US Army Corps of Engineers ®
Walla Walla District

YAKIMA RIVER DELTA ECOSYSTEM RESTORATION

Final Feasibility Report with Integrated Environmental Assessment

Appendix A

Climate Change Assessment

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1 Introduction

An assessment of climate change vulnerability was completed for restoring aquatic habitat and ecosystem functionality to the Yakima Delta in Kennewick and Richland, Washington under Section 1135 of the Continuing Authorities Program (CAP). The purpose of this climate assessment was to highlight existing and future challenges and risks facing the project due to past and future climatic changes, in accordance with the guidance in Engineering Construction Bulletin (ECB) 2018-14, *Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects*, (revised 19 August 2022). This climate assessment is a screening-level assessment focused on trends in temperature, precipitation, snowpack, and seasonality. It is not an in-depth analysis. The feasibility report is intended to evaluate the proposed action of complete removal of the causeway located near Bateman Island. Without the causeway in place, more Columbia River flow is predicted to dynamically mix around Bateman Island, which will benefit native fish and wildlife, including juvenile and adult salmon and steelhead as they migrate through the delta.

1.1 Study Background

The Yakima Delta lies within the Columbia Plateau Ecoregion (a semiarid shrub-steppe zone) at the confluence of the Yakima (HUC 170300031205) and Columbia Rivers (HUC 170200160604) located in southeastern Washington State. Bateman Island lies east of the Delta and is connected to the right bank of the Columbia River with an earthen causeway that blocks active flow around the south side of the island and hydraulically shelters a local marina to the east. The general project location is circled in red in Figure 1-1 below and in more detail in Figure 1-2 on the following page.

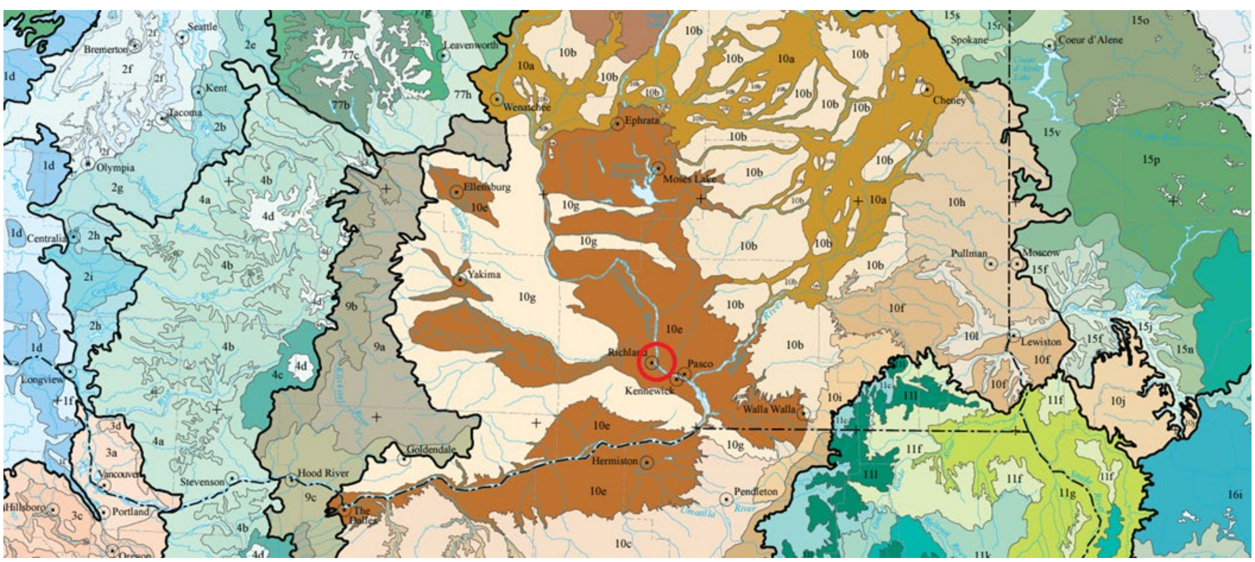


Figure 1-1 Project vicinity and regional ecoregions. (EPA 2016)

Regional temperatures, precipitation, and winds in the surrounding area are greatly influenced by the presence of mountain barriers. The Cascade Mountains, west of Yakima, influence the climate in the area by their rain shadow effect. The Rocky Mountains and ranges in southern British Columbia protect the inland basin from the more severe polar masses moving across Canada and the associated winter storms (Hoitink et al., 2005). The study area receives an average annual rainfall of 7 to 8 inches, and a yearly snowfall average of 7 inches. Winds periodically exceed 30 miles per hour, and blowing dust is a common occurrence.

