Climate and Hydrologic Projections for the Creston Area and Kootenay Lake Region: Estimated peak Goat River Flows and Kootenay Lake Levels

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Contents

EXECUTIVE SUMMARY

This report provides climate information to support flood risk assessments of the Creston dike system. The findings are arranged as follows: 1) a summary of the climate history of the area, 2) projections of selected climate indices for the 2030s and the 2070s and 3) hydrologic model projections for peak annual flow in the Goat River and peak annual Kootenay Lake water levels.

Climate has warmed significantly over the last century and the changes in temperature have been accompanied by changes in precipitation that have varied according to season. Downscaled climate models indicate that trends in rising temperatures will continue in the region with higher rates of change associated with the higher (RCP85) emissions pathway. Mean annual temperatures in the region could be up to approximately 4°C warmer than 1990 by the 2070s. Increases in precipitation are expected in all seasons with the exception of summer which will likely experience declines in precipitation. Extreme precipitation is also expected to increase in the future; the 100-year event in the 2070s could deliver up to 30% more precipitation than during the 1981 - 2010 base period.

The hydrologic model output indicates that future peak levels in Kootenay Lake and peak flows in the Goat River are expected to decline over time. This is related to the effects of projected climate change on snow dynamics in the watersheds; peak flows and levels are strongly linked with maximum winter snowpack. As the regional climate warms over the coming decades, winter precipitation is projected to increase. At higher elevations, this could lead to higher maximum snowpack that would tend to increase peak river flows and lake levels. However, warming winter and spring temperatures will continue to diminish regional snowpack as more winter and spring precipitation falls as rain and snowmelt intensifies at progressively higher elevations in future decades. The model projections indicate that the impact of increasing temperature on snowpack becomes dominant over time ultimately resulting in declining peak flow/level. This has already occurred in the Goat watershed, and because the Kootenay watershed has higher elevation regions, is expected to occur in the 2030s in the Kootenay watershed.

Probabilities for threshold exceedance were calculated for a number of specific thresholds for peak Goat River flow and peak Kootenay Lake levels. These include the annual exceedance probability (AEP) and the cumulative risk (CR). The AEP (and its inverse the return period) changes over time in non-stationary climate. The CR represents the likelihood of exceeding a given threshold once within a planning timeframe.

The threshold exceedance probabilities based on hydrologic model projections were found to be highly sensitive to outliers in the data and this is related to the relatively small number of models in the ensemble. A novel approach was used in this study to complement the model results. This method isolates the variability of observed peak annual river flow and peak annual lake levels and superimposes multiple simulations of observed variability on to the general hydrologic model trends. Goat River threshold exceedance probabilities were calculated with both methods and are in general agreement. The AEPs for all lake level and river flow thresholds decline over time with higher rates of decline associated with the higher emissions pathway (RCP85). The CR for exceeding thresholds in Kootenay Lake levels and Goat River flows both increase over future decades. However, this increase is significantly less that what would be associated with stationary or increasing AEPs over time.

INTRODUCTION

The concentration of carbon dioxide in the atmosphere has increased from pre-industrial levels of about 280 ppm to greater than 410 ppm today, an increase of over 40%, and without significant global greenhouse gas (GHG) reductions, levels of CO_2 in the atmosphere will continue to increase for the foreseeable future. Over the last century, mean global temperature has increased by more than 1.1^{o}C and the impacts associated with the changing climate are becoming more apparent and costly. It is widely accepted that the increasing global temperature over the last 65 years is largely attributable to the observed increasing concentrations of CO_2 (and other GHGs) (e.g. NAS, 2020), and given our current emission pathway, it is possible that global mean annual temperatures could reach 4^{o}C above pre-industrial temperatures by the end of this century. In short, the planet is warming, and it is expected that warming will continue. Consequently, communities must now take steps to anticipate the magnitude of local climate change in the coming decades and to plan accordingly.

As the atmosphere warms, its capacity for carrying more water vapour increases. The consequence of this is that, in many regions around the globe, extreme precipitation events have been increasing in frequency and/or magnitude and, in many cases, this has resulted in more severe flooding. This general trend is expected to continue over the coming decades as the planet continues to warm and will very likely become more severe. However, the severity will be strongly influenced by local circumstances and should be evaluated on the scale of individual watersheds.

Based on an ensemble of hydrologic models that have been forced by statistically downscaled global climate model projections, this report compiles projections for peak flows in the Goat River and for peak Kootenay lake water levels. Low points in the Goat dike system may be vulnerable to overtopping should the Goat River flow exceed critical thresholds, and this may be exacerbated by the back-water effect of high Kootenay Lake levels. A solid understanding of how peak Goat River flows and Kootenay lake levels may respond to projected changes in local climate is a prerequisite for community planners, engineers and policy makers to make well-informed decisions on the best approaches for adapting to the anticipated changes in climate and for improving the resilience of the Creston dike system. In addition, these data can inform design guidelines and policies, and the process of incorporation of such policies into development plans, through the provision of defensible projections of future climate conditions in the area.

This report provides an overview of the climate history of the Creston area and larger Kootenay lake region, general climate projections for these areas, projected trends for peak flows for the Goat River and peak levels for Kootenay Lake and estimates of the probability of exceeding a number of thresholds in peak river flow and lake levels.

SETTING

The Kootenay Lake watershed cover approximately ~50,000 km^2 in southeast British Columbia, northern Idaho and Montana and includes high elevation regions which are currently glaciated (Figure 1). The Goat River watershed is a relatively small (1,259 km^2), high-gradient subdrainage in the Kootenay watershed that does not include areas that are high enough to support glaciers. The climate of the Kootenay watershed is relatively warm and moist in the central and western regions and more continental in the east. High annual precipitation is typical for the higher regions of the Rockies, Purcell and Selkirk mountains with local rain shadows in the major valley bottoms. The Goat River flows south and west from the crest of the Moyie Range of the Purcell Mountains. The Kootenay Lake and the Goat watersheds are both nival hydrologic regimes strongly dominated by a peak flow in spring associated with the annual melting of the snowpack and this is reflected in the annual peak flow record of the Goat River and annual peak Kootenay Lake levels.

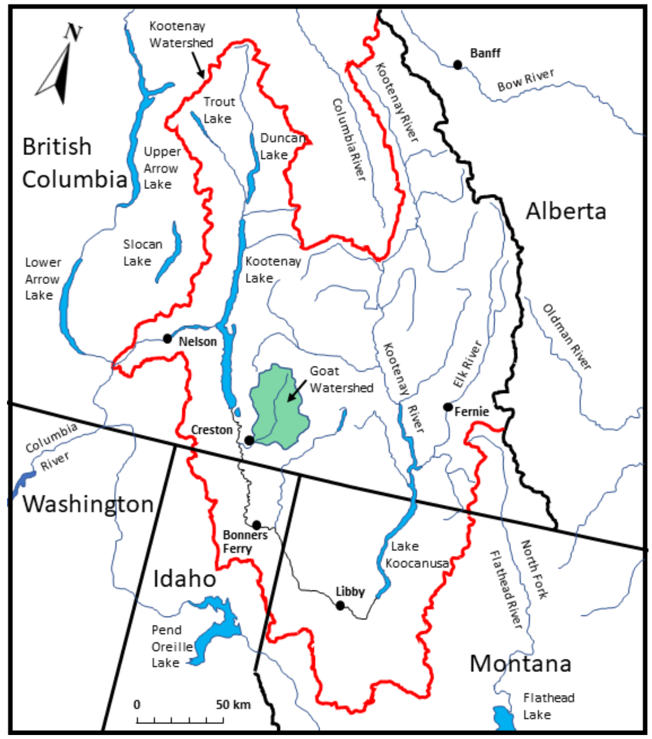


Figure 1 Location map for the Kootenay Lake and Goat River watersheds.

METHODS

Both climate and hydrologic model projections used in this study are based on two emissions scenarios, Representative Concentration Pathways (RCP) 45 and 85. The RCPs are numbered (e.g. RCP4.5 or RCP8.5) according to the radiative forcing in watts per square metre (W/m^2) that will result from additional GHG emissions by the end of the century under the low and high carbon emissions pathways. Higher W/m^2 associated with high carbon emissions pathways ultimately lead to warmer temperatures over the course of this century. These two emissions trajectories reflect 1) a lower carbon future (RCP45) which involves significant global reductions in greenhouse gas emissions that are midway between Paris Agreement goals and current commitments and 2) a high carbon future (RCP85) which would result from largely unrestrained greenhouse gas emissions. The latter is generally thought of as an ‘worst case’ scenario that is unlikely to be realised. However, it is becoming increasingly apparent that many countries are not on track to reach their Paris commitments (Liu and Raftery, 2021). Consequently, is likely that the future emissions pathway will fall between RCP85 and RCP45 and this applies to the climate and hydrologic model projection in this report. Despite the global efforts over recent decades to reign in emissions (e.g. Koyto Protocol, Copenhagen Agreement, Paris Agreement), the concentration of CO2 in the atmosphere continues to increase at an increasing rate. Until this trend starts to bend toward lower rates of increase, it is prudent to not rule out model projections associated with the RCP85 pathway for the foreseeable future.

Although the CMIP6 model results represent a significant update from the CMIP5 models, this report uses CMIP5 projection to be consistent with the hydrological models which are forced by CMIP5 projections. Using CMIP6 projections would alter some of the details but would not change the overall findings of this report. Figures 2a and 2b show the difference in projected mean annual temperature and precipitation for Creston based on CMIP5 and CMIP6 models.

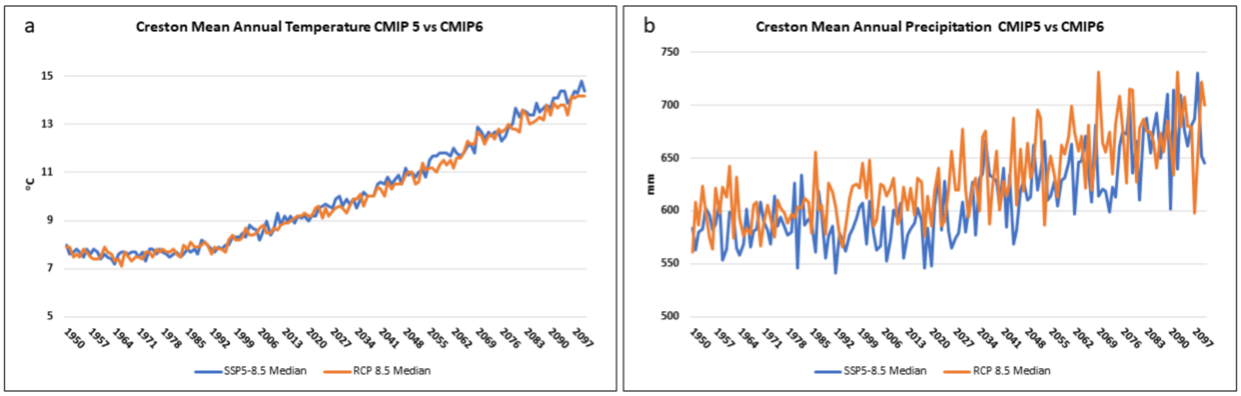


Figure 2 a) Mean annual temperature projections for the Creston are based on CMIP5 (RCP) models and CMIP6 (SSP) models. b) Mean annual precipitation projections for the Creston are based on CMIP5 (RCP) models and CMIP6 (SSP) models. The orange curves represent CMIP5 and the blue curves represent CMIP6.

Climate History

The century-scale climate history for the Creston area and the broader Kootenay Lake region are based on data from the Environment and Climate Change Canada (ECCC) Adjusted and Homogenized Canadian Climate Data (AHCCD) climate station at Creston. Missing data were estimated using the 'buddy system' with nearby records (Campbell Scientific) or gridded data available from (Climate BC/WNA, 2023). Climate station records at Nelson, Kaslo, Creston, Cranbrook and Fernie are located in the Kootenay Lake watershed and were complied to represent the climate history of the broader Kootenay Lake region. Records from AHCCD stations have undergone refinements to account for station moves, changes in instruments or exposure and changes in observation practices and are the most reliable records available for climate research. Trends in temperature and precipitation time series were computed for the last 100 years and for the last 50 years. The significance of the trends was determined using the Mann-Kendall test after removing lag-1 autocorrelation with the Zhang (1999) method (described in Wang and Swail, 2001). P values of <0.05 indicate a significant trend at the 95% confidence level. The magnitude of the trends was determined with the Theil-Sens estimator.

100-year 1-day and 3-day annual maximum precipitation were calculated by fitting a Gumble distribution to the Rx1 and Rx3 data over the historical period of observations (1913 To 2021). This approach was used to maintain consistency with the method used by ECCC for determining the probability of rainfall events from daily and hourly IDF data (Climate Data Canada, 2023).

Records of annual maximum snowpack are based on Apr 30 snow water equivalent (SWE) records from high-elevation snow survey stations in the region (Upper Grey Cr, East Cr, Morrissey Ridge, Floe L, Moyie Mt and Redfish Cr). The upper Grey Creek snow survey station is located approximately 18 km northwest of the northern boundary of the Goat R watershed.

Historical Peak Goat River flow and Kootenay Lake levels

Historical annual maximum Kootenay Lake levels were obtained from Water Survey of Canada (08NH064) record at Queens Bay. The record spans 1931 to present and is continuous after 1947. Annual maxima and instantaneous peak levels are highly correlated, and an average offset (approximately 1 cm) was added to annual maximum values to obtain annual peak levels. Historical annual peak levels of Kootenay Lake were significantly influenced by the construction of the Duncan and Libby dams that were completed in 1967 and 1972 respectively (Figure 3a). Flood control measures reduced the magnitude of annual peak lake levels associated with spring freshet. Since 1972, annual peak levels have been increasing in Kootenay lake.

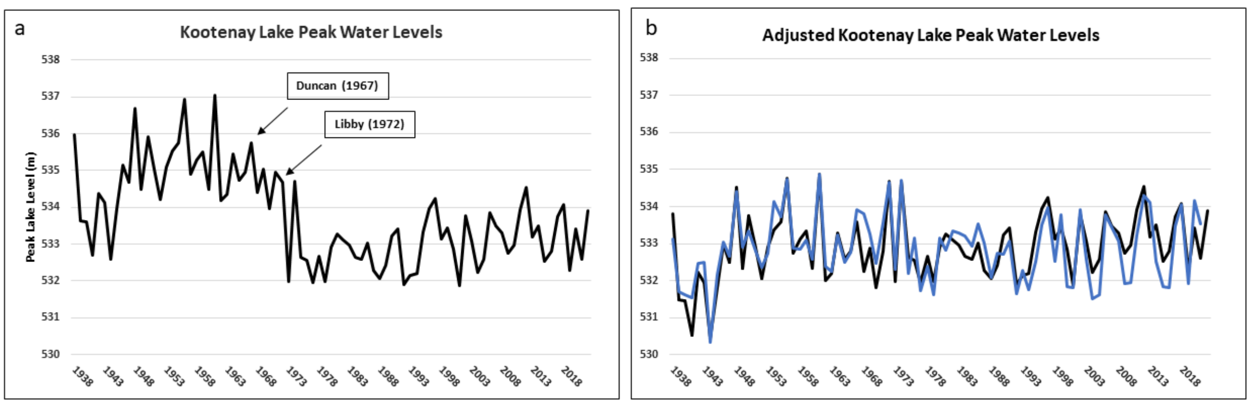


Figure 3 a) Kootenay Lake peak water levels from 1938 to present showing completion years for the Duncan and Libby dams. b) shows the Kootenay Lake Peak levels with Pre-Duncan\Libby years adjusted to post Duncan\Libby levels (black) compared with the regional unregulated river peak flow record (blue).

In order to obtain a record of lake level variability that includes an interval of pre-Duncan/Libby high levels associated with a period with strongly negative Pacific Decadal Oscillation (PDO) indices (ca. 1945 – 1957), the pre-Duncan/Libby Kootenay Lake levels were adjusted to post-Duncan/Libby levels. This was achieved by subtracting the difference between the 10 years preceding Duncan and the 10 years following Libby from the pre-Duncan record Figure 3a. Figure 3b shows the adjusted record compared with the maximum annual flow anomalies for regional unregulated rivers (Slocan, Lardeau, Moyie, Kaslo, Duncan, Kootenay at Ft. Steel and Boundary). The adjusted record correlates well with the regional unregulated maximum flow record (r^2 = .68) and the pre-Duncan\Libby peaks are in close alignment. This essentially brings the Pre-Duncan\Libby variability in line with the Post Duncan\Libby record and, although this adjustment introduces some uncertainty int the record, it provides a more complete record of historical variability for estimating historical return Intervals and threshold exceedance probabilities. Annual exceedance probabilities (AEP) and return periods (RP) for peak lake levels were obtained by fitting the annual peak level data (including adjusted) to a generalized extreme value (GEV) distribution using the method of moments.

The Goat River hydrological record recorded near Erikson began in 1914 and provides a continuous record from 1955 until 1994 (08NH004). In 1933, a relatively small concrete arch dam was built near Erikson in a canyon approximately 6 km upstream of Creston. At the time of construction, the reservoir created by the dam was insufficient for significant modulation of peak flows due to its very small size. The reservoir had largely filled with sediment within 15 years of construction (BGC 2020) thereby eliminating the small dampening effect the dam may have had on peak flows. Consequently, the Goat River essentially behaves as an unregulated river.

The Goat River historical record of annual peak flow is required to assess the historical variability and to use the observed variability to assess future changes in peak flow. Hydrological data is available for the Goat River starting in 1938, however, the record is incomplete and ends in 1994. In order to compile a complete record peak flow for the Goat River, missing years and data for the post 1994 record, were estimated using the ‘buddy system’ with the Moyie River record. The Moyie River watershed boarders the Goat watershed on the east, is similar in size and orientation, and has a complete hydrological record spanning 1938 – 2018 (Figure 4a). These adjacent watersheds have similar hydrologic characteristics, and their annual maximum flows show a strong correlation (R^2 = 0.71) over the period 1945 – 1994 (Figure 4b). In addition, years with the 10 highest maximum flows in the Moyie are all years within the 20 highest maximum flow years of the Goat River. The similarity between the Moyie and Goat River maximum flow records enables infilling for missing years in the Goat record and estimating post 1994 annual maximum flow to assemble a composite record that extends to 2018 (Figure 5). Goat River annual maximum flows are highly correlated with peak instantaneous flows and were adjusted to reflect peak flows.

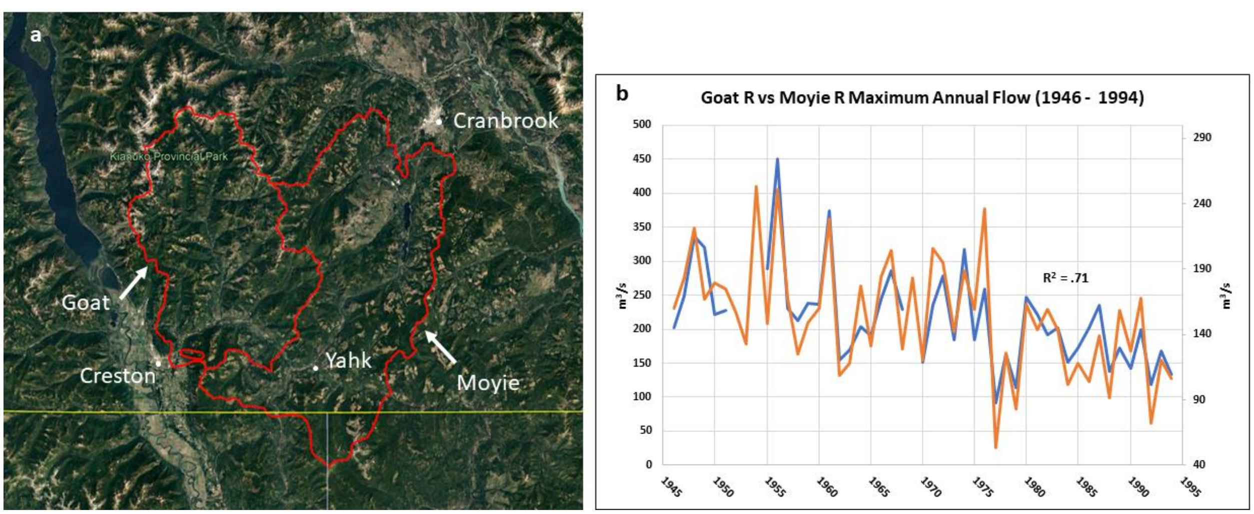


Figure 4 a) Satellite image (Google Earth) of the Goat and Moyie watersheds in southeast BC. b) Annual peak flow of the Goat and Moyie Rivers over the period 1946 to 1994. The blue curve represents the Goat River, and the orange curve represents the Moyie River. The two records are highly correlated (R^2 = .71) over this period.

