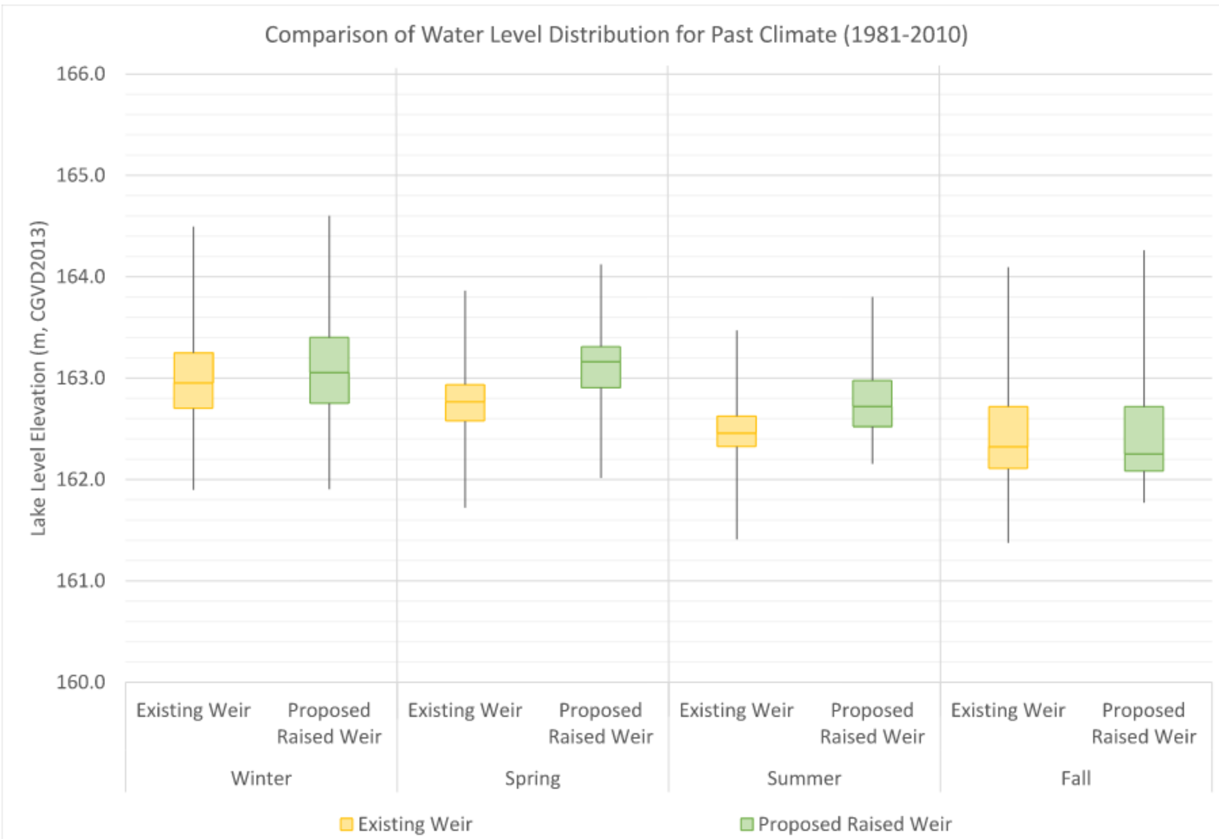

Figure 8-4: Seasonal Lake Level Statistics for Existing and Proposed Weir for Past Climate