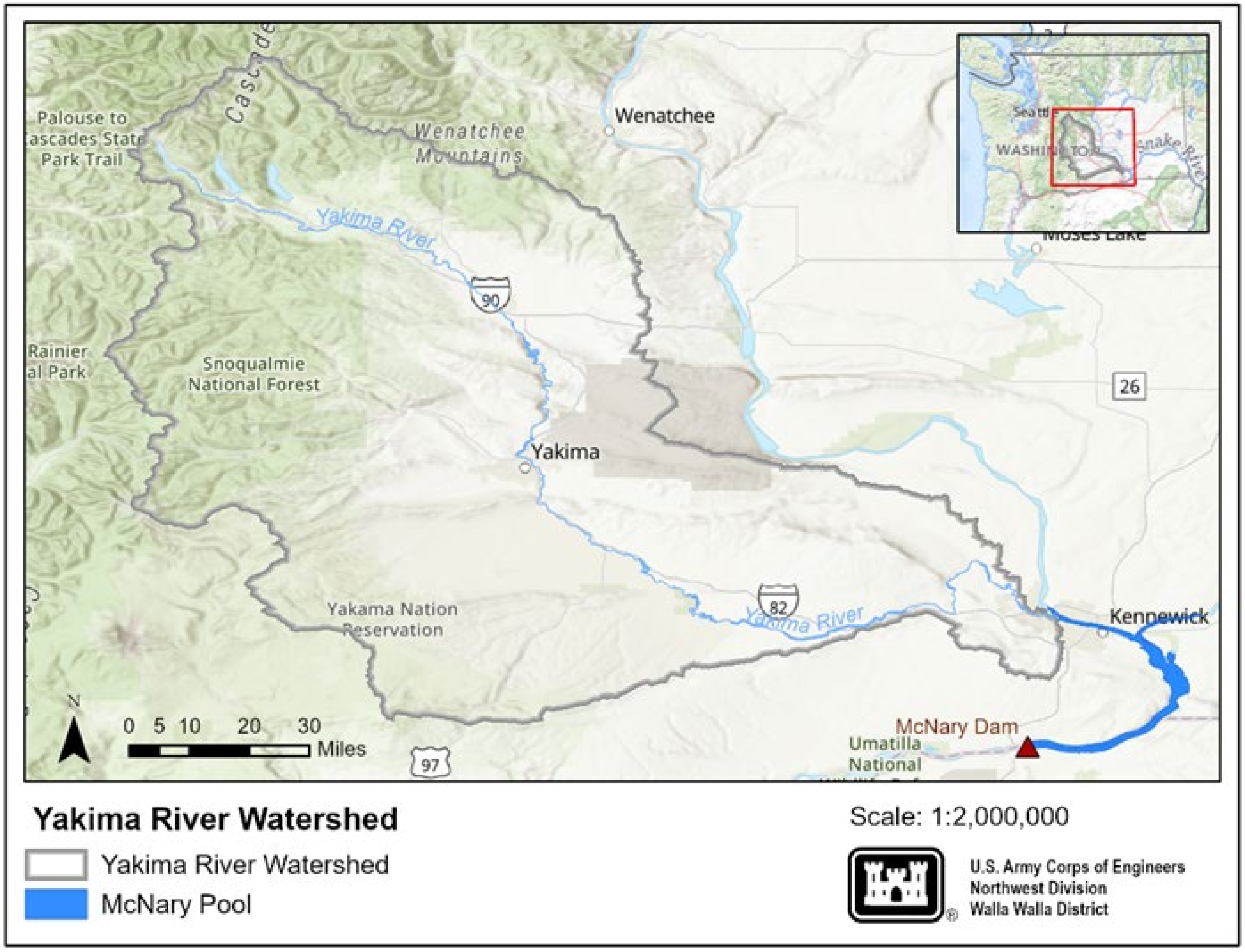


Figure 1-2 Location of Yakima River Watershed and McNary Dam

Hydrology in the Yakima River Basin is characterized by high precipitation in the Cascade Mountains and low precipitation in the lower Yakima River Basin. Most annual precipitation occurs from October to March, and primarily falls in the form of snow. During the late spring and early summer, precipitation changes to rain and temperatures increase to produce snowmelt runoff. A portion of this runoff is captured in the five major Yakima River Basin reservoirs for storage and released during the summer and fall, when water demand is higher and there is less natural precipitation. This operation causes streamflow within the upper Yakima River to be higher than natural streamflow in the summer and fall and lower than natural streamflow in the winter and spring.