Historical return periods (RP) and annual exceedance probabilities (AEP) were determined by fitting the full Goat River record of annual peak flow (with estimated values for missing years) to a generalized extreme value distribution (GEV) with the method of moments. Peak flow return periods (2, 5, 10, 20, 25, 50,100, and 200-yr) available from the BGC (2020) report were calculated for the Goat River using a regional analysis. RPs calculated for the full Goat River peak flow record (1925 – 2018) are in close correspondence with those determined by the regional analysis (Table 1). Although some uncertainty is introduced with estimating missing years in the Goat River record, the correspondence between RPs determined by different methods suggests the estimates for missing years in the Goat River record are robust.

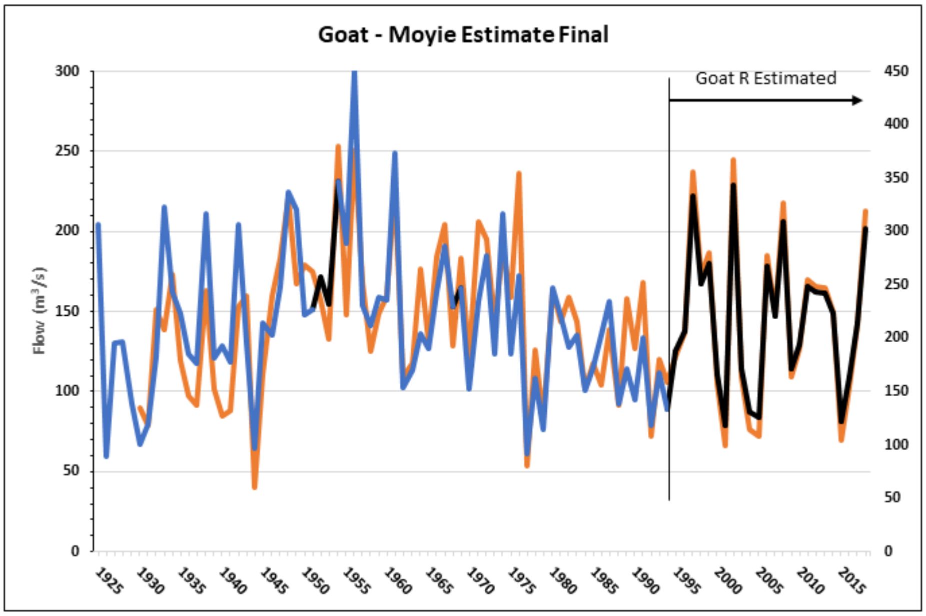


Figure 5 Peak flow records for Goat River (blue) and Moyie River (orange). The years in the Goat River record that were estimated from the Moyie River are shown in black.

Table 1 Return period discharge for the composite Goat River peak flow record and those determined from regional analysis (BCG 2020).

RP (years)	500	200	100	50	25	20	10	5	2
This Study (m3/s)	534	498	468	436	402	390	351	308	236
BCG (m3/s)	530	495	465	435	400	385	350	305	235

Model Projections

Climate model projections in this report are based on an ensemble of 24 statistically downscaled General Circulation Model (GCM) projections available from the Climate Atlas of Canada (Climate Atlas of Canada, 2023). The model data is downscaled to approximately 10km resolution from the Coupled Model Intercomparison Project Phase 5 (CMIP5) sources (Taylor et al., 2012,) using Bias Correction/Constructed Analogues with Quantile mapping recording (BCCAQv2) for RCP45 and RCP85 emissions scenarios (PCIC 2018). Climate model data are presented in the form of selected annual and seasonal indices for the baseline period of 1976 - 2005 and the projected climatology of 2021-2050 (2030s) and 2051 -2080 (2070s).

Hydrologic model projections were obtained from PCIC's Gridded Hydrological Model Output and Station Hydrologic Model Output for the Goat River and for Kootenay Lake respectively (PCICa, b, 2023). The hydrologic projections are simulated by the VIC-GL model which is driven by 6 statistically downscaled CMIP5 GCM and each were run under RCP45 and RCP85. The PCIC hydrologic model ensemble was selected to span a wide range in future climate extremes.

Climate projections for the Local Creston area were based on the model projections for the grid cell that bounds the Town of Creston; the grid cell is roughly 60 km^2 in size. The Climate projections for the larger Kootenay Lake region are based on the average values for the 5 regions that contain the climate stations used for compiling the historical climate records. Each of these regions contains 18 grid cells and represents approximately 1000 km^2. Climate projections for Rx1 and Rx3 based on the model ensemble means are included with the climate indices. In addition, projections of Rx1 and Rx3 based on the 7%/^{o}C Clausius Clapeyron scaling method (Climate Data Canada, 2023) are included for comparison.

a) Goat River Hydrologic Projections

For large watersheds, such as the Kootenay Lake watershed (~50,000 km^2), a routing model is required to simulate the flow of water through the river network. The Goat River watershed is a relatively steep mountain drainage of approximately 1,185 km^2 with an average channel gradient above the Creston Valley of 1.5% over approximately 60 km (BGC, 2020). Although stream velocity varies widely across stream channels (faster in the thalweg and slower near the margins), it is estimated that the average travel time through the Goat watershed is on the order of 24hr or less (Carver pers com., 2023). Consequently, VIC-GL model output are summed for the 54 grid cells to simulate Goat River discharge at Erikson (Schnorbus, pers com., 2023). A LOWESS smooth of the model ensemble maximum flow data provides the projected trend for maximum flow of the Goat River from 1946 to 2099. The projected trend of Goat River maximum annual flow is adjusted so that the projected trend is in alignment with the observed peak flow of the Goat River over the last 50 years.

Timeseries of the probability of exceeding specific flow thresholds based on model projections were compiled by fitting the projected annual peak flow data for each model to a GEV (method of moments) in 30-year moving windows centered on each year between 1960 and 2084. The annual exceedance probabilities determined from the individual GEV model fits were averaged to obtain projected annual exceedance probabilities for the Goat River for 5 thresholds (420, 440, 460, 480, and 500m^3/s).

The VIC-GL model incorporates a number of factors that contribute to the baseflow and surface runoff of each grid cell, including snowpack represented by snow water equivalent (SWE). Projections of SWE were derived from the model output for three locations in the region: 1) a low-elevation grid cell that contains the Town of Creston, 2) a mid-elevation grid cell that covers the Upper Grey Creek snow survey station and 3) a high-elevation grid cell over the MacBeth glacier.

Over the common period of projections and observations (1945-2022) the variability of the projections for peak Goat River flow are, with the exception of 2 outliers, generally consistent with observed variability of peak Goat River flow (Figure 6a). Further, return periods calculated for the models and observed over the common period of observations are in close agreement. However, the ensemble is based on 6 models which limits the confidence that can be placed in estimates of threshold exceedance, particularly at extreme levels. With an ensemble of six models, outliers can have a significant influence on the annual exceedance probabilities based on 30-years windows of projected maximum flow data. For example, a single data point in the CanESM2 projections is responsible for the conspicuous peak at 2047 (Figure 7). Including this outlier in the Return Period calculations for 2036 to 2065 results in an ensemble average RP of 86 years for a flow of 450m^3/s. Excluding this single outlier yields an ensemble average RP of 127 years for the same flow threshold over the same time interval. The high sensitivity of the RP calculations to individual outliers would be significantly reduced with a larger number of models included in the ensemble.

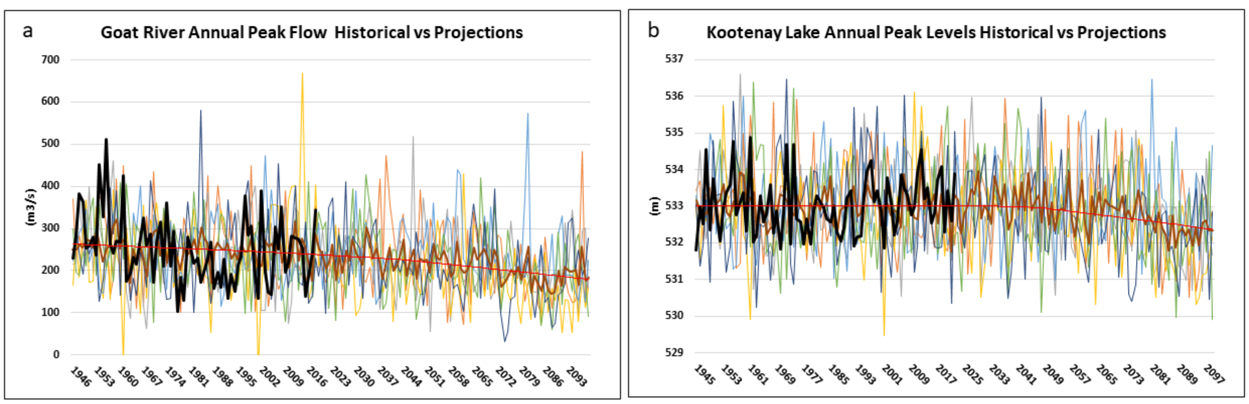


Figure 6 a) Observed peak annual Goat River flow and model projections adjusted to observed over the last 50 years. Black curve shows observed data. b) Observed peak annual Kootenay Lake levels and model projections adjusted to observed over the last 50 year. Thin colored lines represent model projections. Rust curve shown the model ensemble mean and the red curve shows a LOWESS smooth of the projections.

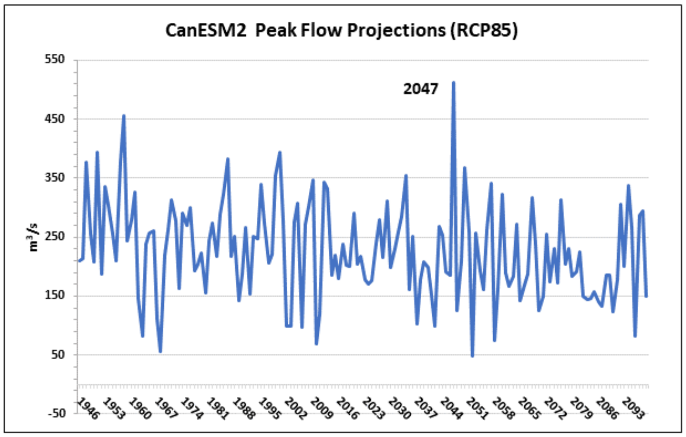


Figure 7 Projected peak annual flow of the Goat River based on the CanESM2 (RCP85) model. The 6-model ensemble RP for a flow threshold of 450m3/s over the period 2036 – 2065 is 86 yrs. Excluding this single outlier from the 6-model average RP yields an average RP of 127 yrs for the 2036 – 2065 interval.

b) Kootenay Lake Hydrologic Projections

Hydrologic model projections are not available for Kootenay Lake levels. However, long hydrologic records for the Slocan River and the Kootenay River at Corra Linn are available and their combined peak flow records are highly correlated with Kootenay Lake levels (R^2 = 0.985; Figure 8a). In addition, PCIC's routed hydrologic model output is available for the Kootenay River at Brilliant directly southwest of the confluence of the Slocan and Kootenay rivers (Figure 8b). Consequently, model projections of future maximum annual streamflow for the Kootenay River at Brilliant are an ideal proxy for projections of future maximum annual Kootenay Lake levels. The regression coefficients (observed annual peak Kootenay Lake levels vs annual maximum Kootenay at Brilliant flow) were used to transform the projected maximum annual Kootenay River flow at Brilliant to projections of Kootenay Lake levels. Maximum annual flow was determined for each of the 12 model projections, and these were assembled into timeseries of maximum annual flow from 1945 to 2099. This data was fitted with a LOWESS smooth to obtain the general trends in future lake levels.

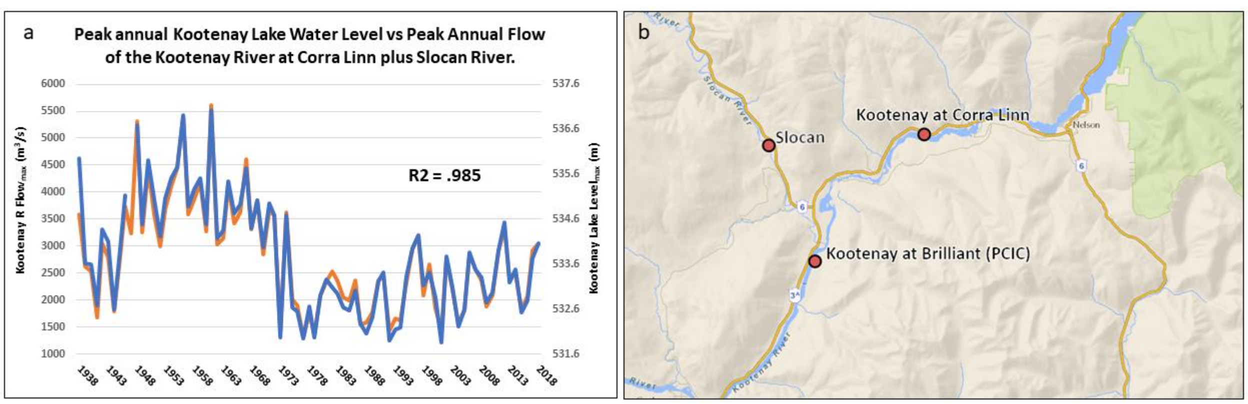


Figure 8 a) Summed maximum annual flow for the Kootenay River at Corra Linn and the Slocan River (orange) and peak annual Kootenay Lake Levels (blue). b) Location map showing the location of the gauged stations at Kootenay River at Corra Linn and the Slocan River and the location for PCIC's Statin Hydrologic model output (Kootenay at Brilliant).

PCIC's hydrologic model output represents flow in the absence of the upstream regulation associated with the Duncan and Libby dams. The individual model projections were adjusted to align with the historical record (with pre-Duncan/Libby adjustments)) over the last 50 years. This aligns the flow projections to lake levels controlled by Duncan/Libby regulation and provides projected future trends in lake levels with the assumption that there will not be significant changes in the flood management of the dams (Figure 6b). Annual maximum lake levels outflow is not regulated at Grohman Narrows (Kootenay Lake outlet) or by the hydro dams located between Kootenay lake and the confluence of Kootenay and Slocan rivers (Utzig, 2021).

Over the common period of projections and observations (1945-2022) the variability of the projections for peak Kootenay River flow at Brilliant differs significantly from the observed variability of peak Kootenay river flow and this is also evident in the estimates of Kootenay Lake levels that are based on the flow data (Figure 6b). The 200-yr flow event based on the observed data over the period of observations is 5991 m^3/s. The average 6-model RP for 5991 m^3/s (RCP85) over the same interval is 50 yrs.

Simulations

To address the high sensitivity of the 6-model ensemble RPs to outliers, a novel approach was used to provide estimates of probabilities of threshold exceedance for Kootenay Lake levels and to compliment the model projections for Goat River. This approach uses multiple simulations of the observed variability (in this case 1000 simulations) which are superimposed onto the projected model trend in order to estimate the probabilities of future threshold exceedance.

Firstly, the modeled river flows and lake levels were assembled in to timeseries of maximum annual flow for each of the 6 models. Future trends for maximum annual flow were derived from the VIC-GL projections by fitting a LOWESS smooth to the ensemble average of the projected data for RCP45 and RCP85 (Figures 6 a, b). This provides projected model trends for annual maximum flow and lake levels and these trends were adjusted to align with the last 50 years of the Goat River peak flow and Kootenay Lake peak level records.

The general trends derived from the hydrologic model projections for annual peak flow and lake levels (described above) represent the future model trends with the model variability removed. The unexplained variability of the observed annual peak river flow lake level records was determined by regressing against time and obtaining the residuals. The residuals are essentially the variability of the observed peak river flow and peak lake level data around the linear trend over the period of observations. The residuals were fitted to a GEV to using the method of moments to obtain the GEV location, scale and shape parameters for the residuals.

Future annual peak flows of the Goat River and peak levels of Kootenay Lake were estimated by 1) simulating the observed variability with a random number using the GEV parameters obtained from the observed residuals and 2) adding these simulations to the projected general model trends for peak river flows and peak lake levels that were derived from the hydrologic model ensembles. The approach uses 1000 simulations of projected peak river flows and lake levels in order to estimate the probabilities of threshold exceedance. The annual exceedance probability (AEP) for specified thresholds is determined for each year from 1946 to 2099 by summing the number of times the threshold is exceeded in each year and dividing by the number of simulations (1000). The cumulative risk (CR) is the probability that the threshold will be exceeded once within a planning timeframe and is determined by

$$CR = 1-((1-AEP_1)*(1-AEP_2)*(1-AEP_3)...)$$

where AEPn are the AEPs for the individual years. CR are calculated for future years starting in 2023. Each 'run' of the simulation is repeated 10 times to estimate AEP and CR for a given threshold.

Figure 9 shows the AEP and CR for a threshold of 440 m^3/s in the Goat River based on the projected trend for RCP85. The AEP curve (blue) shows the trend in threshold exceedance probability on an annual basis and the return period (not shown) is the inverse of the AEP. For example, for a flow threshold of 440m^3/s, the annual exceedance probability falls below 1% by about 2050 (and the return period rises above the 100-year event). In non-stationary climate, these AEPs and RPs are only relevant for the year of assessment. At about 2050, the CR curve (orange) rises above about 30% which is the likelihood of exceeding the 440 threshold once within the next 27 years.

For clarity, it is useful to consider the probabilities of rolling a 6-sided die as an analogy. Each time a die is rolled, there is a 1/6 (0.166%) chance of rolling a six. However, if the die is rolled 6 times, the probability of rolling a six is much higher. The AEP is analogous to the probability of rolling the die once (one year) whereas the CR is analogous to rolling the die multiple times (number of years in the planning timeframe).

In order to assess the sensitivity of the projected exceedance probabilities to outliers in the hydrologic model projections, the CR was calculated with 3 outliers removed from the six 150-year model data sets. The outlies were identified by visual inspection of the timeseries for individual years with values that are much higher relative to adjacent years. The flow value at 2047 in the CanESM2 RCP85 is an example of one of the three outliers identified (Figure 7). Two additional clear outliers were removed, one from the CCSM4 RCP85 and one from the CNRM RCP85 timeseries. Figure 9 shows the AEP and CR for the Goat River for a threshold of 440 m^3/s with the model CR with the 3 outliers removed (red line) and included (green line). The calculated CR values are quite sensitive to the removal of 3 outliers from the 900 data points in the six model timeseries. The model CR including outliers is similar to simulated CR until about 2050 and shows higher values thereafter (about 5% higher by 2070); the model CR with the 3 outliers removed yield consistently lower CR values.