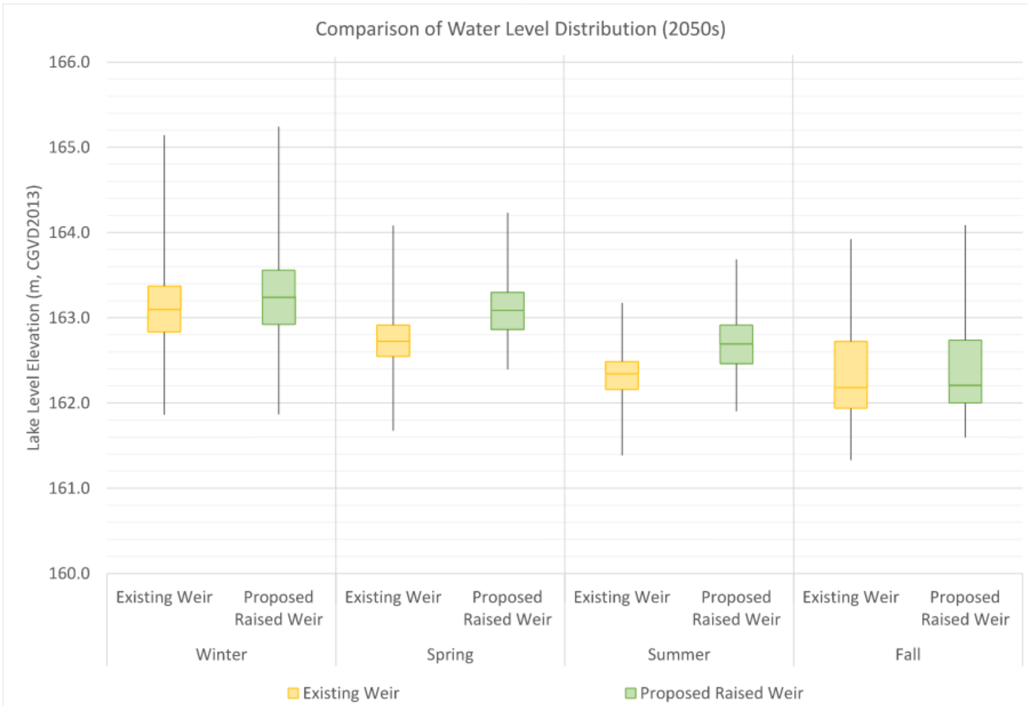

Figure 8-5: Seasonal Lake Level Statistics for Existing and Proposed Weir for Projected 2050s

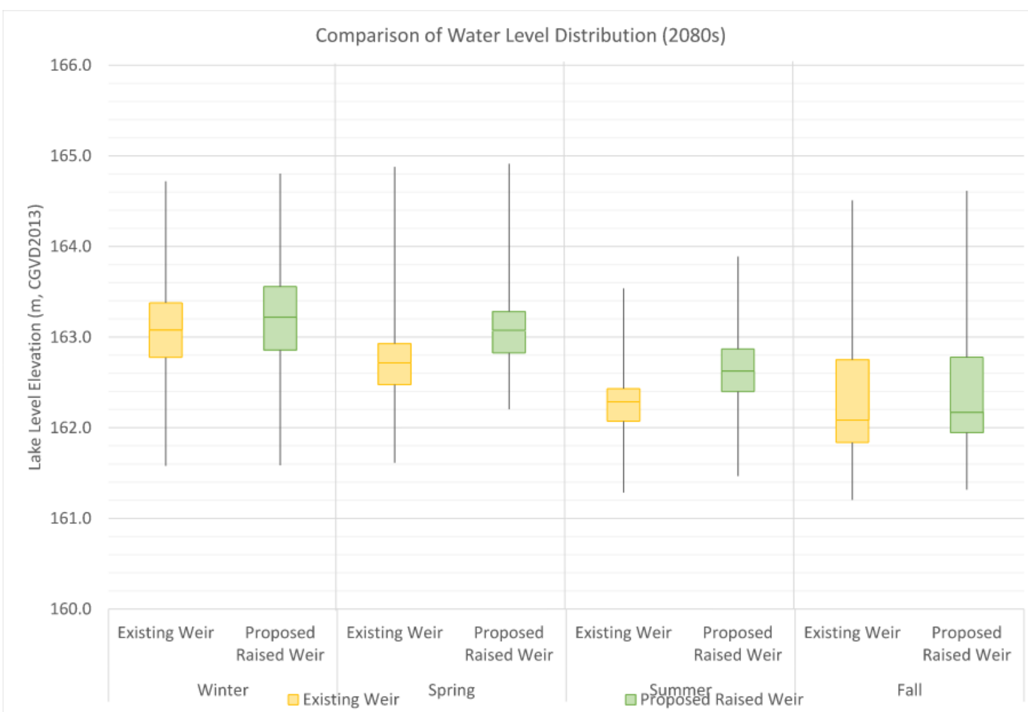

Figure 8-6: Seasonal Lake Level Statistics for Existing and Proposed Weir for Projected 2080s

In addition to the figures which show change in the frequency of lake levels within each elevation band, a summary of the statistics for four distinct ranges of lake levels has also been considered including:

1. Normal High Lake Level Levels above the proposed weir crest and below the mean annual HWM.
2. Additional Storage Lake Levels between the existing weir crest and proposed weir crest.
3. Existing Storage Lake Levels below the existing weir crest.

The change in frequency of the lake levels within each of these bands has been summarized for both changes due to operation of the proposed raised weir over time (see Table 8-1), as well as between current conditions (current weir with historical climate) and proposed future conditions (proposed weir with future climate) (see Table 8-2). The frequency of how often lake level is projected to drop below zero storage with the existing weir and the proposed raised weir is shown in **Error! Reference source not found.**.

Discussion of changes to maximum annual high lake levels or flood levels is included in Section 8.2.

Table 8-1: Change in Lake Level Frequency Due to Operation of Proposed Raised Weir

Lake Level Range	Past Climate			2050s Climate			2080s Climate		
	Existing Weir	Proposed Raised Weir	Change	Existing Weir	Proposed Raised Weir	Change	Existing Weir	Proposed Raised Weir	Change
Above proposed raised weir crest	11%	20%	+9%	6%	13%	+7%	7%	13%	+6%
Between proposed raised weir crest and existing weir crest	36%	46%	+10%	35%	50%	+15%	33%	48%	+15%
Below existing weir crest	53%	34%	-19%	59%	37%	-22%	60%	39%	-21%

HWM = high water mark for existing weir
Note: Water level frequency for past and future climate with existing and proposed weir are based on modelled water levels with modelled inflows to be consistent between the data sets.