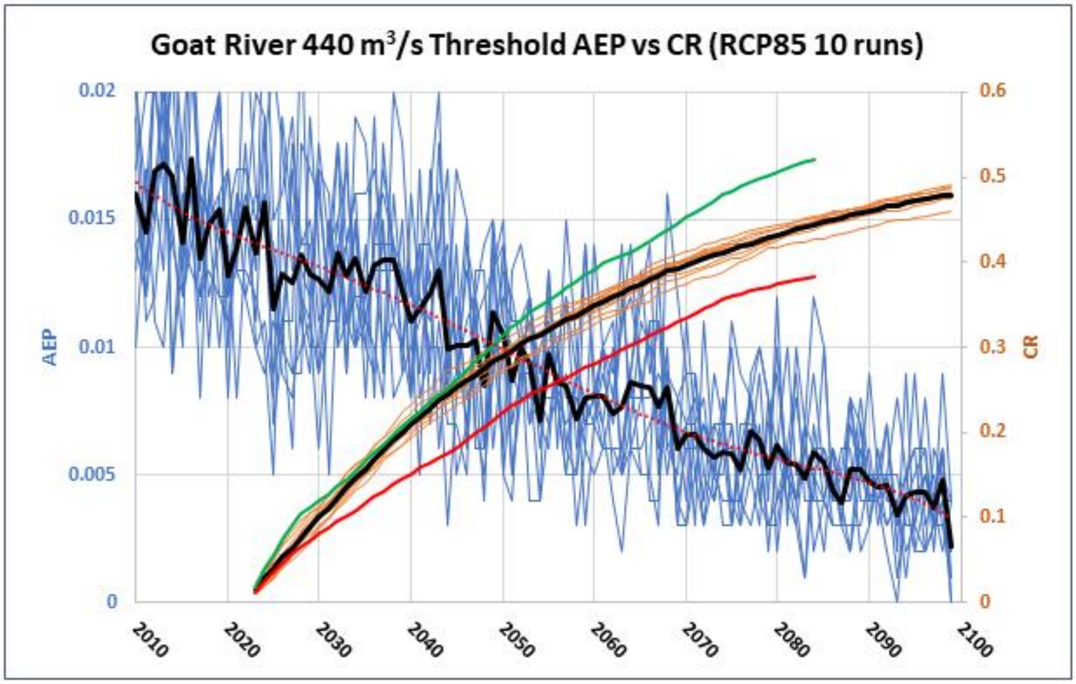


Figure 9 Simulated Annual Exceedance Probability (AEP) and Cumulative Risk (CR) plots for Goat River flow threshold of 440m^3/s with RCP85. Orange curves show CR and blue curves show AEP. Heavy black curves show the average of 10 simulations. The green curve shows the CR based on the 6-member ensemble of PCIC Hydrologic models and the red curve shows the same 6-model ensemble with 3 outliers removed.

The simulated projections are realistic in the sense in that they are based on the observed flow variability over the historical period, however, these are limited in time to the period of observations. On the other hand, the outliers in the model dataset may be representing extremely rare events that emerge from the model projections, but the accuracy of a single model data point is questionable. Consequently, the Goat River projections of threshold exceedance probabilities include estimates based on simulated and model data.

RESULTS

Climate History

Climatic conditions in the Creston area have been changing over the last century and the changes have been substantial (Figures 10a, b; A1 to A4). Mean annual temperature has increased by about 1°C since 1913 and the rate of warming has increased to approximately 2.5 °C per century over the last 50 years. Although the rate of increase in winter temperature over the same periods is similar to annual rates, the frequency of extremely cold winters has declined markedly during the last century. Prior to 1993, winters with mean temperature below -4.0 °C occurred on average every 8 years and the Creston area has not experienced a winter with mean temperature below -4.0 °C for 30 years. The rate of warming has been significantly higher in the summer and in particular over the last 50 summers (over 4 °C per century). The slowest rates of warming over the last century have occurred in spring and fall but both show increases in warming rates over the last 50 years.

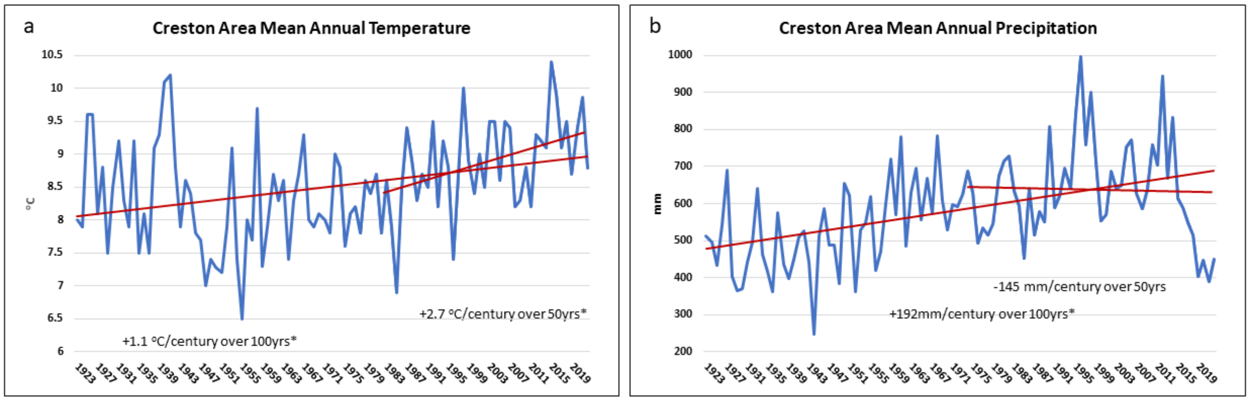
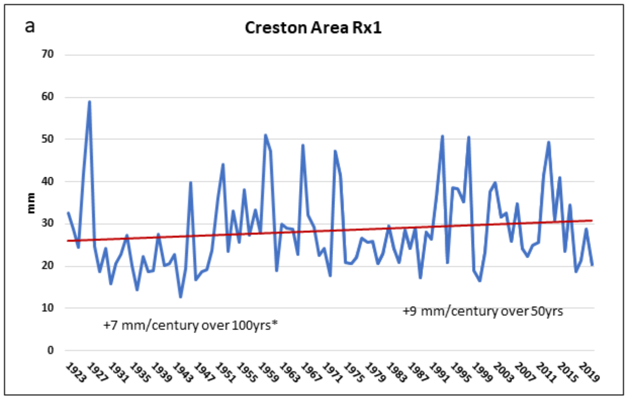


Figure 10 a) Creston area mean annual temperature over the last 100 years with 100-year trend and trend over the last 50 years. b) Creston area mean annual precipitation over the last 100 years with 100-year trend and trend over the last 50 years. Trends that are statistically significant at the 95% confidence are identifies with *.

Mean annual precipitation in the in the Creston area has increased by about 200mm since early in the last century and this increase is reflected in all seasons over this time period. Over the last 50 years, precipitation in the spring has increased at a slow rate whereas winter and fall seasonal precipitation have not changed appreciably. However, summer precipitation has been declining markedly over the last 50 years. Winter, spring and summer precipitation have declined sharply in the last decade, however, whether or not this apparent trend is significant will require more years to assess. Increasing trends in extreme precipitation are evident in the Creston record (Figure 11a, b) although the trends are not significant at the 95% confidence level. 1-day and 3-day maximum precipitation have increased slightly (+7 mm) over the last 100 years. The 2013 peak in Rx3 record, the highest in the Creston record, is significant in that this was a regional precipitation event that had major consequences. Lastly, over the last 50 years, snow season precipitation (Nov – April) in the Creston area and Grey Creek Upper Stn (1930 m) Apr 30 snowpack have both remained essentially stable (Figure 12).

Historical mean annual and season temperature and precipitation plots for the broader Kootenay Lake region are shown in Figures 13a, b; A5 to A8. The observed trends in annual and seasonal temperature and precipitation across the Kootenay Lake region are similar to those of the local Creston record which, in general terms, indicates that local variability in the primary climate parameters is not significant.



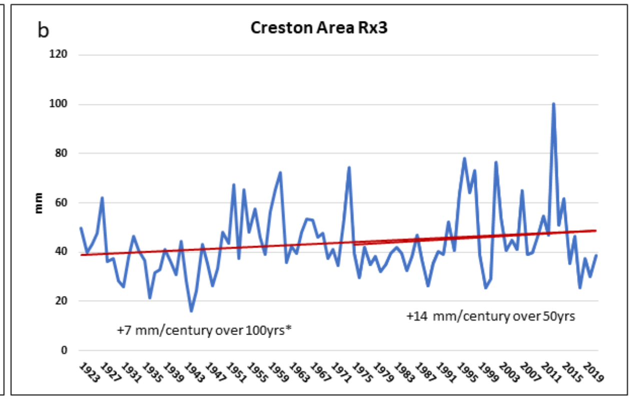


Figure 11 a) Creston area maximum annual 1-day precipitation (Rx1) over the last 100 years with 100-year trend and trend over the last 50 years. b) Creston area maximum annual 3-day precipitation (Rx3) precipitation over the last 100 years with 100-year trend and trend over the last 50 years. Trends that are statistically significant at the 95% confidence are identifies with *.

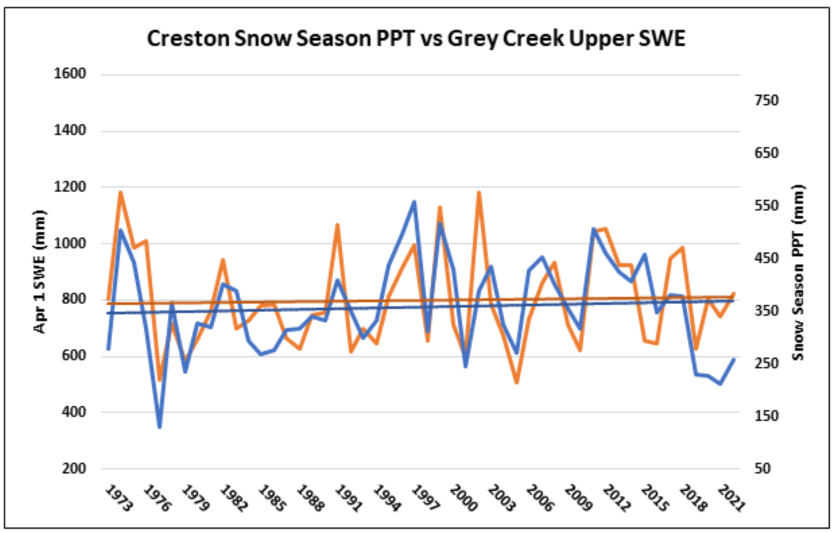


Figure 12 Snow season precipitation (blue curve) at high elevation in the Creston area (Nov – Apr) and snowpack record (SWE) at the Grey Cr Upper snow survey station (orange curve).

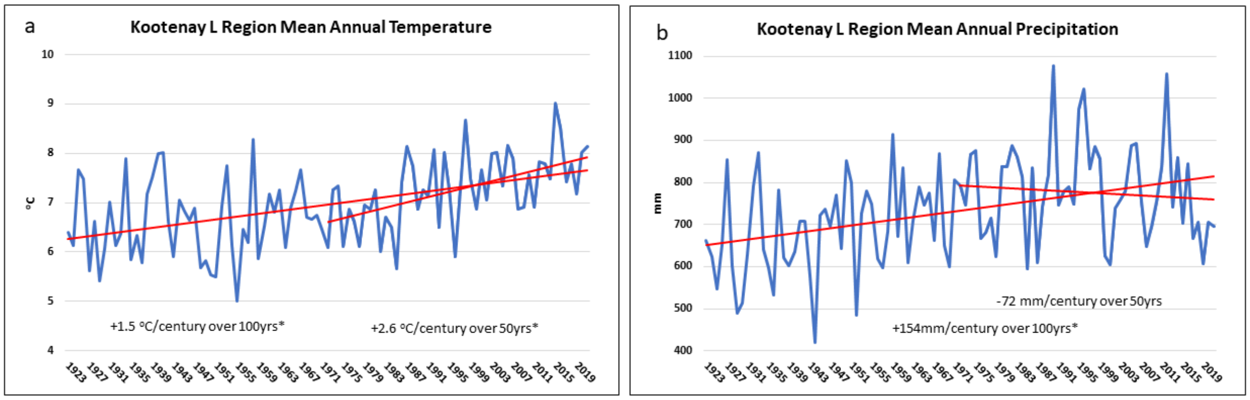


Figure 13 a) Kootenay Lake region mean annual temperature over the last 100 years with 100-year trend and trend over the last 50 years. b) Kootenay Lake region mean annual precipitation over the last 100 years with 100-year trend and trend over the last 50 years. Trends that are statistically significant at the 95% confidence are identifies with *.

Historical Goat River flow and Kootenay Lake levels

The records of annual peak Kootenay Lake water levels and peak Goat River flows are shown in Figure 14. The records are broadly similar which underscores the influence of regional climate on local hydrology. Both records show high levels in the 1950 which is an interval dominated by strongly negative PDO. The Kootenay Lake record includes the pre-Duncan/Libby years (pre-1967) which have been adjusted to correspond with the post-Duncan/Libby (post-1972) record. The Goat River record includes missing years in the record and the estimation of the post-1994 record based on extrapolation from the Moyie River record. Return Periods were calculated for Kootenay Lake levels and Goat River flow over the common period of observations and model projections for both records (1945 – 2022 for Kootenay Lake and 1946 – 2018 for Goat River) and these results are summarised in Table 2.

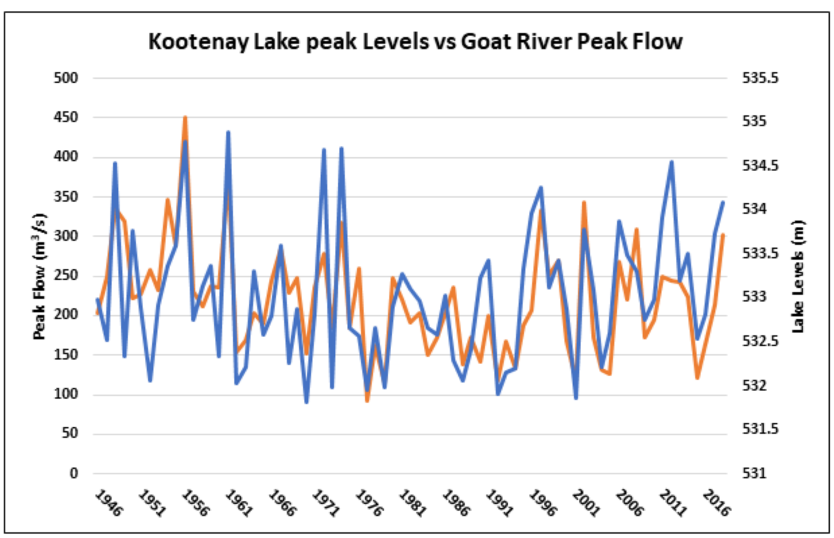


Figure 14 Annual peak Kootenay Lake water levels and peak Goat River flows over 1946 to 2018. Blue curve shows the Kootenay Lake record and the orange curve shows the Goat River record.

Table 2 Return periods for Kootenay Lake peak levels and Goat River peak flows. The RPs are based on records with estimated values over the common period of model projections and observations.

Return Period	200	100	50	25	10	5	2
Goat River (m3/s)	514.1	480.8	445.7	408.7	355.9	311.6	240.2
Kootenay Lake (m)	535.4	535.1	534.8	534.5	534.0	533.6	532.9

Goat and Kootenay peak records are typical for nival hydrological regimes. Peak lake levels and stream flow are strongly linked to snowmelt in the spring and dominate peaks associated with extreme rainfall events. Figures 15 a and b show the relationship between regional Apr 30 SWE and Kootenay Lake peak Levels and the Grey Creek Upper Apr 30 SWE and Goat River peak flows respectively. Although winter and spring temperatures have increased significantly over the last 50 years, Apr 30 SWE at high-elevation snow survey stations in the region (Grey Cr Upper, East Cr, Fernie, Floe, Moyie, Redfish) have been essentially stable (Figure 15). Over the last 30 years, the mean peak flow date for the Goat River is approximately May 8, which is about 9 days earlier than mean peak flow dates in the 1961-1990 interval. The average peak Lake level date for Kootenay lake over the last 30 years is approximately June 9 and this has not changed appreciably since the 1980s. There are 4 years in which the Kootenay Lake level peak did not occur at spring freshet, 1941, 1973, 1977 and 1979 but occurred between late October and early December. The three peak levels in the 70s may have been influenced by Duncan/Libby flow regulation and were all below 532m. In 1941 December peak level reached 532.7m which was slightly above the very low 1941 freshet peak of 532.65m.

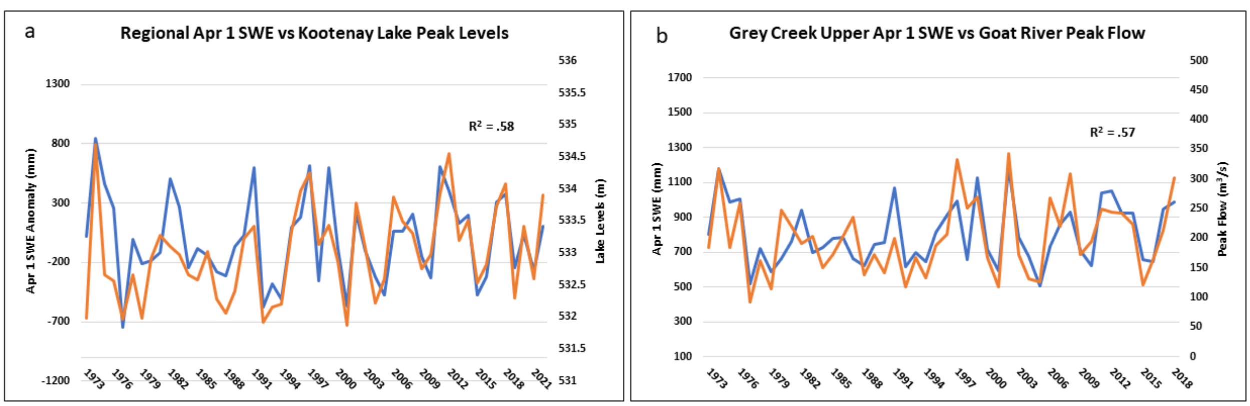


Figure 15 a) Annual peak Kootenay Lake levels and regional high elevation Apr 1 SWE (Grey Cr Upper, East Cr, Fernie, Floe, Moyie, Redfish snow survey stations). a) Annual peak Goat River flow and April 1 SWE at the Grey Creek Upper snow survey station. Blue curves represent lake levels and streamflow. Orange curves represent SWE.

General Climate Projections

Climate model projections for the Creston area and the Kootenay Lake region are summarised in tables 3 – 6. Climate model projections for the Creston area and larger Kootenay Lake regions are broadly similar and indicate that both annual and seasonal temperatures will warm significantly over the coming decades and these temperature increases will be accompanied by changes in precipitation. The changes are relative to the 1976-2005 base period and tend to be more pronounced under the higher emissions pathway (RCP85). Mean annual temperatures are projected to be between 2.7 °C and 4.0°C warmer by the 2070s depending on which emissions pathway is followed. Mean annual precipitation is also projected to increase under both emissions pathways. However, with respect to seasonal precipitation, summer precipitation is expected to decline, whereas precipitation is expected to increase in all other seasons. Additional details for projected indices for the Creston area are summarized in Tables 3 and 4.

After the 2050s, the temperature projections show a clear separation between outcomes for the low (RCP45) and high (RCP85) emissions pathways with higher temperatures associated with the high emissions pathway. This divergence between low and high emissions model projections of mean annual temperature increases significantly by the end of this century. With respect to modeled mean annual and seasonal precipitation, the divergence between emissions pathways is less pronounced.

Model projections indicate that extreme precipitation (Rx1 and Rx3) will increase in the coming decades. Under RCP45, Rx1 and Rx3 will increase by +6% to +7% respectively by the 2030s and by +8.1% and 9.7% respectively by the 2070s. Under RCP85, Rx1 and Rx3 will increase by +6% and +6% respectively by the 2030s and by +12.7% and +13.1% respectively by the 2070s (Table 7). Estimates of future Rx1 and Rx3 based on %7/°C Clausius Clapeyron scaling indicate 100-year Rx1 and Rx3 precipitation events will increase from by 10% to 30% relative to 1981 – 2005 depending on emissions pathway and timeframe (Table 4).

Hydrologic Projections

The PCIC ensemble of hydrological models provide projections of general trends for future peak annual flow for the Goat River and for the Kootenay River at Brilliant. As peak flow in the Kootenay River at Brilliant is highly correlated with Kootenay Lake peak levels, model projections for peak flow of the Kootenay River at Brilliant and can be used as a proxy for future Kootenay Lake levels. The projected trends for peak Kootenay Lake levels and Goat River flow based on RCP45 and RCP85 are shown in Figure 16 a, b. Current and future changes in peak lake levels and stream flows are linked to changes in snow dynamics and this is reflected in the projected trends in Goat River flow and peak Kootenay lake levels.

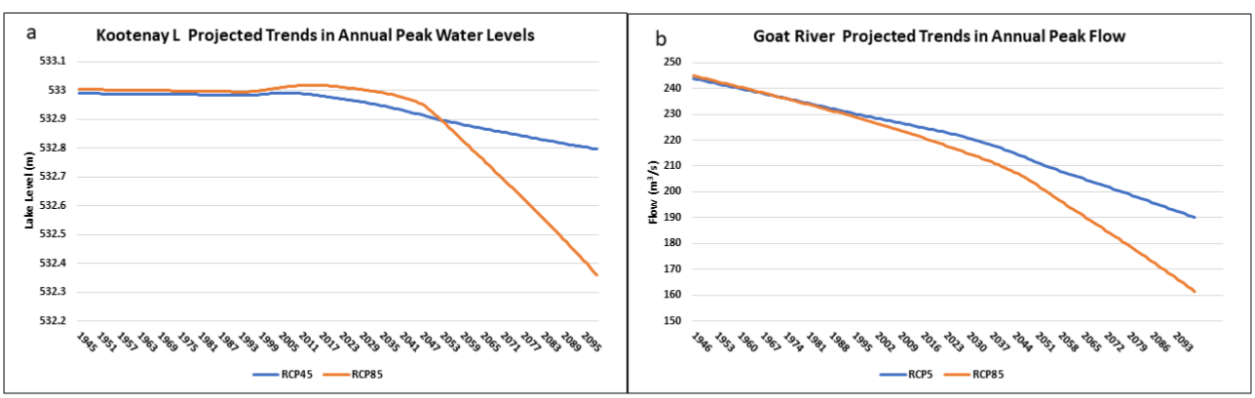


Figure 16 General projected trends for peak annual Kootenay Lake levels. Figure 16b. General projected trends for peak annual Goat River flow. Blue curves represent RCP45 model projections. Orange curves represent RCP85 model projections.

Table 3 Climate projection or the Creston area (RCP45)

RCP45		1976 to 2005	2021 to 2050			2051 to 2080			2021 to 2050	2051 to 2080
Variable	**Period**	**Mean**	**10 %ile**	**Mean**	**90 %ile**	**10 %ile**	**Mean**	**90 %ile**	**Change**	**Change**
Precipitation (mm)	annual	610	502	641	792	500	649	806	+5.1%	+7.8%
Max 1-day Precipitation (mm)	annual	24.1	24	25.8	27.1	24	26.1	28	+6.9%	+8.1%
Max 3-day Precipitation (mm)	annual	34.9	34.9	36.9	39.1	35	38.2	42	+5.9%	+9.7%
Precipitation (mm)	spring	135	92	147	207	94	149	212	+8.9%	+15.2%
Precipitation (mm)	summer	124	54	122	199	53	119	191	-1.6%	-9.3%
Precipitation (mm)	fall	150	94	159	223	93	161	234	+6.0%	+11.7%
Precipitation (mm)	winter	201	133	214	300	137	221	315	+6.5%	+15.0%
Mean Temperature (°C)	annual	8	8.5	9.7	10.9	9.4	10.7	12.1	+1.7	+2.7
Mean Temperature (°C)	spring	7.9	7.7	9.8	11.8	8.8	10.7	12.7	+1.9	+2.8
Mean Temperature (°C)	summer	18.2	18.5	20.1	21.8	19.2	21.2	23.2	+1.9	+3.0
Mean Temperature (°C)	fall	7.7	7.7	9.2	10.6	8.5	10.1	11.5	+1.5	+2.4
Mean Temperature (°C)	winter	-2	-2.7	-0.4	1.7	-1.6	0.7	2.8	+1.6	+2.7
Tropical Nights	annual	0	0	0	2	0	2	6	0.0	+2.0
Very hot days (+30°C)	annual	22	19	36	55	25	46	68	+14.0	+24.0
Cold days (-15°C)	annual	5.1	0.02	3.0	9.5	0	1.5	6.4	-2.1	-3.6
Date of Last Spring Frost	annual	Apr. 19	Feb. 27	Mar. 29	Apr, 28	Feb. 12	Mar. 18	Apr. 21	-21.0	-32.0
Date of First Fall Frost	annual	Oct. 8	Sep. 28	Oct. 20	Nov. 11	Oct. 5	Oct. 29	Nov. 22	+12.0	+21.0
Frost-Free Season (days)	annual	169	165	202	239	180	222	264	+33.0	+53.0

Table 4 Climate projection or the Creston area (RCP85)

RCP85		1976 to 2005	2021 to 2050			2051 to 2080			2021 to 2050	2051 to 2080
Variable	**Period**	**Mean**	**10 %ile**	**Mean**	**90 %ile**	**10 %ile**	**Mean**	**90 %ile**	**Change**	**Change**
Precipitation (mm)	annual	610	498	637	786	515	671	837	+4.4%	+12.2%
Max 1-day Precipitation (mm)	annual	24.4	23	25.8	28.1	25	27.5	30.1	+5.9	+12.7%
Max 3-day Precipitation (mm)	annual	34.8	34	36.9	39.2	36.9	39.4	43.1	+6.0%	+13.1%
Precipitation (mm)	spring	135	88	146	211	99	155	222	+8.1%	+22.7%
Precipitation (mm)	summer	124	56	121	198	49	120	199	-2.4%	-7.1%
Precipitation (mm)	fall	150	88	156	232	97	166	246	+4.0%	+18.2%
Precipitation (mm)	winter	201	133	214	295	144	230	329	+6.5%	+21.8%
Mean Temperature (°C)	annual	8	8.8	10	11.2	10.4	12	13.5	+2.0	+4.0
Mean Temperature (°C)	spring	7.9	8	10	12	9.6	11.7	13.9	+2.1	+3.8
Mean Temperature (°C)	summer	18.2	18.8	20.4	22	20.5	22.7	24.9	+2.2	+4.5
Mean Temperature (°C)	fall	7.7	8	9.5	10.9	9.7	11.4	13.2	+1.8	+3.7
Mean Temperature (°C)	winter	-2	-2.7	-0.1	2.1	-0.7	1.8	4.2	+1.9	+3.8
Tropical Nights	annual	0	0	1	3	0	7	19	+1.0	+7.0
Very hot days (+30°C)	annual	22	21	39	58	36	59	83	+17.0	+37.0
Cold days (-15°C)	annual	5.7	0	2.4	8.6	0	0.8	4.7	-3.3	-4.9
Date of Last Spring Frost	annual	Apr. 19	Feb. 25	Mar. 26	Apr, 25	Jan. 27	Mar. 6	Apr. 8	-24.0	-44.0
Date of First Fall Frost	annual	Oct. 8	Sep. 30	Oct. 23	Nov. 14	Oct. 17	Nov. 11	Dec. 10	+15.0	+34.0
Frost-Free Season (days)	annual	169	170	207	243	204	247	292	+38.0	+78.0

Table 5 Climate projection or the Kootenay Lake region (RCP45)

RCP45		1976 to 2005	2021 to 2050			2021 to 2050			2021 to 2050	2021 to 2050
Variable	**Period**	**Mean**	**10 %ile**	**Mean**	**90 %ile**	**10 %ile**	**Mean**	**90 %ile**	**Change**	**Change**
Precipitation (mm)	annual	742.8	628	781.6	948.4	628	792.2	965	+5.2%	+7.9%
Precipitation (mm)	spring	174	127	189.4	258.2	128.8	192.4	264.2	+8.9%	+14.5%
Precipitation (mm)	summer	157.2	78.4	154.8	241.8	75	150.8	233	-1.5%	-8.2%
Precipitation (mm)	fall	176.2	118.4	186.6	257	114.8	188.8	268.6	+5.9%	+10.6%
Precipitation (mm)	winter	236.2	162.2	251.2	343.2	170.6	259.8	361.2	+6.4%	+14.5%
Mean Temperature (°C)	annual	3.58	4.02	5.3	6.54	4.84	6.3	7.76	+1.7	+2.7
Mean Temperature (°C)	spring	3.04	2.6	4.88	7.12	3.76	5.84	8.04	+1.8	+2.8
Mean Temperature (°C)	summer	13.86	14.08	15.7	17.54	14.76	16.8	18.86	+1.8	+2.9
Mean Temperature (°C)	fall	3.62	3.4	5.14	6.74	4.2	6.08	7.64	+1.5	+2.5
Mean Temperature (°C)	winter	-6.4	-7.44	-4.8	-2.34	-6.3	-3.68	-1.2	+1.6	+2.7

Table 6 Climate projection or the Kootenay Lake region (RCP85)

RCP85		1976 to 2005	2021 to 2050			2051 to 2080			2021 to 2050	2051 to 2080
Variable	**Period**	**Mean**	**10 %ile**	**Mean**	**90 %ile**	**10 %ile**	**Mean**	**90 %ile**	**Change**	**Change**
Precipitation (mm)	annual	742.8	624.4	778	944	642.4	818.2	1001.8	+4.7%	+12.1%
Precipitation (mm)	spring	174.2	124.4	189.4	263.4	135.8	202	277	+8.7%	+22.3%
Precipitation (mm)	summer	157	81.4	154.4	241	69.8	152	244.8	-1.7%	-6.1%
Precipitation (mm)	fall	176.2	111	183	262.4	120.2	194	278.2	+3.9%	+16.0%
Precipitation (mm)	winter	236	165.4	251.4	338.6	177.6	270.6	375.6	+6.5%	+20.9%
Mean Temperature (°C)	annual	3.58	4.24	5.56	6.82	5.92	7.56	9.12	+2.0	+4.0
Mean Temperature (°C)	spring	3.02	2.86	5.08	7.28	4.56	6.86	9.24	+2.1	+3.8
Mean Temperature (°C)	summer	13.86	14.42	16.04	17.72	16.12	18.34	20.54	+2.2	+4.5
Mean Temperature (°C)	fall	3.62	3.66	5.38	7	5.44	7.38	9.3	+1.8	+3.8
Mean Temperature (°C)	winter	-6.42	-7.38	-4.48	-1.9	-5.46	-2.58	0.2	+1.9	+3.8

Table 7 100-yr Rx1 and Rx3 events based on Clausius Clapeyron scaling (+7% per °C).

	1981 - 2010	2021 - 2050	2051 - 2080	2021 - 2050	2051 - 2080
Rx1 (RCP45)	56.9	63.0	67.9	+10.72%	+19.33%
Rx3 (RCP45)	90.5	102.3	107.9	+13.04%	+19.23%
Rx1 (RCP85)	56.9	64.3	73.6	+13.01%	+29.35%
Rx3 (RCP85)	90.5	102.3	117.1	+13.04%	+29.39%

The projected (RCP85) trend for peak Kootenay Lake Levels shows a very slight increase over the historical period, which is consistent with the observed trend, and subsequent steady declines after about 2030. The RCP45 trend is similar but is essentially stable until about 2040 and declines thereafter but at a lower rate than the RCP85 trend. Peak lake levels are strongly correlated with maximum snowpack which, in turn, is influenced by winter precipitation and winter temperature. Although winter temperature has been increasing significantly over recent decades, and this trend is expected to continue for the foreseeable future, peak lake levels remain stable or increases slightly until about 2032. This is likely in response to increasing projected winter precipitation which adds to snowpack, especially at higher elevations. However, later in the century, warming temperatures become the dominant factor for snowpack and override the effect of increasing winter precipitation resulting in a decline in maximum snowpack and peak lake levels. Consequently, assuming the operations of the Libby and Duncan Dams remains unchanged, peak lake levels are expected to decline after the mid-2030s under both RCP45 and RCP85 emissions pathways. The declining trend is more pronounced with the RCP85 emissions pathway.

The RCP85 and RCP45 projected trends for peak flow in the Goat River show continuing and intensifying decline and are in line with the observed record over the period 1946 to 2018. It is likely that increasing winter and spring temperatures are already the primary driver of changes in the winter snowpack in the Goat watershed. The Nelson snow survey station (2D04), which is about 60 km west of, and 100m lower than the centroid elevation of the Goat watershed, shows a clear trend in declining Apr 1 snowpack SWE at a rate of 290 mm/century over the last 50 years. The declining future trend in Goat River peak flow is more pronounced with the RCP85 projections which reflects the stronger impact of warmer temperatures associated with higher greenhouse gas forcing.

RCP85 projections of annual maximum SWE for 3 grid cells in the region (low elevation – Creston, mid elevation – upper Grey Creek and high elevation – MacBeth) are shown in Figure 17. These timeseries show the projected climate change impacts on snowpack in the region over the course of the century. Snowpack decline begins prior to ca 1970 at the low elevation grid cell, after ca 2035 at the mid elevation grid cell and remains stable at the high elevation grid cell. The projected trend in annual peak flow of the Goat River resembles a projected trend in annual maximum snowpack that falls between the low and mid elevations grid cells, which is consistent with the location of the Goat watershed. The projected trend in Kootenay lakes levels resembles a projected trend in annual maximum snowpack that falls in between the mid and high elevations grid cells, which reflects the high-elevations areas in the Kootenay watershed.

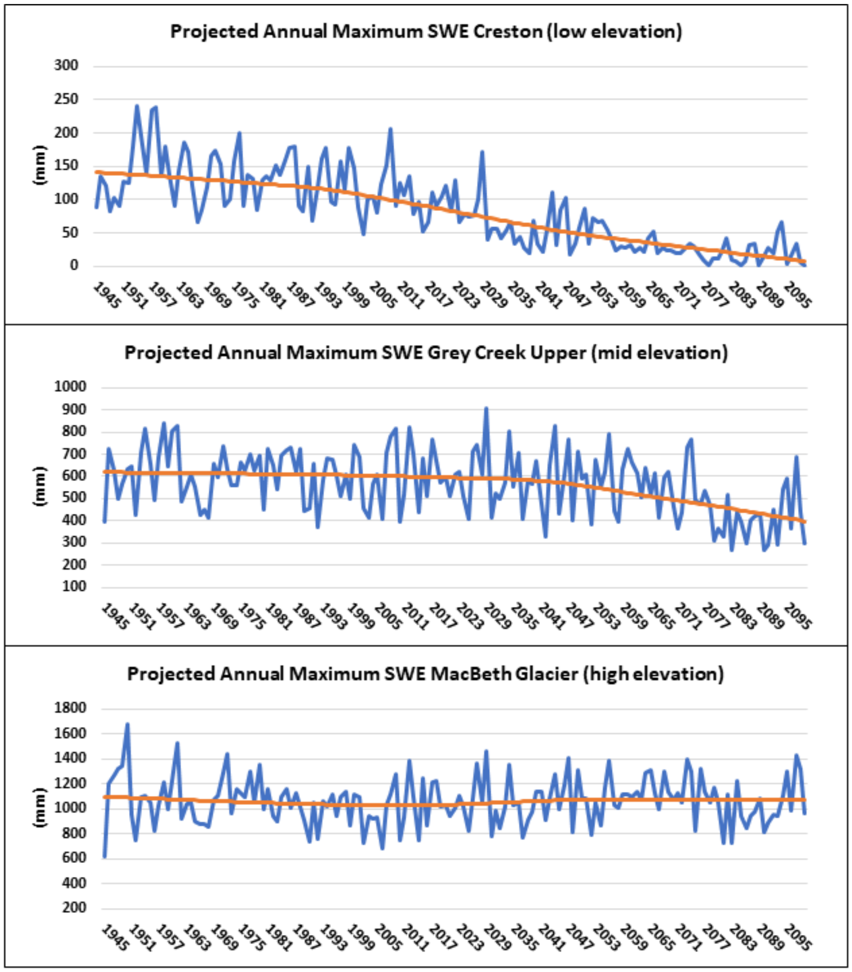


Figure 17 Upper plot shows the projected SWE for a low-elevation grid cell that includes the Town of Creston. The middle plot shows the projected SWE for a mid-elevation grid cell that includes the Grey Creek Upper snow survey station. The lower plots show the projected SWE for a high-elevation grid cell that includes the MacBeth Glacier.

Threshold Exceedance Probabilities

Figures 9, and B1 to B12 show projected AEP and CR (RCP45 and RCP85) for the Goat River and for Kootenay Lake levels respectively. The Goat River plots include projected AEP and CR for 6 flow thresholds (420, 440, 460, 480, 500 and 520m^3/s) and the Kootenay Lake plots for 6 lake level thresholds (534.8, 535.0, 535.2, 535.4, 535.6 and 535.8 m). In both cases, the annual exceedance probabilities decline over time which reflects the general trend in projected declining peak river flows and lake levels. Also, in both cases the AEPs decline is more pronounced with the high emissions RCP85 emissions pathway. The cumulative risk curves increase over time; however, this increase is significantly less that what would be associated with stationary or increasing AEPs over time.

The Goat River AEP and CR plots also include the CR curve based on the 6-model hydrologic projections which include all outlies in these data sets. For all thresholds, the RCP85 model-based CR curves indicate a higher probability of threshold exceedance than the curves based on simulated data. RCP45 model-based CR curves track closer to the curves based on simulated data. This difference is approximately -2% at 2050 and +1% at 2070 with RCP45 and +3% at 2050 and +6% at 2070 with RCP85. If a conservate approach for planning purposes is desired, the CR estimates could be based on the model rather than simulated curves which would add on average 3% to 6% to the estimates prior to 2070 under RCP85.

The CR curves provide potentially valuable information for assessing the vulnerability of the Creston dike system to anticipated changes in climate. Whereas the AEP curves provide information for a given year (including the return period for that year, which is the inverse of the AEP), the CR provide the likelihood of exceeding a particular threshold over time. This is useful for circumstances in which a single exceedance of a threshold will be consequential, such as the failure of a dike. For example, Figure B2 (480 m^3/s flow) indicates that the probability of Goat River flow exceeding 480 m^3/s will surpass 10% at about 2043. If this level of flow represents a potential threat to the viability of a particular sections of dike, and the risk tolerance for this section failing is 10%, then there is a 20-year period in which to take steps to reenforce the dike before the likelihood of exceedance surpasses the risk tolerance. Should the potential failure of the dike be more consequential and the risk tolerance lower, the timeframe for adaptative measures can be determined from the plot.

Conversely, the threshold exceedance probabilities approach can be used to estimate the flow (or levels) that sections of dike should be designed for in order to have a specified confidence that they will not fail. For example, in Figure B1 (520 m^3/s flow), the CR curve reaches 5% at about 2050. This indicates that there is 95% confidence that the Goat River will not reach a flow of 520m^3/s before 2050. In other words, planners can assume with 95% confidence that a dike designed to withstand a peak flow of 520m^3/s will not be overtopped before 2050. In this case, the confidence level based on model rather than simulated data is about 93%.

In response to the anticipated changes in climate in the region, the Goat River is expected to evolve from a nival toward a nival-pluvial hydrologic regime (Figure 18). Model projections show that peak flow associated with spring freshet will decline over time and, in the last 2 decades of the century, the spring freshet peaks become largely indistinguishable from peaks associated with increasingly intense precipitation events. However, although precipitation is projected to increase in winter spring and fall, and decrease in the summer, the projected maximum flow peaks associated with increases in precipitation do not approach the maximum flow levels of the 20th century and early 21st century (Figure 18).