Table 8-2: Change in Lake Level Frequency Under Current/Future Climate and Weir Conditions

Lake Level Range	Existing Weir with Past Climate	Proposed Raised Weir with 2050s Climate	Change	Existing Weir with Past Climate	Proposed Raised Weir with 2080s Climate	Change
Above proposed raised weir crest	11%	13%	+2%	11%	13%	2%
Between proposed raised weir crest and existing weir crest	36%	50%	+14%	36%	48%	+12%
Below existing weir crest	53%	37%	-14%	553%	39%	-16%

HWM = high water mark for existing weir
Note: Water level frequency for past and future climate with existing and proposed weir are based on modelled water levels with modelled inflows to be consistent between the data sets.

Table 8-1 shows that with the proposed weir the lake levels will be at higher elevation for longer periods than with the existing weir. For current climate conditions, the analysis indicates that for the proposed weir the modelled water levels are above the existing weir crest elevation about 19% of the time or about 69 days per year compared to the existing weir condition. Comparing values from present climate to future projected climate conditions indicates that compared to current conditions, water levels are projected to be lower on average reflective of the projected decrease in spring and summer inflows to Cowichan Lake. For instance, modelled water levels for the existing weir condition are between the are above the existing weir crest about 47%, 41% and 40% of the time for past climate, 2050s climate and 2080s climate, respectively. Comparatively, the modelled water levels for the proposed raised weir show similar reduction in the time water levels are above the existing weir crest from 66% of the time for past climate to 63% of the time and 61% of the time for 2050s and 2080s, respectively.

Table 8-3: Change in Frequency of Lake Level Dropping Below Zero Storage Level

# of Years Lake Level Below Zero Storage Level (161.6 m CGVD2013) Over 30 year Period					
Past Climate		2080s Climate		2080s Climate	
Existing Weir	Proposed Raised Weir	Existing Weir	Proposed Raised Weir	Existing Weir	Proposed Raised Weir
2	0	3	1	10	3

The results in Table 8-3 provide an indication of the change in the reliability of the Cowichan Lake Weir to support preferred flows in the Cowichan River over time. It shows that the proposed raised weir reduces the number of times lake level is projected to drop below the zero storage level but also that the frequency lake level drops below the zero storage level is projected to increase for both the existing weir (to about 1/3 of time) and the proposed raised weir (about once in every ten years on average). This assumes that preferred flows in the Cowichan are maintained, with no in season drought management flow reductions for storage conservation. The projections are different than the results provided in the original Cowichan WUP, due to updates in regional climate change projections and updates to projected Cowichan Lake inflows.

8.2 Impacts on Maximum Annual High Lake Level

The proposed upgrades to the Cowichan Lake weir have been designed such that there is no change in the relationship between lake level and discharge in Cowichan River for lake levels above the average HWM. However, to check on potential for changes in frequency of high lake levels, flood frequency analysis has been carried out using the historical lake level data as well as the modelled lake level data for both the current weir and proposed weir conditions.

The analysis has been carried out for past climate and future 2050s and 2080s periods.

The flood frequency results for the past climate with the existing weir using observed lake level data in this study similar to the lake level results for Cowichan Lake presented in the CVRD Risk Assessment of Floodplains and Coastal Sea Level Rise report (NHC, 2019). Therefore, for consistency with the previous study, the flood frequency values from the 2019 report are presented here.

The results for the existing weir and historical climate condition are shown in Table 8-4. For comparison to the peak annual lake levels, the floodplain level including freeboard as shown on the Provincial Floodplain mapping for Cowichan Lake is 167.53 m CGVD2013[7].

To understand how peak lake levels are projected to change over time, a flood frequency analysis was carried out using model results for the existing weir and proposed weir conditions. This is based on 30-year climate normal periods (1991-2020, 2030-2069, 2070-2099) to capture how flood frequency is likely to change as a result of climate change for the existing weir and proposed weir over time. In order to capture the impact of weir operation on peak lake levels, the maximum modelled annual peaks were divided into two periods:

- on-control from March 1 to Nov 1; and
- off-control from Nov 1 to end of February the following year.

It should be noted that for existing weir, on-control period starts April 1. However, to capture the impact of the change in water levels during the proposed on-control period starting March 1 for the proposed weir, the same period was used to analyse flood frequency for the existing weir.

Separate flood frequency analysis was carried out for the two series of modelled maximum annual peaks and then combined back together into a single population using joint probability analysis. This was carried out for each of the time periods to assess how the peak lake level is projected to change over time. The flood frequency curves for the on-control and off-control period with the existing weir and the proposed weir under past climate conditions are shown in Figure 8-7. The results for past climate and future climate conditions are shown in Table 8-4.

As indicated above, changes in peak lake level have been calculated by comparing the flood frequency analysis results for the modelled existing weir and modelled future weir conditions using the projected climate to calculate inflows to the lake. Using modelled lake levels for both existing and proposed weir conditions results in a consistent data set to develop relative comparison of change in peak lake levels. The change in flood frequency in the modelled lake levels was then applied to the flood frequency results using the historical observed record to derive absolute peak water elevation values for the expected existing and proposed weir conditions.

[7] BC MoE Floodplain Mapping Cowichan Lake (Dwg 84-33-1 to 84-33-60, File No 0305030-20, June 1984. https://www.env.gov.bc.ca/wsd/data_searches/fpm/reports/keyplans-html/cowichan-lk.html

Table 8-4: Change in Peak Lake Level at Return Periods with Proposed Weir – Historical Climate

Return Period (Years)	Existing Weir Peak Lake Level (m-CVGD2013)	Change in Peak Lake Level for Proposed Raised Weir
500	166	0.00 m
200	165.9	0.00 m
100	165.7	0.00 m
50	165.5	+0.01 m
20	165.3	+0.03 m
10	165	+0.04 m
2	164.2	+0.1 m
Note: Cowichan Lake Provincial Floodplain Elevation is 167.53 m CGVD2013 including freeboard allowance		

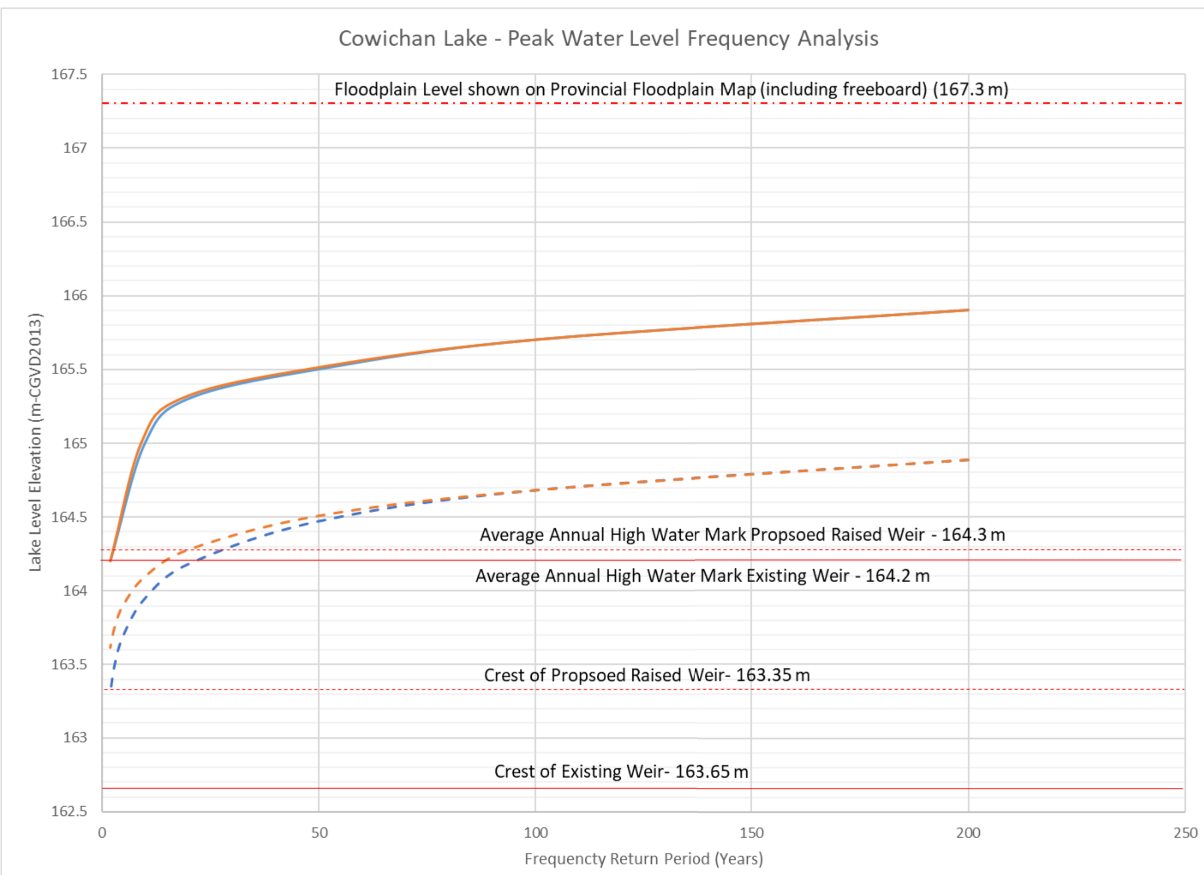

Figure 8-7: Seasonal Lake Level Statistics for Existing and Proposed Weir for Projected 2080s

8.3 Lake Level Analysis Summary

The key findings of the lake level modelling and frequency analysis are:

1. **The proposed raised weir has minimal impact on maximum annual peak lake level (increase of 0.01 m for the 50-year return period up to 0.1 m for the 2 year return period with no change expected for extreme high water levels (above 50-year return period.**

   The design of the proposed raised weir aimed to limit the potential for impacts to high lake levels by matching the lake level-discharge relationship above the average annual HWM elevation which results in limited impact to higher lake levels. However, below the annual HWM elevation there is some change in the peak water levels with the proposed raised weir due to differences in the lake level-discharge relationship combined with the dynamic nature of changing inflows. This results in a 0.1 m increase in the average HWM elevation to El. 164.3 m for the proposed weir.