The effect of the highest Rx3 event in the Creston record on the flow of the Moyie River, which has a similar extreme flow history with the Goat, may provide some additional insights into the potential impact of extreme precipitation on Goat River flow. Figure 19a, b shows Moyie River flow for the spring of 2013 and the Creston Rx3 record. The flow peak that is associated with the record rainfall event is evident in the flow record (75m^3/s). This event occurred 5 weeks after spring freshet peak when flow had dropped below 25m^3/s; the June Rx3 rainfall event was not superimposed on the tail of higher flows associated with spring freshet. The 2013 flow peak associated with the record precipitation event did not approach the 2013 freshet peak of 165m^3/s and the 2013 freshet peak was significantly lower than the recent high peak flow in the Moyie record (e.g. 245m^3/s in 2002). Assuming all other contributing factors are unchanged, it follows that an extremely large (well above those projected by climate models and Clausius Clapeyron scaling) rainfall event would be required to drive peak flow in the Moyie to record freshet levels. Because of the similarities in peak flow history of the Goat and Moyie Rivers, this likely applies to the Goat River as well. However, the magnitude of rainfall events is clearly not the only factor that may contribute to extreme streamflow. For example, the record-breaking November 2021 floods in southwestern BC were primarily driven by extreme precipitation (intensified by human-induced climate change) but would have been less extreme (and damaging) had they not been exacerbated by saturated ground from antecedent precipitation and snowmelt associated with a rapid rise in temperature (Gillett et al., 2022).

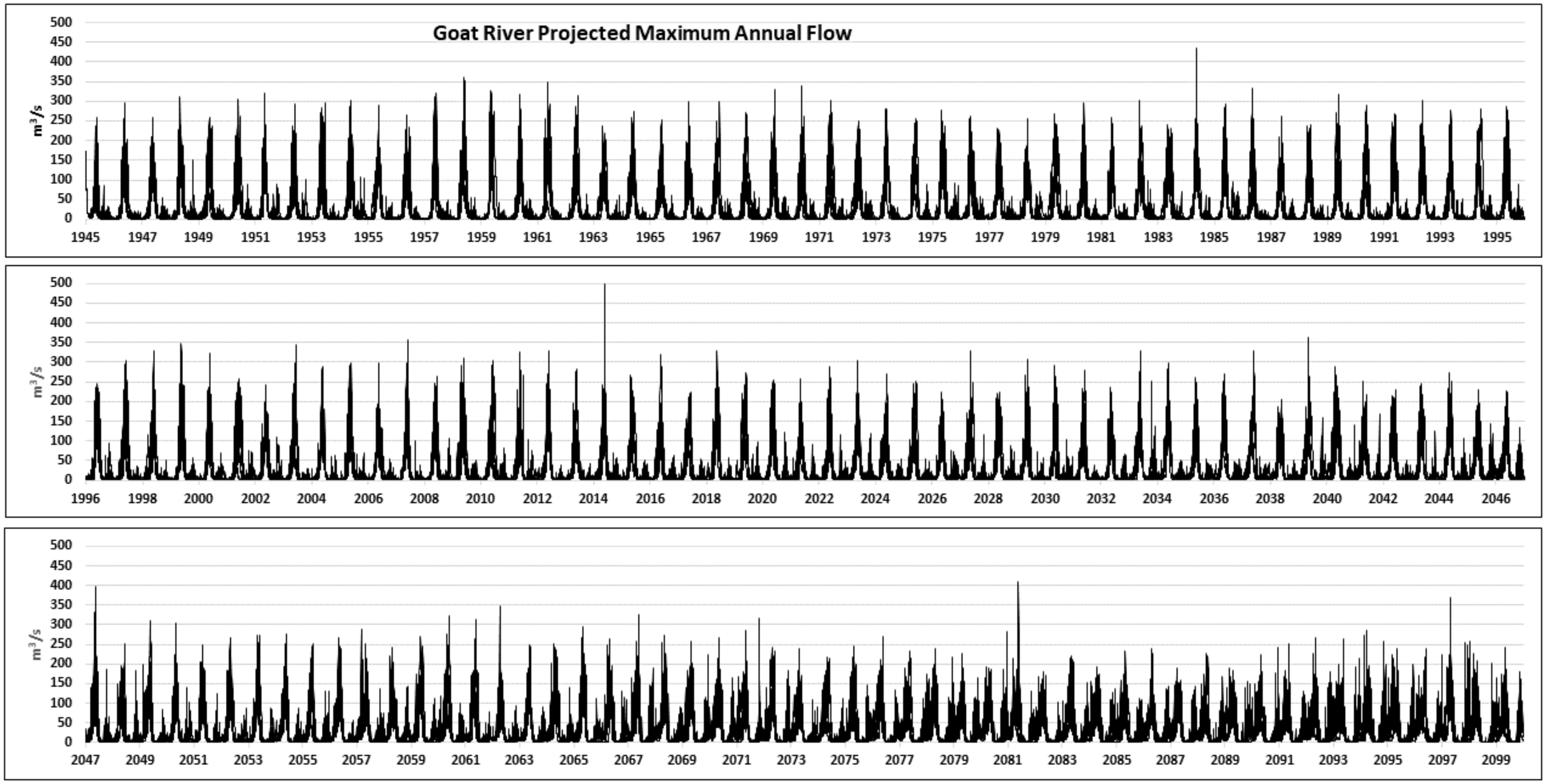


Figure 18 Individual daily model projections for Goat River maximum annual flow (RCP85). The timeseries shows the evolution of the Goat River from a nival toward a nival-pluvial hydrologic regime. Maximum flow associated with spring freshet will decline over time and high flow events associated with precipitation events will increase in spring winter and fall seasons.

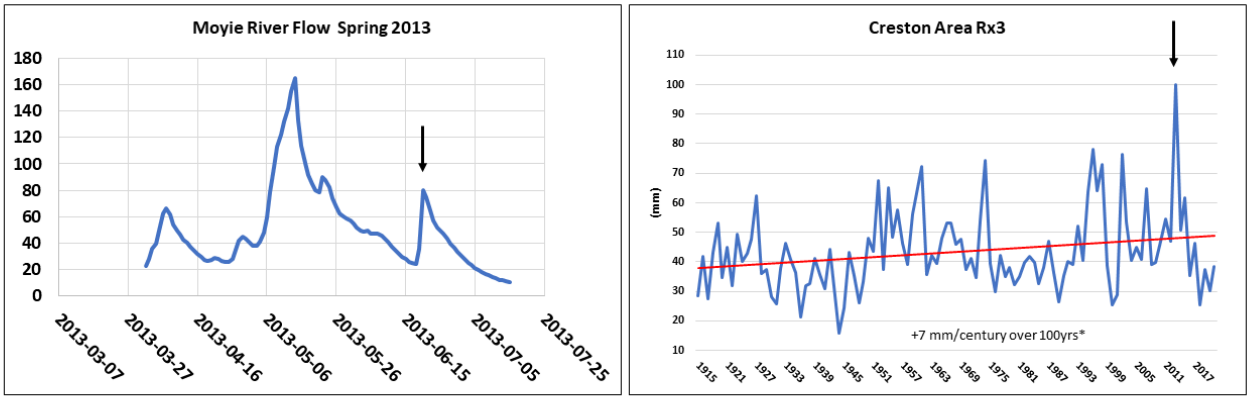


Figure 19 a) Moyie River flow from Apr 1 to July 15, 2013. The black arrow highlights the flow peak associated with the extreme Rx3 event. b) Maximum Annual 3-day precipitation (Rx3) at Creston. Rx3 has been increased by 7 mm over the last century and the rate of increase is significant at the 95% confidence level. The black arrow highlights the 2013 record Rx3 event of 100.2 mm.

SUMMARY AND RECOMMENDATIONS

Changes in climate in the Kootenay Lake region over the last century have been significant and the rate of change for many indices (e.g. mean summer temperature) have increased in recent decades. Climate model projection indicate the changes that have already been experienced in the region, will continue over the coming decades and will be more severe if humanity is unable to reign in emissions and follows a carbon intensive emissions pathway in the future. The climate and hydrologic models in this report reflect potential outcomes from an emissions pathway (RCP45) that is roughly midway between the Paris Agreement goals (<2°C) and commitments (~3°C) and a pathway that does little to mitigate carbon emissions in the future (RCP85). It is difficult to predict the degree to which the global community will be able to reduce emissions in the future. However, it appears that many countries are not on track to meet their Paris commitments (Liu and Raftery, 2021) and, consequently, it is prudent not to rule out the RCP85 projections for planning purposes.

The hydrological model projections used in this study are based on 6-model ensembles for RCP45 and RCP85 emissions pathways. Their output provides robust projections for the general trends in peak annual Goat River flow and Kootenay Lake levels for future decades. The trends for streamflow and lake levels both decline over the coming decades and the decline is more significant with the RCP85 projections. Both Goat River and Kootenay Lake watersheds are nival hydrologic regimes and peak flow and lake levels are strongly correlated with maximum annual snowpack; high water levels generally tend to occur in years that have high Apr 30 snowpacks. Consequently, the key link between climate projections and future streamflow and lake levels is the effect that future changes in precipitation and temperature will have on maximum annual snowpack in the region.

The Kootenay Lake watershed includes high-elevation areas that are currently glaciated. Projected increases in winter precipitation, which falls as snow at the higher elevations, will likely maintain or increase snowpack in these higher areas over the near term. However, by the mid 2030s, increasing winter temperature becomes the dominant factor influencing snow dynamics which will result in decreasing maximum annual snowpacks, which in turn, drives the projected trend in declining peak lake levels. The more rapidly temperatures warm (RCP85 vs RCP45), the more rapidly peak lake levels will decline. The Goat River watershed is a sub-drainage of the Kootenay and does not include topography that is high enough to currently support glaciers. The observed trend in annual peak flow of the Goat River is already in decline which reflects declining maximum snowpack in the watershed. The model projections indicate the decline will intensify in the coming decades, particularly with the RCP85 projections. In general terms, and in the absence of any significant changes in future variability of observed streamflow or lake levels, the likelihood of peak water levels reaching or exceeding those experienced in the historical record will decline over time.

For some planning purposes, this general picture of the expected future trends in peak annual Goat River flow and Kootenay Lake levels may be sufficient. This study adds detail to the general projections by attempting to quantify the future probabilities of threshold exceedance for Kootenay Lake levels and Goat River flows. Two approaches were used for peak Goat River flow projections. Annual exceedance probabilities for specified thresholds in Goat River flow were determined by fitting the hydrologic model data to generalized extreme value (GEV) distributions in future 30-year windows. This approach is limited by the relatively small number of models in the ensemble and is very sensitive to outliers in the projected flow datasets. The second approach involved isolating the observed variability of the peak flow record and superimposing simulations of the observed variability onto the general model trends. This approach is limited in that the variability is restricted to the period of observations. Future probabilities for threshold exceedance in Goat River flow include the results from both methods and the results are generally similar. The projections for peak Kootenay Lake levels rely on the simulated approach only due to a poor fit between model and observed variability over the period of observations.

The threshold exceedance probability plots include timeseries of Annual Exceedance Probabilities (AEP) and Cumulative Risk (CR) (Figures 9, B1 to B12). AEP represents the likelihood of exceeding the specified threshold in a specific year and the return period (RP) is the inverse of the AEP. Both AEP and RP are relevant only for the year in question; in a non-stationary system, the 100-yr event today will not be the 100-year event in 5 years. The CR is the probability that the specified threshold will be exceeded within a planning timeframe and is the probability of threshold exceedance that 'accumulates' over time. For example, if the end of the planning timeframe is 2063, the CR curve for Goat River threshold of 440 m^3/s indicates there is a 36% chance of exceeding this threshold within the next 40 years (Figure 9, B3). This approach may be most useful for situations where a threshold exceedance will be consequential, such as the overtopping of a dike.

Lastly, both model projections and Clausius Clapeyron scaling (+7%/°C) suggest future extreme precipitation events will likely be insufficient to result in extreme stream flows (or lake levels) that will exceed the maximum freshet peaks observed in the historical period. However potentially high-water levels associated with future extreme precipitation events cannot be ruled out; the 'perfect storm' of antecedent conditions and rapidly changing temperatures could significantly intensify high water levels especially if an extreme precipitation event follows snowfalls or coincides with spring freshet.

Some of the more detailed results of this study are based on novel approaches for estimating future probabilities of threshold exceedance and it is very likely that these methods will be refined in the future. More generally, climate change science is constantly evolving and updating. For example, many model projections made over the last decade are now updating to CMIP6. With respect to hydrologic model output, PCIC has already provided new and improved hydrologic model projections for the Fraser Basin (PCIC Climate Explorer) and these will likely be expanded to the Peace Basin shortly and to Columbia Basins in about a year baring unforeseen circumstances (Schnorbus pers.com., 2023). It is recommended that information related to climate and hydrologic projections are periodically updated as new information becomes available.

REFERENCES

BGC. (2020). *RDCK Floodplain and Steep Creek Study, Goat River*. Prepared by BGC Engineering Inc. for: Regional District of Central Kootenay.

ClimateBC/WNA. (n.d.). ClimateBC/WNA. Retrieved March 27, 2023, from https://cfcg.forestry.ubc.ca/projects/climate-data/climatebcwna/

Climate Change in Canada | Climate Atlas of Canada. (n.d.). Retrieved March 27, 2023, from https://climateatlas.ca/

Gillett, Nathan P., et al. "Human influence on the 2021 British Columbia floods." *Weather and Climate Extremes* 36 (2022): 100441.

Climate Data Canada - IDF Data and Climate Change. (n.d.). Retrieved February 1, 2023, from https://climatedata.ca/resource/best-practices-for-using-idf-curves/

Liu, Peiran R., and Adrian E. Raftery. "Country-based rate of emissions reductions should increase by 80% beyond nationally determined contributions to meet the 2 C target." *Communications earth & environment* 2.1 (2021): 29.

National Academies of Sciences, Engineering, and Medicine. "Climate change: evidence and causes Update 2020." *The National Academies Press, Washington. https://doi. org/10* 17226 (2020): 25733.

PCIC Statistically Downscaled Climate Scenarios. (2018, June 1). Statistically Downscaled Climate Scenarios. https://www.pacificclimate.org/data/statistically-downscaled-climate-scenarios

PCICa Gridded Hydrologic Model Output. (n.d.) Retrieved February 1, 2023, from https://www.pacificclimate.org/data/gridded-hydrologic-model-output

PCICb Station Hydrologic Model Output. (n.d.) Retrieved February 1, 2023, from https://www.pacificclimate.org/data/station-hydrologic-model-output

Taylor, Karl E., Ronald J. Stouffer, and Gerald A. Meehl. "An overview of CMIP5 and the experiment design." *Bulletin of the American meteorological Society* 93.4 (2012): 485-498.

Utzig, G. “Alterations to the Hydrology of Kootenay Lake” (2021). Kutenai Nature Investigations Ltd.

Wang, Xiaolan L., and Val R. Swail. "Changes of extreme wave heights in Northern Hemisphere oceans and related atmospheric circulation regimes." *Journal of Climate* 14.10 (2001): 2204-2221.

APPENDIX A   CLIMATE HISTORY PLOTS

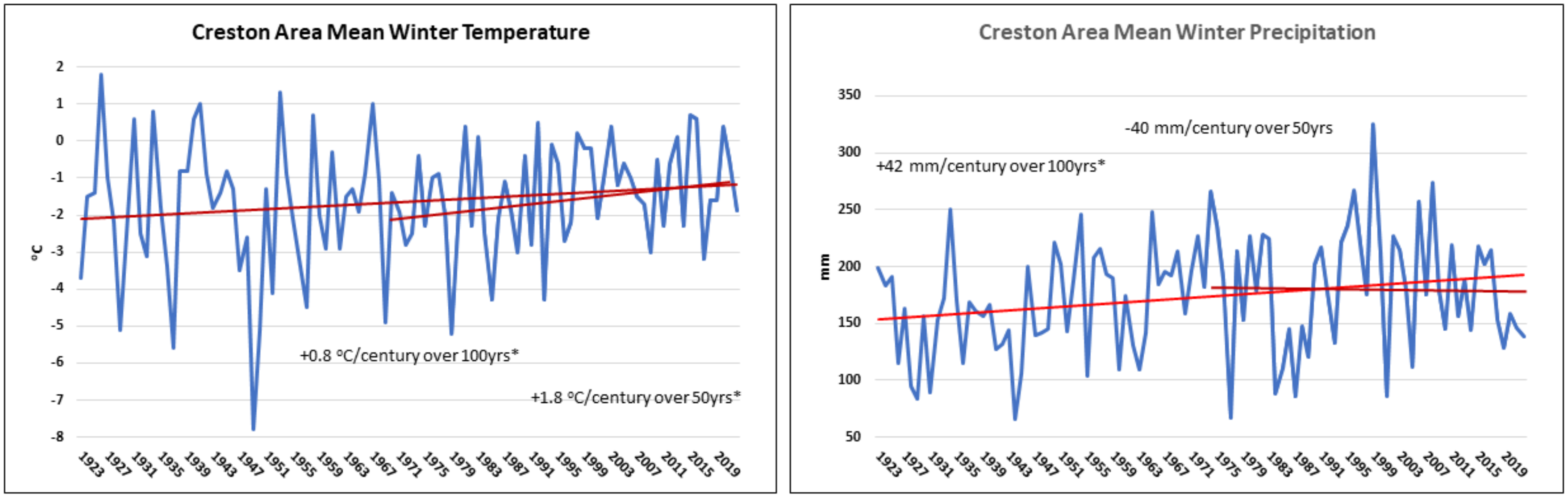
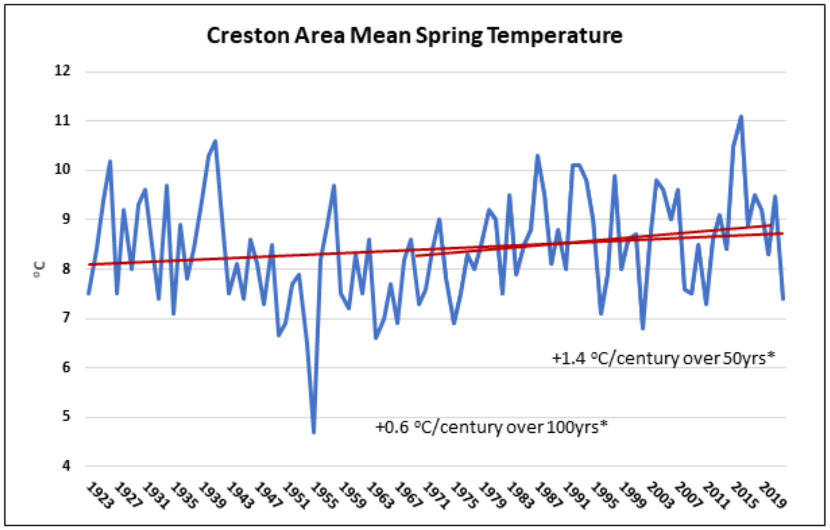


Figure A 1 a) Creston area mean winter temperature over the last 100 years with 100-year trend and trend over the last 50 years. b) Creston area mean winter precipitation over the last 100 years with 100-year trend and trend over the last 50 years. Trends that are statistically significant at the 95% confidence are identifies with *.