2. **With additional storage, the lake level is more frequently between the current average annual HWM (El. 164.2 m) and the proposed raised weir crest (El. 163.35 m), and the lake level is projected to be slightly more frequently within this range with climate change.**

   Modelled water levels are within this range for the existing weir under past climate conditions about 39 days on average. With the proposed raised weir, the frequency of lake level within this range is projected to increase by 9% of the year (to 75 days per year on average) for past climate, 2% of the year (to 48 days per year on average) for 2050s climate, and 2% of the year (to 46 days per year on average) for 2080s climate compared to the past conditions with the existing weir The projected increase in frequency of lake level between the proposed weir crest and the annual high-water mark is reflective of the alteration of the rating curve due to the proposed raised weir, which results in a higher lake level for the same river discharge, for lake levels within this range during the winter off-control period. In addition, operation of the proposed raised weir results in lake levels being maintained near the proposed raised weir crest during the early part of on-control period - part of the increase is due to lake levels being marginally above the proposed weir crest during this time.

3. **The lake level is more frequently between the existing weir crest (El. 162.65 m) and the proposed raised weir crest (El. 163.35 m) and the frequency of lake level within this range is expected to decrease with climate change.**

   Modelled water levels are within this range for the existing weir under past climate conditions about 132 days on average. For the proposed raised weir, the frequency lake levels are within this range is projected to increase by 10% (to 168 days per year on average), by 15% (to 181 days per year on average), and by 15% (to 175 days per year on average) compared to the existing weir condition for the past climate, projected 2050s climate, and projected 2080s climate, respectively. The projected increase in frequency of lake levels between the existing weir and proposed weir is reflective of the operation of the proposed weir, which will aim to maintain lake levels near the proposed weir crest provided there is sufficient inflow to support flow releases into the river.

4. **The lake level is less frequently below the existing weir elevation (162.65 m) for the proposed raised weir compared to the existing weir, and the frequency lake level within this range are projected to slightly increase with climate change.**

Modelled water levels are within this range for the existing weir under past climate conditions about 193 days on average. For the proposed raised weir, the frequency of lake levels in this range are projected to decrease by 19% (to 124 days), by 22% (to 135 days), and by 21% (to 142 days) for past climate, projected 2050s climate, and projected 2080s climate, respectively. The decrease in frequency of lake levels below the existing weir is reflective of operation of the proposed weir which aims to maintain higher lake levels in spring, summer, and early fall to support flow releases into the Cowichan River.

5. **The comparison of the seasonal lake level statistics indicates that in general, the proposed weir will result in increased median lake levels across all seasons.**

   In fall and winter the maximum lake levels are not projected to change significantly. The model results indicate that maximum lake levels in spring could increase as a result of operation of the proposed weir. With projected future climate change, median seasonal lake levels in winter are expected to increase for both the existing and proposed weir conditions while median seasonal lake levels for all other seasons are projected to decrease with projected future climate change. For all seasons, the median seasonal lake levels with the proposed weir are higher than the existing weir with projected climate change conditions.

6. **The proposed raised weir reduces the frequency that the lake level is projected to drop below the zero storage level.**

   With reduced summer inflow due to climate change the frequency that lake level drops below zero storage level is projected to increase for both the existing weir and proposed raised weir scenarios.

9. Limitations

The projected future changes presented in this report for Cowichan Lake inflows resulting in changes in lake levels with both the existing weir and the proposed raised weir are based on output from global circulation models, hydrological models and modelling of the existing weir and the proposed raised weir operations. There are uncertainties and assumptions with each of these modelling steps which influence the results. Some key uncertainties and limitations are:

1. Uncertainties related to future green house gas emissions and impacts on future climate and uncertainties in GCM modelling which impact projected changes in temperature and precipitation.
2. Uncertainties and potential bias in hydrological modelling due to limitations in climate data used in model calibration/verification and focus on calibrating model to average conditions which may limit accuracy of modeled Cowichan Lake Inflows at extremes (drought and flood).
3. Hydrological modelling assumes that land cover in the watershed will not change significantly over time and does not account for potential changes such as forestry/development, forest fires or changes in land cover due to changes in climate.
4. The assumption that future weir operation follows rules set out in the Cowichan WUP without accounting for potential drought management measures which may be implemented through water management decisions by the future licence holder.

Both lake level frequency results and peak lake level analysis results under future climate conditions are based on Cowichan Lake inflow calculated using climate data input from a single downscaled GCM (CanESM2-r1 GCM). This model was selected as the results lie near the median values across the range of results from the twelve GCM models included in the CMIP5 model ensemble. Therefore, the projected in changes in lake level frequency and changes in peak lake levels as a result of climate change are considered a reasonable estimate. However, as the comparison of water level results from the ensemble of models indicates the uncertainty in projecting future water levels is significant. Throughout the study, the uncertainties have been quantified and the results represent a reasonable future condition which lies in the mid range of uncertainty based on professional judgement. However, it is noted that the uncertainties indicated above do not have relative likelihoods and that actual future conditions are likely to be near the upper or lower bounds than near the middle. Therefore, the results presented are to be considered a reasonable representation of future conditions but may overpredict or underpredict actual future values.

10. Summary

Understanding the impact of climate change on inflow to Cowichan Lake plays an important role in understanding how future operation of the raised Cowichan Lake Weir will impact the lake level compared to the status quo condition.

Based on the climate change projections from GCMs and the hydrological modelling carried out, the key findings are summarized below.

1. Historically summer inflow to Cowichan Lake has been decreasing, roughly 30% since the 1960s, and this trend is projected to continue.
2. Regional climate projections indicate that total spring and summer precipitation is projected to decrease 17% by the 2050s and 26% by the 2080s, while dry periods could increase from an average of 20 days in the past, to 26 days in the 2050s and 29 days in the 2080s.
3. The results of the ensemble of downscaled GCM projections indicate that average daytime high temperature across the region could increase by +2.7°C and +4.5°C by the 2050s and 2080s, respectively, with the number of days above 25°C increasing from an average of 16 days per year in the past, to 39 days per year in the 2050s and 59 days by the 2080s.
4. Reduced summer precipitation, longer dry spells, higher temperatures leading to reduced snowpack, and increasing evaporation are projected to decrease summer inflow a further 30% and 40% by the 2050s and 2080s, respectively.
5. Comparison of projected lake level frequency over time (for the same weir conditions) indicate that in general late fall/winter lake levels will be higher in the future, while spring, summer, and early fall lake levels will be lower in the future as a result of climate change.
6. Comparison of projected lake level for the current weir and proposed raised weir over specific future periods indicate that trends in seasonal lake level frequencies are similar for both the current weir and proposed raised weir, as noted above. However, comparison between the lake level frequency for the current weir and proposed weir indicate an increase in frequency of lake levels between the mean high-water mark and the proposed raised weir crest, an increase in frequency of lake levels between the proposed weir crest and existing weir crest, and a decrease in frequency of lake levels below the existing weir crest.
7. Flood frequency of model results indicates that the proposed raised weir could have some impact (0.1 m increase) to average annual peak lake levels, a slight impact (less than 0.05 m) on maximum lake levels for moderate floods (up to the 50-year return period) and no measurable impact to extreme flood levels greater than 50-year return period. Climate change is projected to increase peak lake levels for both existing weir and proposed raised weir conditions. However, the difference between the peak lake levels with the existing weir and with the proposed raised weir reduces with projected climate change.
8. The proposed raised weir reduces the frequency that lake levels are projected to drop below the zero storage level. However, with reduced summer inflow due to climate change the frequency lake levels drop below zero storage level is projected to increase for both the existing weir and proposed raised weir scenarios.

The lake level frequency results have been used in conjunction with results from a wave energy analysis, to estimate potential changes in the natural boundary of Cowichan Lake. The wave energy analysis, described in *Appendix E of the Cowichan Lake Shoreline Assessment Report*, involved the development of a high-resolution spectral wave model, as well as the collection of local lake wind and wave data to evaluate the model. This wave model was used to develop an understanding of the wave conditions along the lake shore, including the relationship between lake level, wave energy, and the elevation of the natural boundary. The lake levels and wave energy results were then used to estimate the change in location of natural boundary resulting from the proposed raised weir. A detailed description of the estimated natural boundary change assessment is provided in *Appendix F of the Cowichan Lake Shoreline Assessment Report*. Both the modelled change in lake level frequency and the estimated change in the location of the natural boundary as a result of the operation of the proposed raised weir were used to evaluate potential impacts to shoreline properties which are summarised in *Appendix G of the Cowichan Lake Shoreline Assessment Report*.

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12. Report Submission

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EGBC Permit to Practice: 1000696
2022-11-16

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Revision History

Revision #	Date	Status	Revision	Author
1	November 15, 2022	Revised	Updated water level analysis using final rating curve.	
0	June 2, 2022	Final		CS

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Appendix D-1

Cowichan Lake Operational Model Technical Memorandum

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Technical Memorandum

DATE: December 22, 2017

TO: Michael Harstone
Compass Resource Management

FROM: Craig Sutherland, M.Sc., P.Eng.

RE: **COWICHAN WATER USE MANAGEMENT PLAN**
Cowichan Lake Operational Model
Our File 2860.009

The Cowichan Lake Operational Model simulates how the weir as well as operation of the gates and boat lock at the outlet of Cowichan Lake impacts lake levels and discharges throughout the year. It can be used to assess how lake levels and river flows change as a result of:

1. changes in weir operation and prescribed outflow schedule;
2. increasing storage by either raising weir structure and/or pumping; and
3. projected future changes in inflow to the lake.