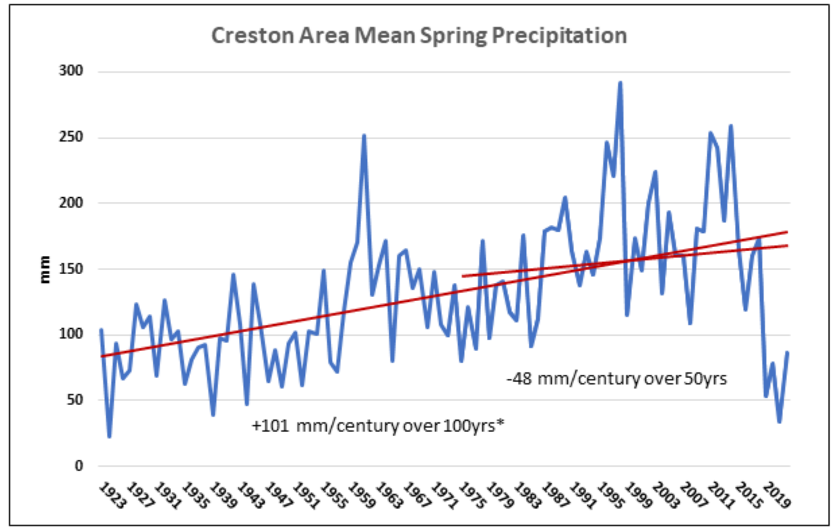
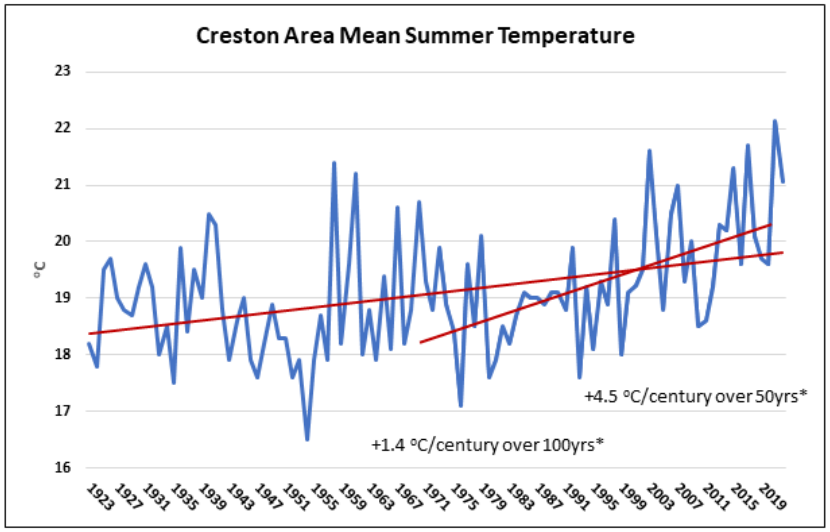


Figure A 2 a) Creston area mean spring temperature over the last 100 years with 100-year trend and trend over the last 50 years. b) Creston area mean spring precipitation over the last 100 years with 100-year trend and trend over the last 50 years. Trends that are statistically significant at the 95% confidence are identifies with *.



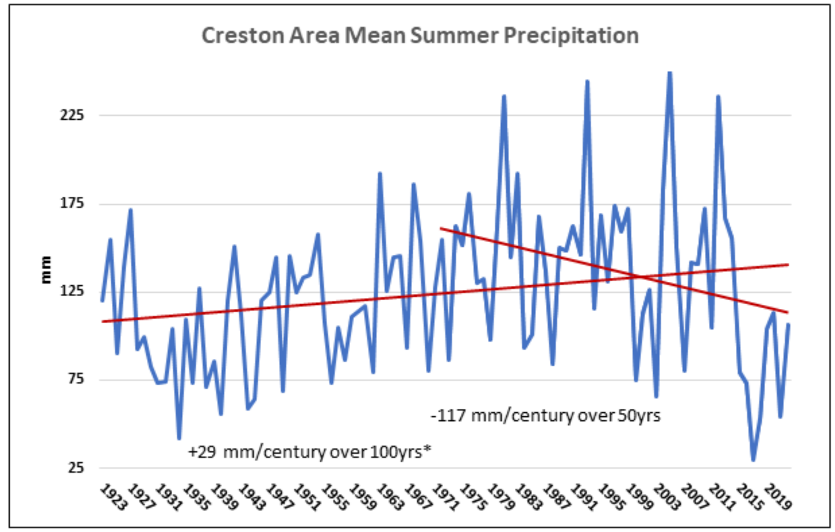
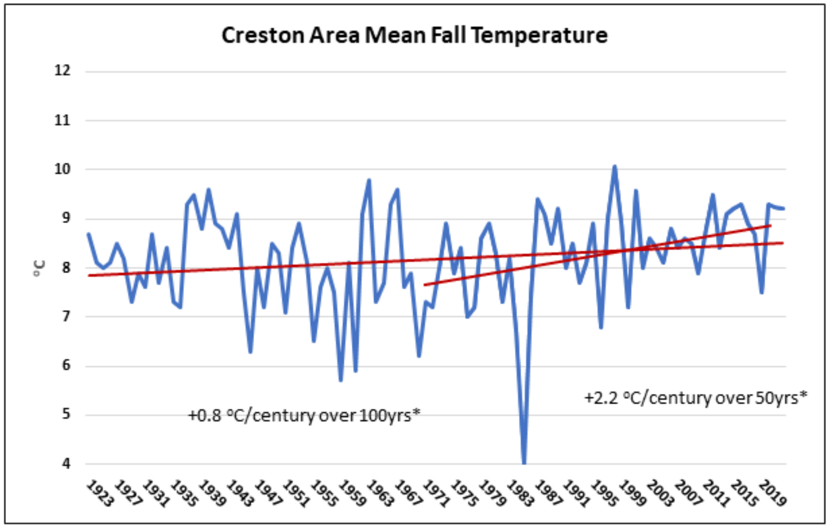


Figure A 3 a) Creston area mean summer temperature over the last 100 years with 100-year trend and trend over the last 50 years. b) Creston area mean summer precipitation over the last 100 years with 100-year trend and trend over the last 50 years. Trends that are statistically significant at the 95% confidence are identifies with *.



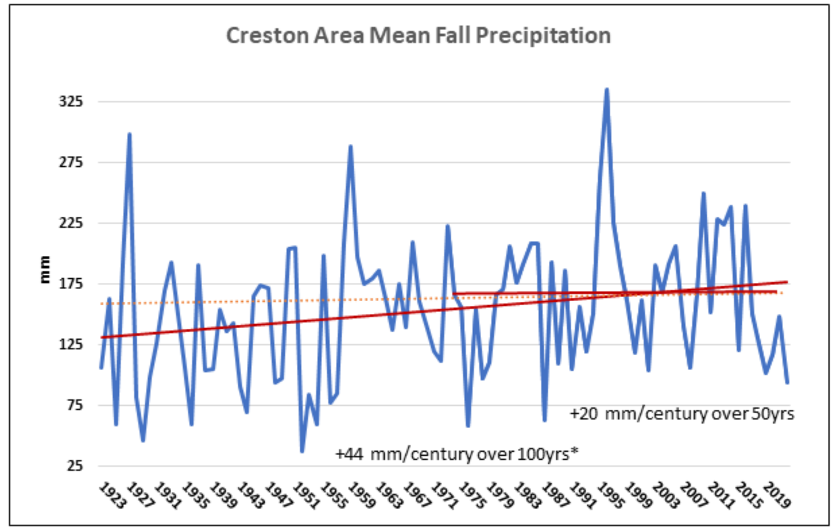
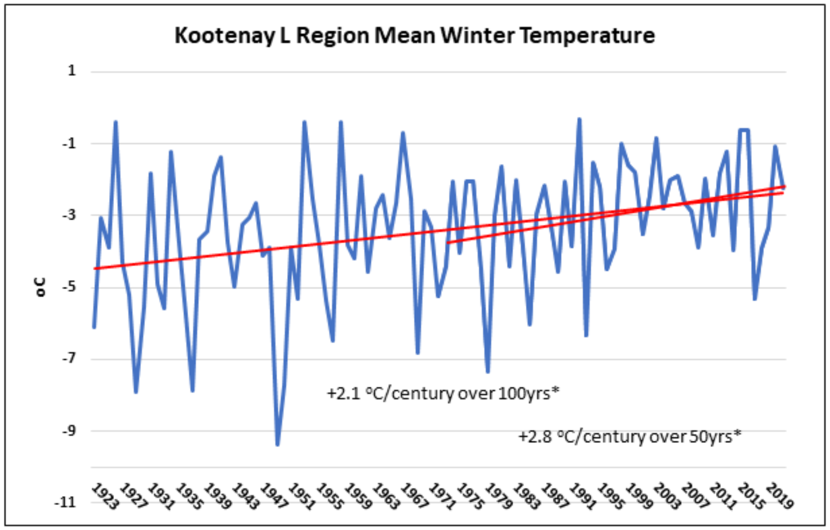


Figure A 4 a) Creston area mean fall temperature over the last 100 years with 100-year trend and trend over the last 50 years. b) Creston area mean fall precipitation over the last 100 years with 100-year trend and trend over the last 50 years. Trends that are statistically significant at the 95% confidence are identifies with *.



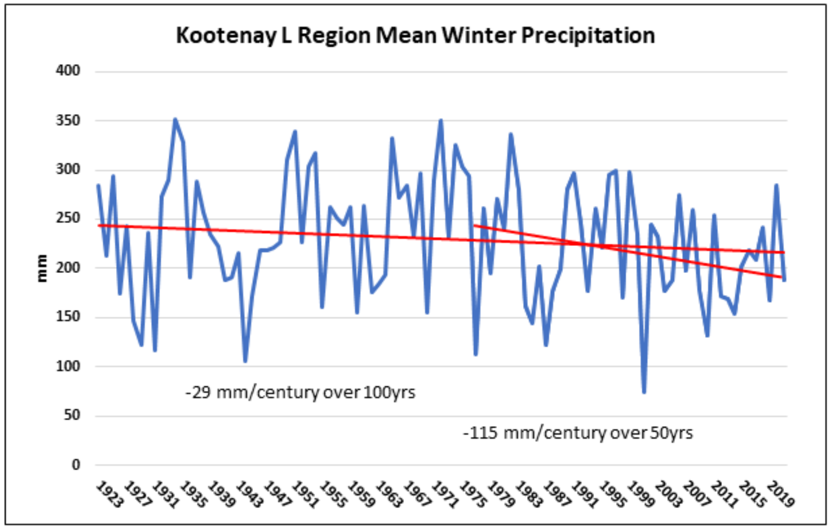
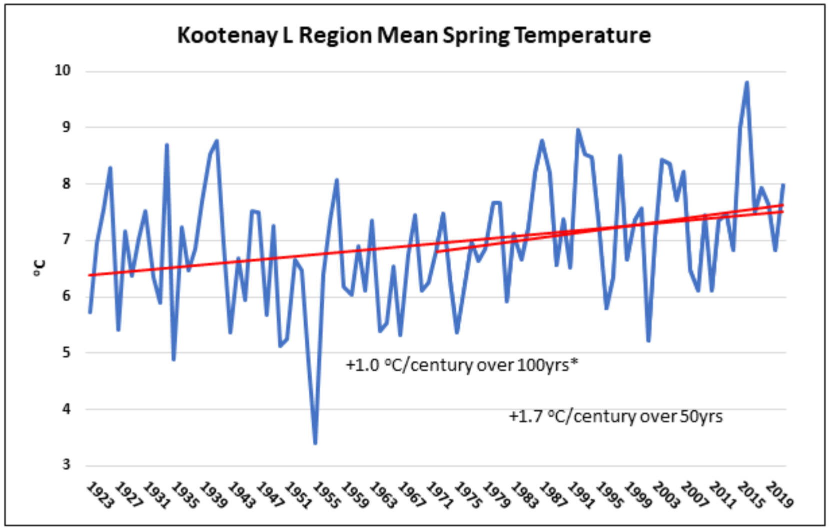


Figure A 5 a) Kootenay Lake region mean winter temperature over the last 100 years with 100-year trend and trend over the last 50 years. b) Kootenay Lake region mean winter precipitation over the last 100 years with 100-year trend and trend over the last 50 years. Trends that are statistically significant at the 95% confidence are identifies with *.



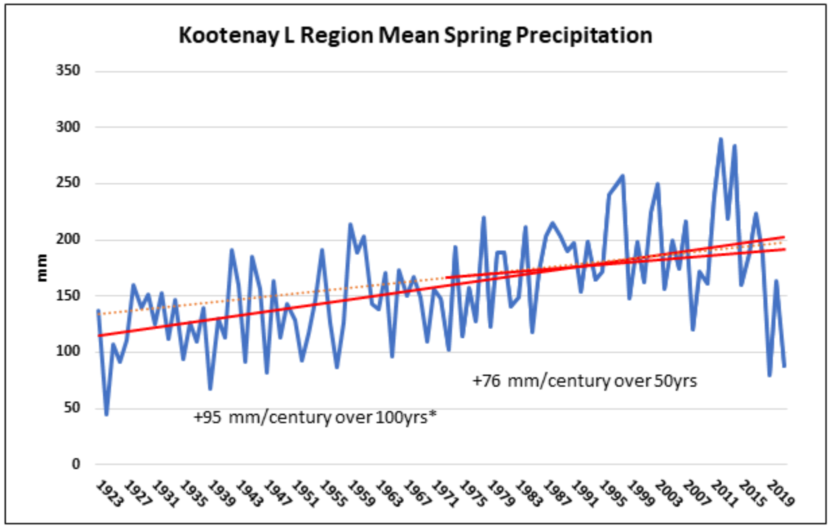


Figure A 6 a) Kootenay Lake region mean spring temperature over the last 100 years with 100-year trend and trend over the last 50 years. b) Kootenay Lake region mean spring precipitation over the last 100 years with 100-year trend and trend over the last 50 years. Trends that are statistically significant at the 95% confidence are identifies with *.

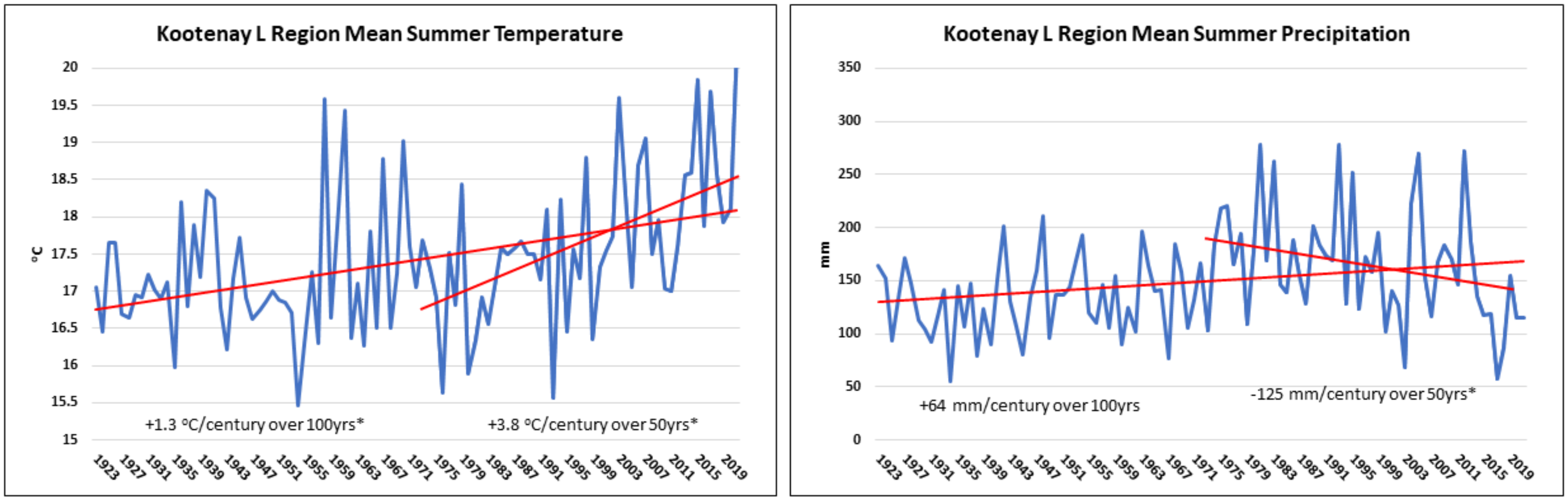
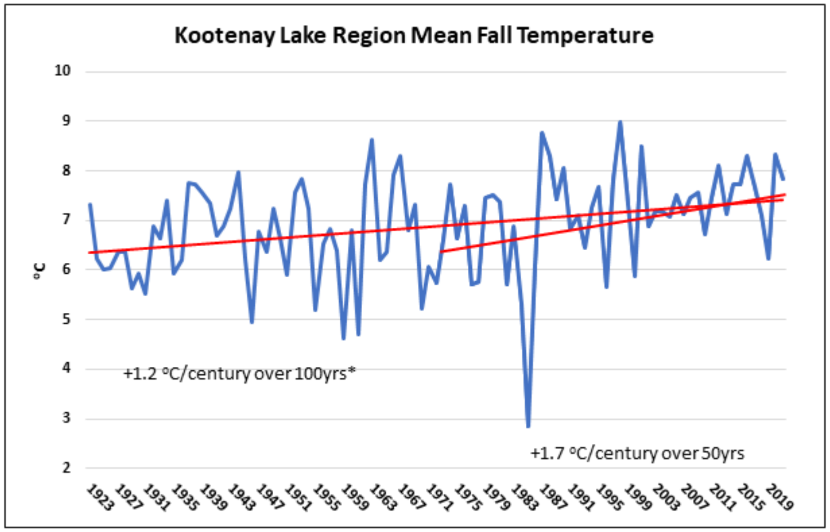


Figure A 7 a) Kootenay Lake region mean summer temperature over the last 100 years with 100-year trend and trend over the last 50 years. b) Kootenay Lake region mean summer precipitation over the last 100 years with 100-year trend and trend over the last 50 years. Trends that are statistically significant at the 95% confidence are identifies with *.



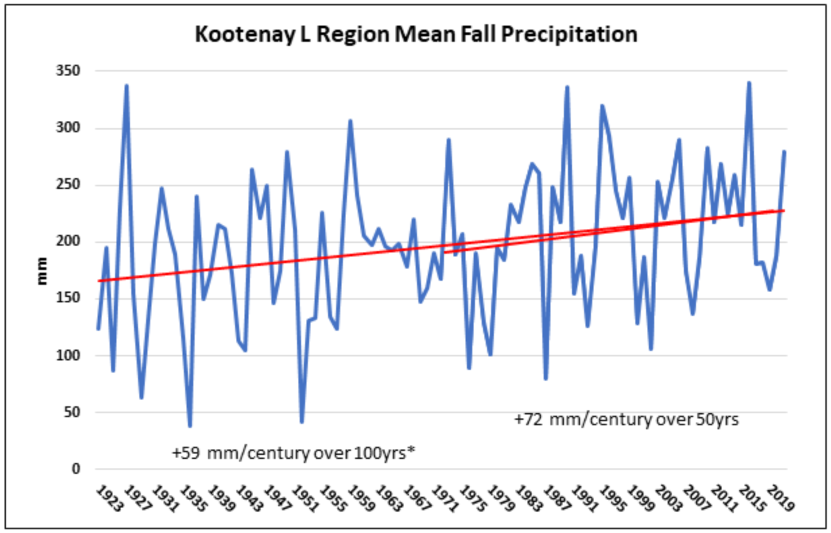


Figure A 8 a) Kootenay Lake region mean fall temperature over the last 100 years with 100-year trend and trend over the last 50 years. b) Kootenay Lake region mean fall precipitation over the last 100 years with 100-year trend and trend over the last 50 years. Trends that are statistically significant at the 95% confidence are identifies with *.