Daily Water Balance

The model is a spreadsheet (MS-Excel) based model which calculates daily water balance through the lake using the simple mass balance equation:

$$I – O = \_S / \_t$$

Where:
Δt is the model time step
I is the average net-inflow over Δt
O is the average outflow over Δt
ΔS is the change in storage in the lake over Δt

Net-inflow is defined as the volume of surface and groundwater runoff from the watershed plus volume of direct rainfall on the lake surface minus volume of evaporation from the lake surface during time step _t. This means that at certain times in the summer the net-inflow is negative when runoff and precipitation to the lake are less than evaporation.

Historical and Future Projected Daily Net-inflow

An average daily net-inflow time series has been back-calculated from daily discharge and lake level records collected since 1953 by the Water Survey of Canada. This record provides a continuous estimate of net-inflow to the lake for a 64-year period up to the end of 2016. The back-calculation is also based on the mass balance equation.

In addition to net-inflow time-series based on historical record, a net-inflow record based on projected changes in climate for the 2050s period can also be used in the analysis. This future projected net-inflow time-series is based on hydrological modelling completed by Simon Fraser University (Foster & Allen, 2015). The climate time series used for the future 2050s period is based on downscaled global circulation model (GCM) projections using the Pacific Climate Impacts Consortium (PCIC) BC Regional Analysis Tool. Specifically, the results of the GCMs used in the TreeGen Ensemble (Cannon, 2008) and the SRES AR4 emissions scenario which represents future emissions for business as usual case. The ten years of projected 2050s inflows for Cowichan Lake are shown in the attached Figure 1 including a comparison of the median daily flows for 2050s and the historical 1981 to 2010 climate normal period.

Cowichan Lake Operational Model Logic

Average daily outflow from the lake is simulated to account for both the proposed weir operation set for the alternative and the physical hydraulic constraints of the system.

The physical constraints that can be adjusted in the model include:

1. Increasing or decreasing the top elevation of available lake storage which would be achieved by raising the weir, increasing the height of the gates and making physical modifications to the boat-lock;
2. Decreasing the bottom elevation of available lake storage by using "negative storage" which would require installation of pumps to lift water from the lake into the river;

The operational constraints that can be adjusted in the model include:

1. the start and end date of the control period for the weir and gates control lake levels and flow in the river,
2. setting preferred minimum flows and absolute minimum flows to control how discharge in the river is adjusted during the control period,
3. setting rule curve that dictate when the modelled river discharges need to be increased to lower lake levels below the control curve;
4. trigger lake levels (rule bands) that dictate when discharge should be decreased to the absolute minimum flows;
5. set of flow ramping rates that dictate how quickly river discharges can change from one day to the next; and
6. the maximum pumping rate for those alternatives requiring negative storage.

The physical constraints that cannot be adjusted in the model are:

1. the lake level vs river discharge rating curve which defines the minimum lake level at which a specified discharge can be released from the lake or the natural outflow limit which is defined by the natural river channel downstream; and
2. the weir/gates rating curve which defines the maximum lake level at which a specified discharge can be released from the lake, this curve is shifted up or down depending on the weir crest elevation set in the model.

Figure 2 shows the rating curves including weir/gate rating curves over a range of potential increases in weir and gate elevation.

The model sets outflow on a daily time-step using a series of following logical statements.

1. Are the weir, gates, and boat lock in operation and controlling the flow (currently control period is from April 1 to Nov 7 or return of fall rains whichever occurs first).
2. Are lake levels greater than and less than the defined control lake level (rating curve) for the proposed alternative?
3. Increase or decrease controlled outflow based on the prescribed ramping rate depending on if lake levels are above or below the control curve.
4. If controlled outflow based on prescribed ramping rate is less than preferred or absolute minimum river flows, then set outflow to minimum flow.
5. If outflow from step 4 above is greater than the natural outflow limit (set by the lake level vs river discharge rating curve) then set outflow to natural outflow limit otherwise use the controlled outflow.

A flow diagram showing the model logic is included in Figure 3.

Model Output

The model output includes time-series of daily average water levels for Cowichan Lake and discharges in Cowichan River immediately downstream of the weir. The model runs continuously such that it calculates water levels and river discharges throughout the year. Currently, the model does not calculate discharge along the length of the Cowichan River.

Model Assumptions and Limitations

The model assumptions and limitations include the following.

1. Net-inflow time-series used as input to the model have been derived from recorded lake levels and river discharges. Therefore, the uncertainty in the net-inflow record is reflective of any errors in the historical lake level or river discharge record.
2. The results of the Cowichan Lake Operation Model represent how lake levels and river discharges would fluctuate based on a set of prescribed rules. The model can only use lake levels and prescribed discharge rates on specific dates for the modelled storage alternative. This constraint in the model may not reflect exactly how the weir may be operated given specific

conditions and management decisions. For instance, using seasonal and short-term weather forecast to provide guidance for river flow and lake water level management decisions.

Closing

Should you have any questions related to the Cowichan Lake Operational Model, please contact the undersigned at 250-595-4223.

KERR WOOD LEIDAL ASSOCIATES LTD.

Prepared by:

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Water Resources Engineer

CS

Encl.: Figure 1 Net-inflow Time-series and Figure 2 Model Logic Diagram

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Revision History

Revision #	Date	Status	Revision Description	Author
A	December 22, 2017	DRAFT	Issued as draft	CS

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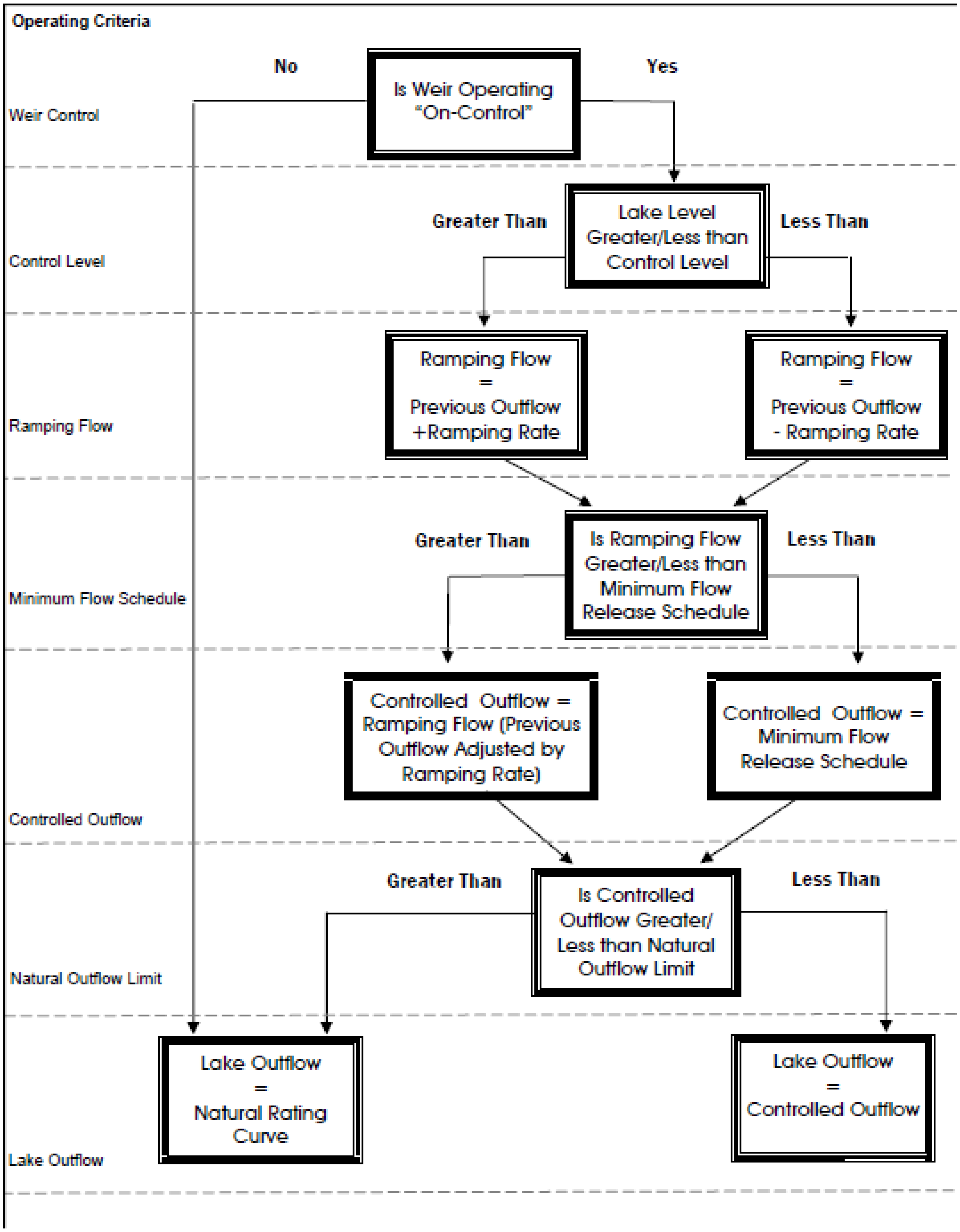

Operating Criteria
Weir Control
Control Level
Ramping Flow
Minimum Flow Schedule
Controlled Outflow
Natural Outflow Limit
Lake Outflow
No
Yes
Is Weir Operating "On-Control"
Greater Than
Less Than
Lake Level Greater/Less than Control Level
Ramping Flow = Previous Outflow +Ramping Rate
Ramping Flow = Previous Outflow - Ramping Rate
Greater Than
Less Than
Is Ramping Flow Greater/Less than Minimum Flow Release Schedule
Controlled Outflow = Ramping Flow (Previous Outflow Adjusted by Ramping Rate)
Controlled Outflow = Minimum Flow Release Schedule
Greater Than
Less Than
Is Controlled Outflow Greater/ Less than Natural Outflow Limit
Lake Outflow = Natural Rating Curve
Lake Outflow = Controlled Outflow