APPENDIX B   THRESHOLD EXCEEDANCE PROBABILITY PLOTS

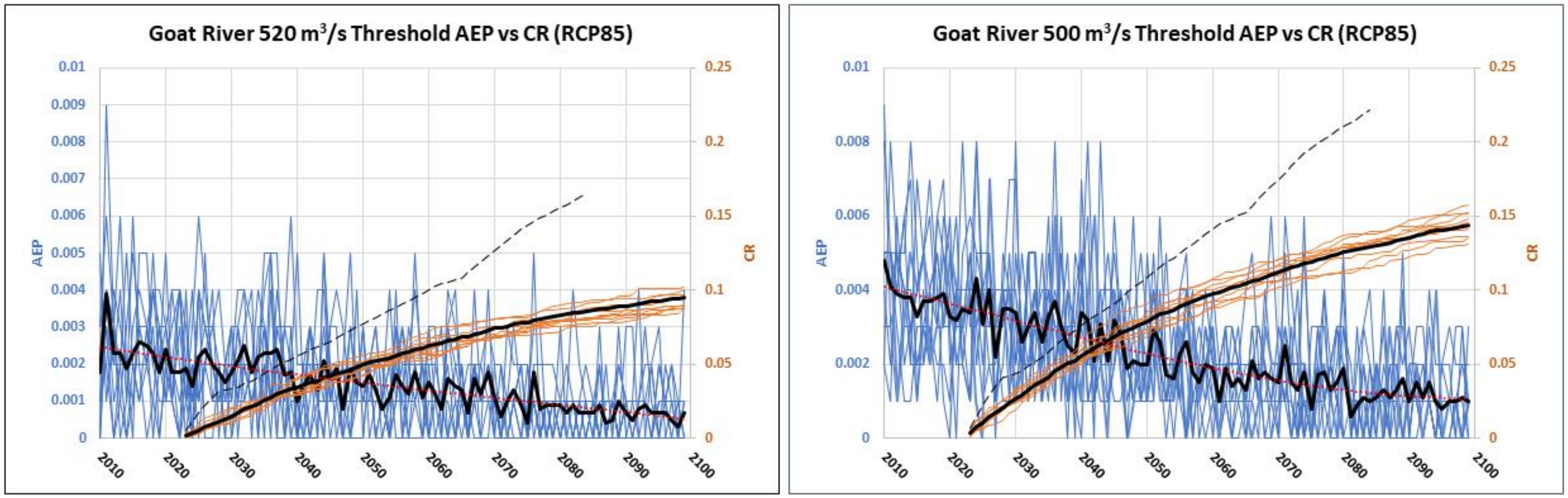


Figure B 1 Simulated Annual Exceedance Probability (AEP) and Cumulative Risk (CR) plots for Goat River flow thresholds of 520m³/s and 500 m³/s with RCP85. Orange curves show CR and blue curves show AEP. Heavy black curves show the average of 10 simulations. The thin dashed curve shows the CR based on the 6-member ensemble of PCIC Hydrologic models. Note scale change between pairs of plots.

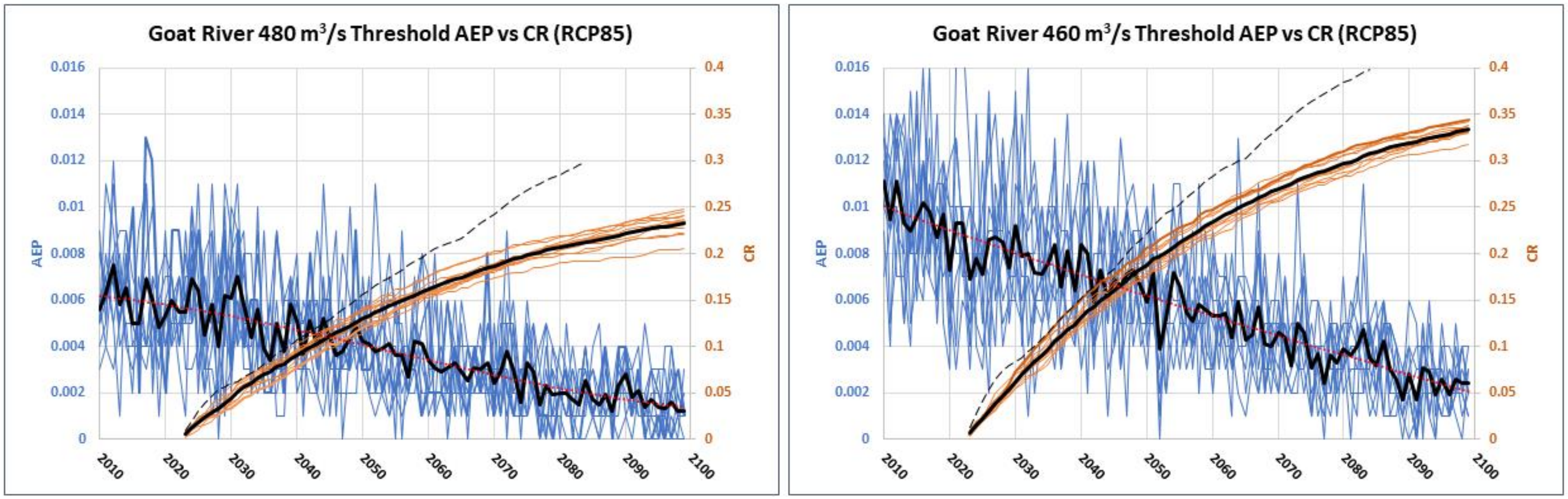


Figure B 2 Simulated Annual Exceedance Probability (AEP) and Cumulative Risk (CR) plots for Goat River flow thresholds of 480m³/s and 460 m³/s with RCP85. Orange curves show CR and blue curves show AEP. Heavy black curves show the average of 10 simulations. The thin dashed curve shows the CR based on the 6-member ensemble of PCIC Hydrologic models. Note scale change between pairs of plots.

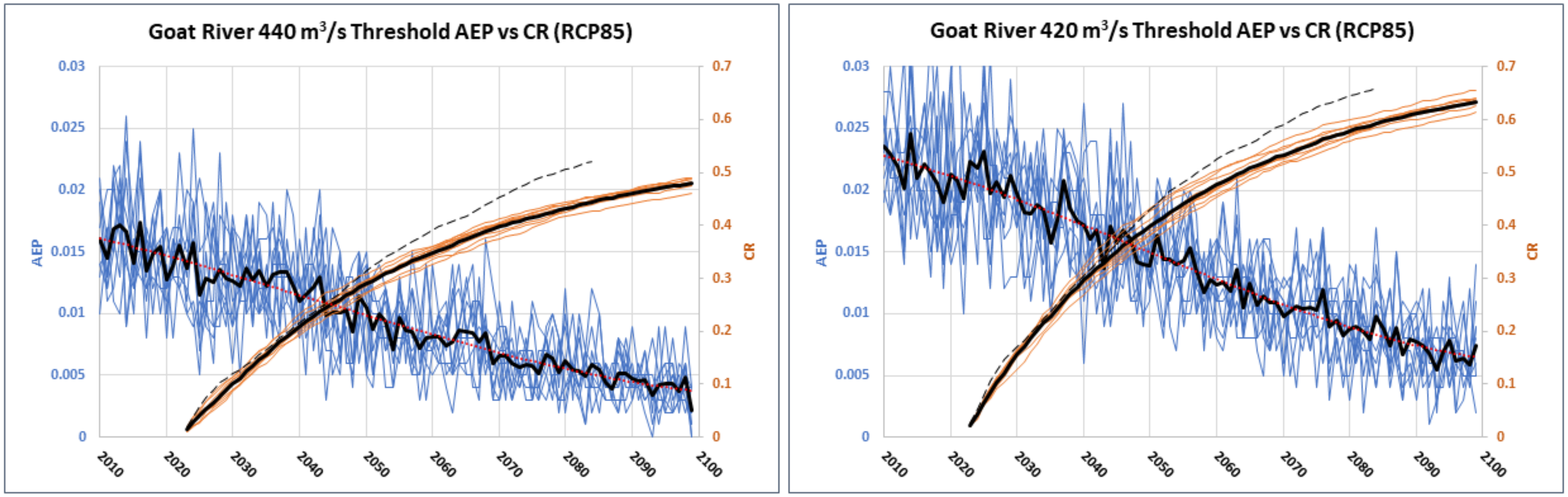


Figure B 3 Simulated Annual Exceedance Probability (AEP) and Cumulative Risk (CR) plots for Goat River flow thresholds of 440m³/s and 420 m³/s with RCP85. Orange curves show CR and blue curves show AEP. Heavy black curves show the average of 10 simulations. The thin dashed curve shows the CR based on the 6-member ensemble of PCIC Hydrologic models. Note scale change between pairs of plots.

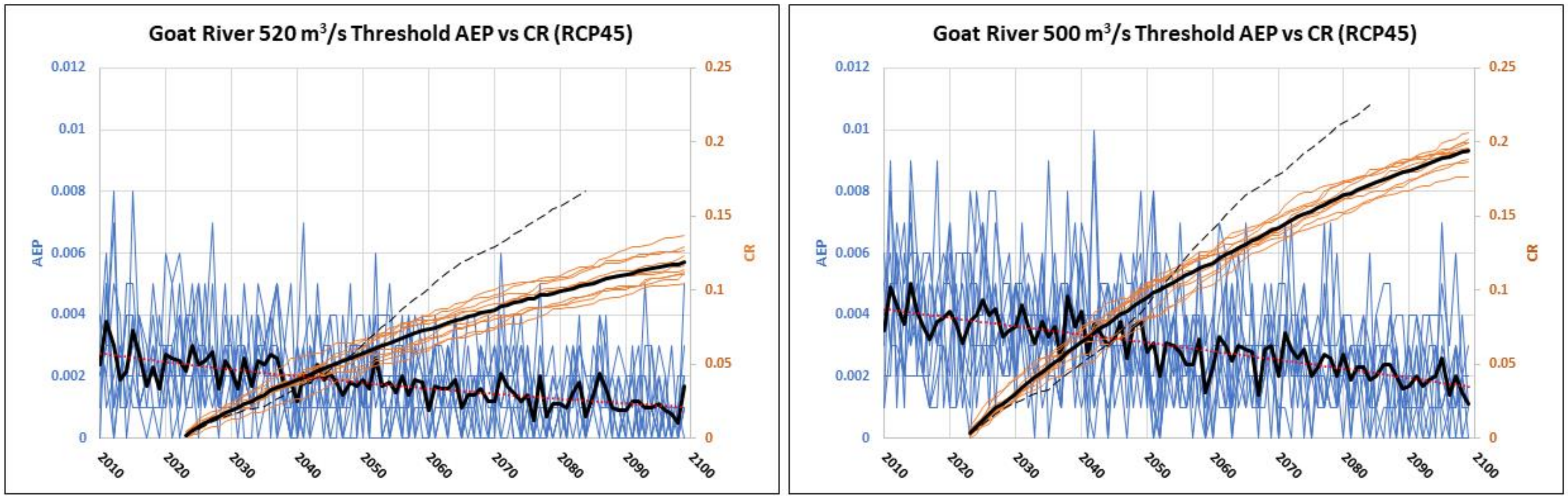


Figure B 4 Simulated Annual Exceedance Probability (AEP) and Cumulative Risk (CR) plots for Goat River flow thresholds of 520m^3/s and 500 m^3/s with RCP45. Orange curves show CR and blue curves show AEP. Heavy black curves show the average of 10 simulations. The thin dashed curve shows the CR based on the 6-member ensemble of PCIC Hydrologic models. Note scale change between pairs of plots.

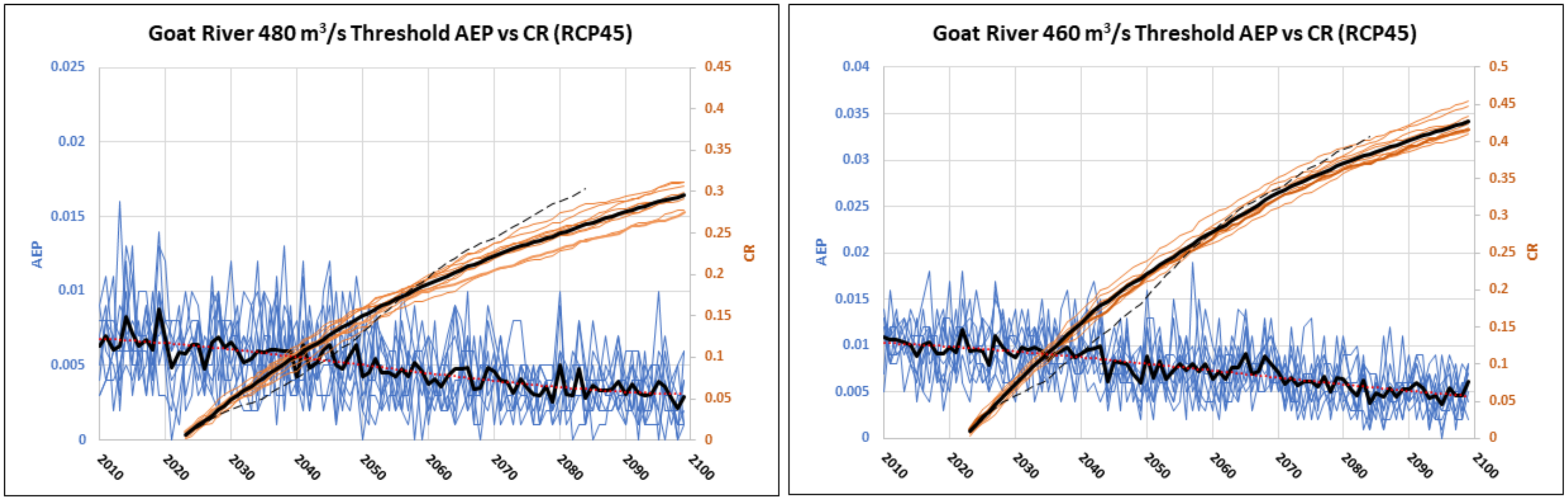


Figure B 5 Simulated Annual Exceedance Probability (AEP) and Cumulative Risk (CR) plots for Goat River flow thresholds of 480m^3/s and 460 m^3/s with RCP45. Orange curves show CR and blue curves show AEP. Heavy black curves show the average of 10 simulations. The thin dashed curve shows the CR based on the 6-member ensemble of PCIC Hydrologic models. Note scale change between pairs of plots.

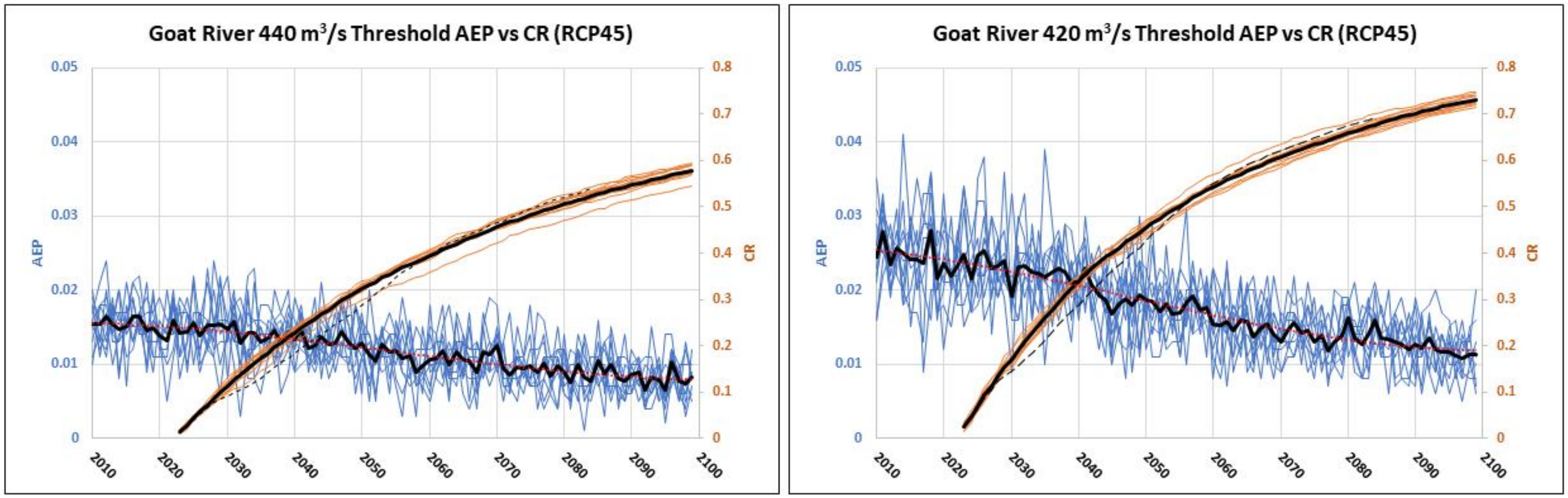


Figure B 6 Simulated Annual Exceedance Probability (AEP) and Cumulative Risk (CR) plots for Goat River flow thresholds of 440m^3/s and 420 m^3/s with RCP45. Orange curves show CR and blue curves show AEP. Heavy black curves show the average of 10 simulations. The thin dashed curve shows the CR based on the 6-member ensemble of PCIC Hydrologic models. Note scale change between pairs of plots.

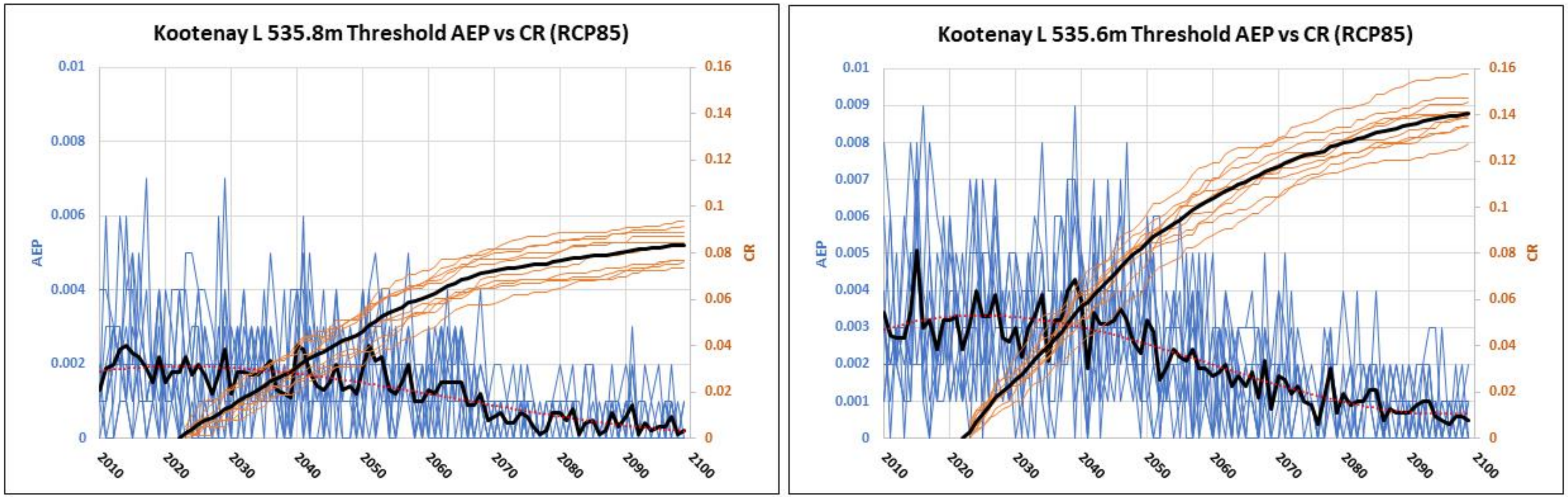


Figure B 7 Simulated Annual Exceedance Probability (AEP) and Cumulative Risk (CR) plots for Kootenay Lake level thresholds of 535.8 m and 535.6 m with RCP85. Orange curves show CR and blue curves show AEP. Heavy black curves show the average of 10 simulations. The thin dashed curve shows the CR based on the 6-member ensemble of PCIC Hydrologic models. Note scale change between pairs of plots.

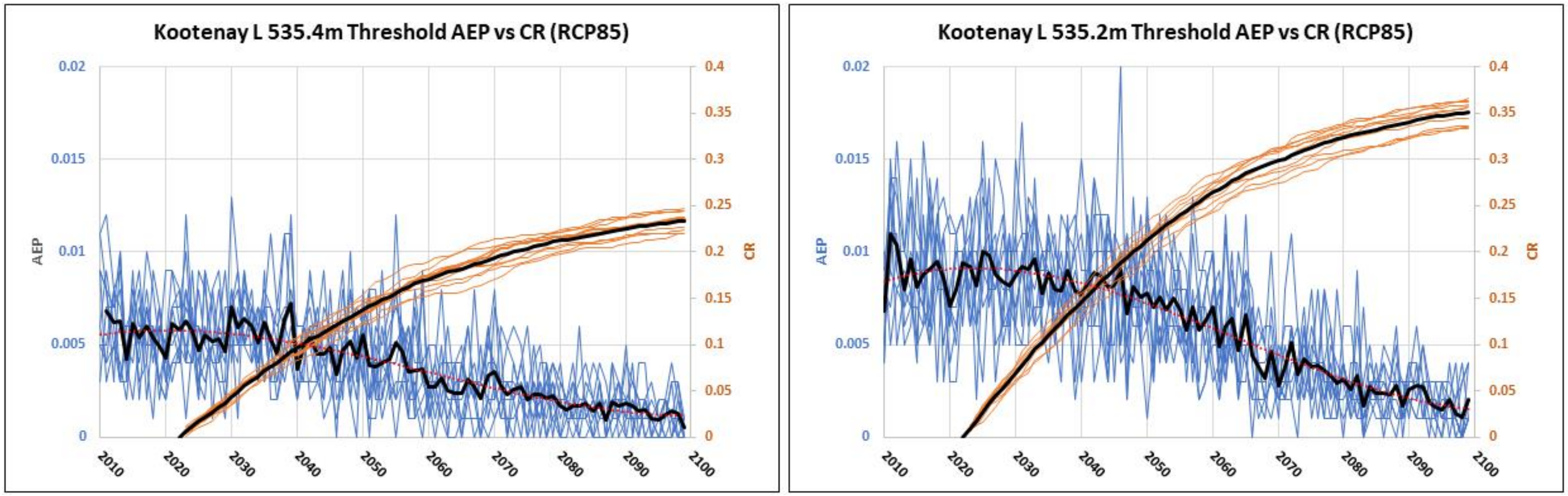


Figure B 8 Simulated Annual Exceedance Probability (AEP) and Cumulative Risk (CR) plots for Kootenay Lake level thresholds of 535.4 m and 535.2 m with RCP85. Orange curves show CR and blue curves show AEP. Heavy black curves show the average of 10 simulations. The thin dashed curve shows the CR based on the 6-member ensemble of PCIC Hydrologic models. Note scale change between pairs of plots.

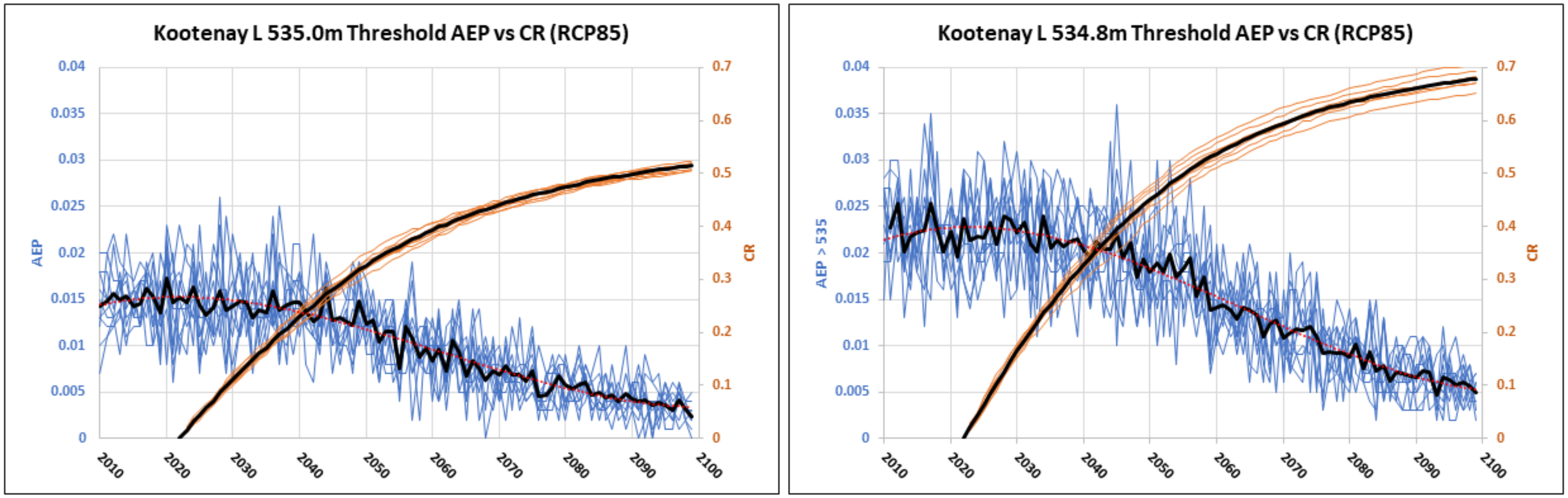
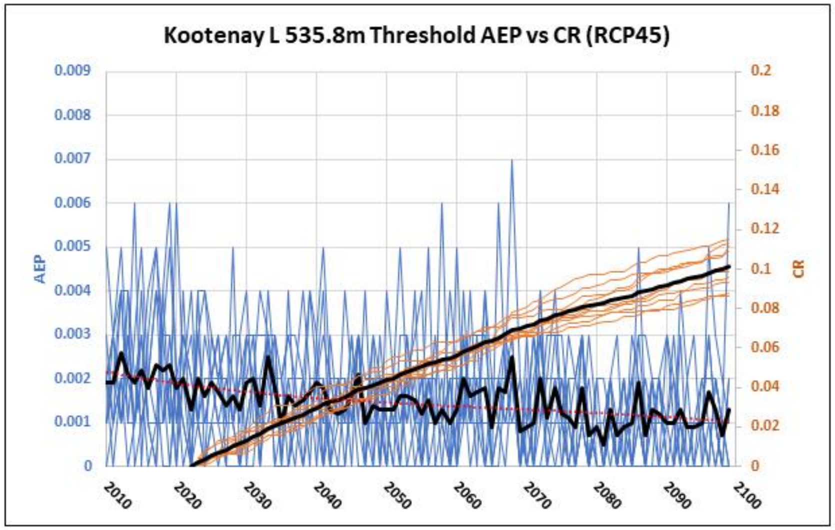


Figure B 9 Simulated Annual Exceedance Probability (AEP) and Cumulative Risk (CR) plots for Kootenay Lake level thresholds of 535.0 m and 534.8 m with RCP85. Orange curves show CR and blue curves show AEP. Heavy black curves show the average of 10 simulations. The thin dashed curve shows the CR based on the 6-member ensemble of PCIC Hydrologic models. Note scale change between pairs of plots.



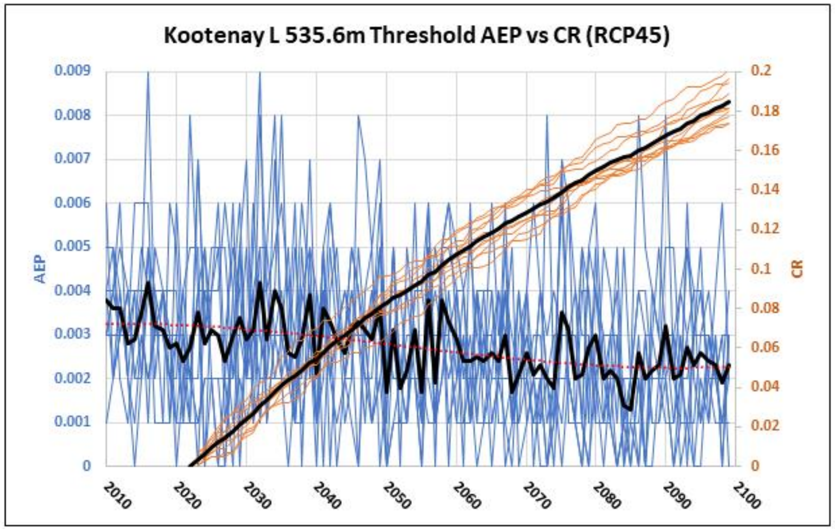
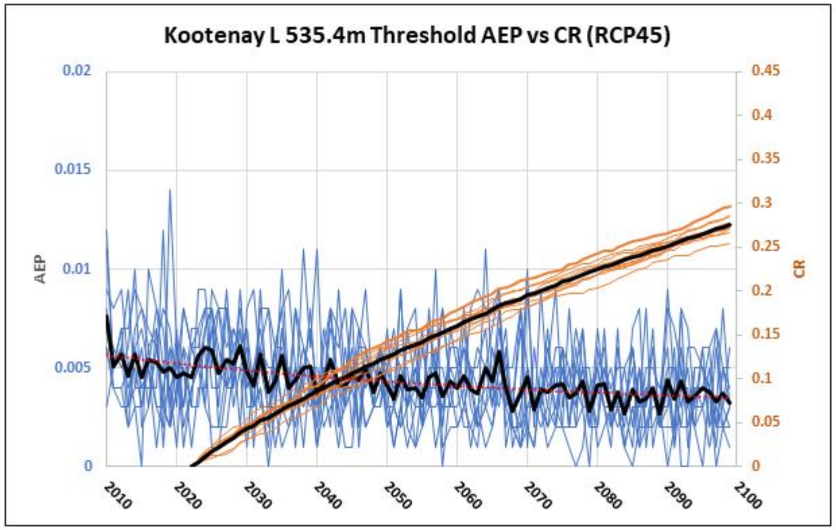


Figure B 10 Simulated Annual Exceedance Probability (AEP) and Cumulative Risk (CR) plots for Kootenay Lake level thresholds of 535.8 m and 535.6 m with RCP45. Orange curves show CR and blue curves show AEP. Heavy black curves show the average of 10 simulations. The thin dashed curve shows the CR based on the 6-member ensemble of PCIC Hydrologic models. Note scale change between pairs of plots.



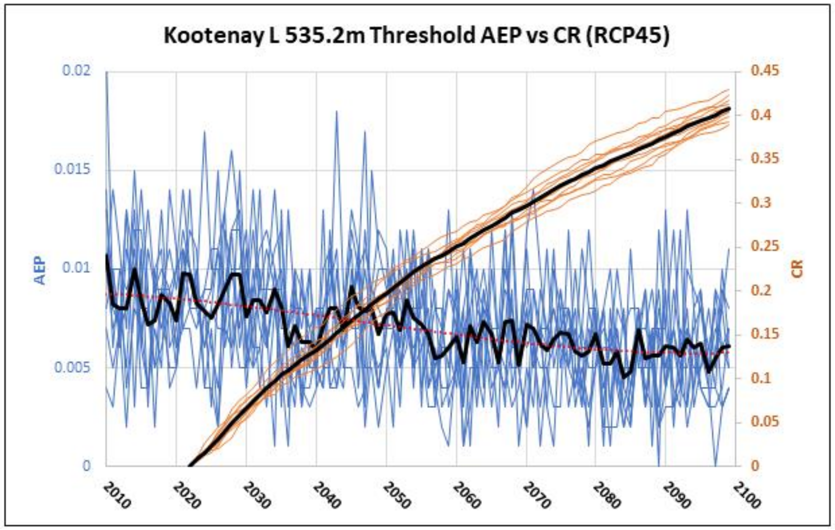
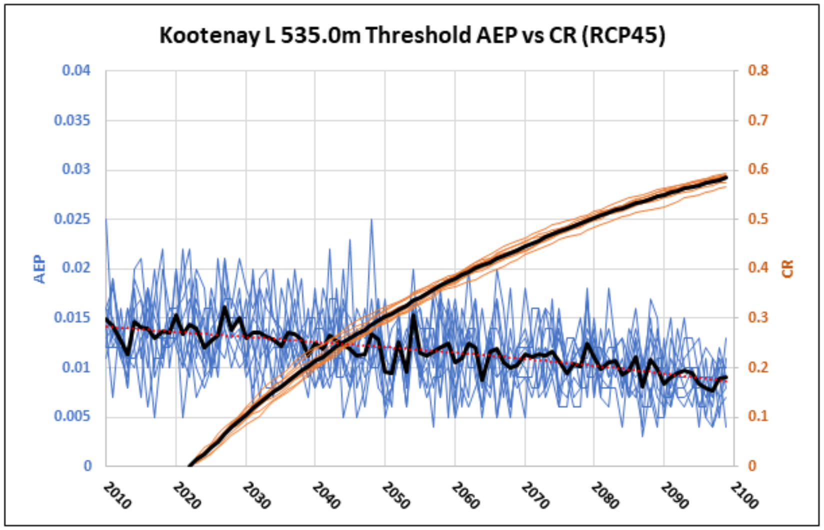


Figure B 11 Simulated Annual Exceedance Probability (AEP) and Cumulative Risk (CR) plots for Kootenay Lake level thresholds of 535.4 m and 535.2 m with RCP45. Orange curves show CR and blue curves show AEP. Heavy black curves show the average of 10 simulations. The thin dashed curve shows the CR based on the 6-member ensemble of PCIC Hydrologic models. Note scale change between pairs of plots.



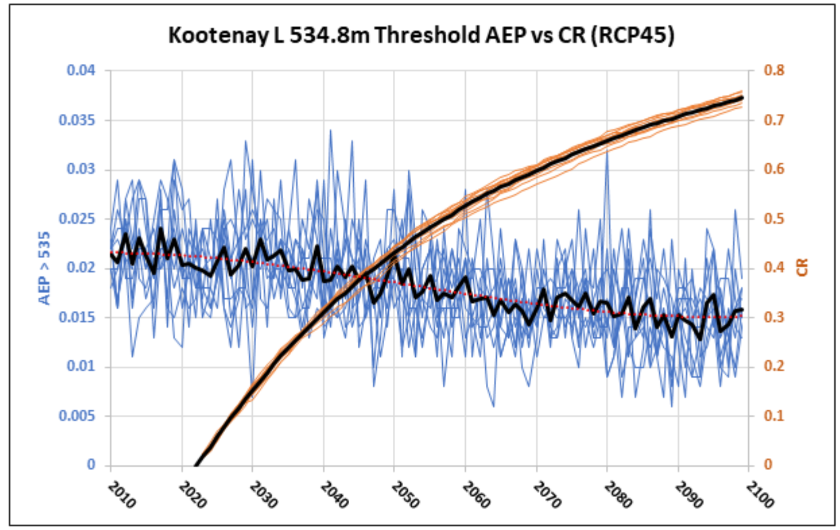


Figure B 12 Simulated Annual Exceedance Probability (AEP) and Cumulative Risk (CR) plots for Kootenay Lake level thresholds of 535.0 m and 534.8 m with RCP45. Orange curves show CR and blue curves show AEP. Heavy black curves show the average of 10 simulations. The thin dashed curve shows the CR based on the 6-member ensemble of PCIC Hydrologic models. Note scale change between pairs of plots.

DEFINTIONS

AEP – Annual Exceedance Probability. The likelihood of exceeding a specified threshold in a single year.

BCCAQv2 - Bias Correction/Constructed Analogues with Quantile mapping. A method for downscaling daily climate model projections developed by the Pacific Climate Impacts Consortium. The method corrects bias in modeled precipitation data to obtain a better match between observed and modeled distributional properties (e.g. mean, variance and quantiles).

Clausius Clapeyron scaling method – A method for projecting changes in extreme precipitation based on the theoretical relationship between atmospheric temperature and water water-holding capacity. This increases by about 7% for every degree C, which roughly matches observed changes in extreme precipitation and is applied to projected changes in temperature.

CMIP5 and CMIP6 – Coupled Model Intercomparison Project. Developed by the World Climate Research Program, CMIP is a global collaboration designed to provide a standard set of climate model simulations that are used to evaluated model performance and provide future projections based on mulit-model ensembles. The IPCC 5^{th} and 6^{th} Assessment Reports rely on CMIP Phase 5 and CMIP Phase 6 respectively.

CR – Cumulative Risk. The likelihood of exceeding a specified threshold within a planning timeframe (multiple years).

ECCC – Environment and Climate Change Canada

Freshet – The annual high-water event that results from the melting snowpack.

GCM – General Circulation Model. GCMs represent physical processes of the atmosphere, oceans land surface and cryosphere to simulate the Earth's climate using a 3-dimentional grid over the globe.

GEV - Generalized Extreme Value Distribution. The GEV is a family of continuous probability distributions developed within extreme value theory and in hydrology is commonly applied to extreme events such as annual maximum discharge.

GHGs – Greenhouse Gases. Gases in the atmosphere that interact with thermal infrared radiation and slow the loss of planetary heat to space. The primary GHGs are CO_2, CH_4, N_2O and HFCs. H_2O is also a powerful GHG but cannot drive climate change because it readily condenses and precipitates out of the atmosphere.

Gumble Distribution – The Gumble distribution is a particular case of the Generalized Extreme Value Distribution and is often used for estimating the probability of extreme events such as annual maximum 1-day rainfall.

IDF Data – Intensity, Duration, Frequency data. IDF data are derived for observed daily and sub-daily records of precipitations. IDF data are used to describe the likelihood of extreme rainfall over a range of durations (5 min to 24 hr).

IPCC – Intergovernmental Panel on Climate Change. An intergovernmental body of the United Nations created to provide policymakers with regular scientific assessments on climate change.

Lag-1 Autocorrelation – Is the correlation between values that are 1 time period apart and is a measure of the relationship between a variable's current value and the value of the previous year (if the time steps are annual).

LOWESS – Locally Weighted Scatterplot Smoothing. A method for producing a smooth curve through a timeseries of data.

Mann Kendall Test – The Mann Kendall test is a statistical test that assesses whether a set of data values is increasing or decreasing over time and if the trend is statistically significant.

Maximum Flow – The maximum daily average flow occurring in a year.

Method of Moments – A statistical technique used to estimate the parameters of a probability distribution.

Nival Regime – Streamflow that is dominated by runoff from snowmelt.

Peak Flow - The maximum instantaneous flow occurring in a year.

Pacific Decadal Oscillation – A long-lived pattern of Pacific climate variability marked by temperature anomalies in the northeast and tropical Pacific Ocean. The phases of the PDO can influence climate in North America and can alter the path of the jet stream which controls the paths of storms in the region.

Pluvial Hydrologic Regime – Streamflow that is dominated by precipitation rather than snowmelt or glacial melt.

RCP45 – Representative Concentration Pathway 4.5. A global GHG emissions pathway that exceeds the Paris Agreement goals but is lower than current emissions reduction commitments for the Paris Agreement. This emissions pathway will lead to approximately 3^{o}C of global warning by the end of the century.

RCP85 - Representative Concentration Pathway 8.5. A global GHG emissions pathway that does not achieve significant emissions reductions. This emissions pathway could lead to more than 4^{o}C of global warning by the end of the century.

RP – Return Period. The inverse of the Annual Exceedance Probability. An event that has a 1% chance of occurring in a given year has a return period of 100 years. In a non-stationary climate, both the AEP and the Rp change over time.

R^2 – R squared. A goodness-of -fit measure that represents the proportion of the variance for a dependant variable that is explained by an independent variable.

SWE – Snow Water Equivalent. Is a measure of how much water the snowpack contains. If a height of snowpack was melted, the height of water created is SWE.

The 'Buddy System' - A method for estimating missing data from a record using a nearby similar record.

Theil-Sens Estimator - A method for fitting a line to data by choosing the median of the slopes of all lines through pairs of data points.

VIC-GL – Variable Infiltration Capacity model reconfigured to couple with an external dynamic glacier model. The VIC model is a macroscale hydrologic model that simulates the movement of water through the land surface including evapotranspiration, infiltration, snowpack, runoff and groundwater recharge. The model considers the effects of meteorological variables including temperature, precipitation humidity and windspeed and can be coupled with climate models to project future streamflow.