The Yakima River is representative of transient watersheds (mix between and rain- and snow-dominant), and the Columbia River is representative of snow-dominant watersheds. Inflows to the Yakima Delta study area include outflow from Priest Rapids Dam (PRDW) on the Columbia River and outflow from Horn Rapids Dam (HRD) on the Yakima River. The flow and temperature of both systems are characterized by regional seasonality, larger volume, and cooler water in the spring versus smaller volume and warmer water in the summer and fall. Columbia River flows can be highly variable between May and November due to upstream operations through a series of coordinated run-of-river hydropower projects below Grand Coulee Dam (GCD), while Yakima River flows are more representative of a spring freshet followed by a descending hydrograph limb as upstream irrigation demands increase through the summer hydroperiod.

Climate change has already impacted the study area and alterations in the amount of snowpack and snowmelt timing and their consequences on salmon habitat are predicted to become increasingly more problematic within the 21st century. Within the Yakima Delta, impacts of climate change are predicted to result in reduced summer/fall flows and increased water temperatures for the Yakima Basin. Historically warm reaches are predicted to have greater increased summer water temperatures with lower flow volumes, resulting in increased thermal stress for migratory salmonids (Mantua et al. 2010).

The Yakima Delta will continue to experience climate change effects such as increased annual air and stream temperatures, a threat to ESA species. Removal of the causeway will mitigate the detrimental effects of climate change by altering the hydrology of the Yakima Delta. Increased mixing of flow between the Yakima River and the Columbia River will reduce average stream temperatures as well as the blockage of sediment on the west side of Bateman Island.

Lowering average stream temperature would have beneficial impacts to aquatic species by producing more favorable water conditions conducive for the migration and spawning success for migratory species of special concern. Yakima River salmon migration would expand into areas that previously experienced high-water temperatures and inconsistent dissolved oxygen levels. Improved migratory spawning conditions could result in an increased population of these fish species due to a decreased risk of mortality.

2 Literature Review

The purpose of this section is to highlight specific publications which summarize historical climate trends and project future trends within the Pacific Northwest. In general, climate trends show increasing temperatures over time as well as decreasing trends in annual flow volume. The Yakima Delta project area is located within the Columbia River basin of southeastern Washington; therefore, the literature review will focus on the Pacific Northwestern region (HUC2: 17).

The three main documents for this review are the Fourth National Climate assessment (NCA4), the USACE Civil Works Technical Report CWTS-2015-23, and the Columbia River System Operations Final Environmental Impact Statement (CRSO EIS, USACE 2020). The focus of these references is on summarizing trends in historic, observed meteorological and streamflow data, as well as providing an indication of trends in future climate impacted hydrology based on the outputs from Global Climate Models (GCMs). The NCA4 considers climate change research at both a national and regional scale based on reports from sources such as the Intergovernmental Panel on Climate Change (IPCC). The Civil Works Technical Report CWTS-2015-23 synthesize information from reports such as the NCA3 to help in USACE planning studies and decision making. The report covers 2-digit, United States Geological Survey (USGS), hydrologic unit code (HUC) watersheds in the United States (U.S) (USACE 2015). The CRSO EIS details the environmental impact of Columbia River system operations as well as climate trends within the Columbia River basin. The CRSO EIS climate projections are based on a planning study performed by the River Management Joint Operating Committee (RMJOC) in conjunction with the University of Washington and Oregon State University.

Historical data such as temperature, precipitation, and streamflow have been measured since the early 20th century and provide insight into how the hydrology in the study region has changed over the past century. Future climate predictions are derived from GCMs loaded with representative concentration pathways (RCPs) reflecting projected radiative forcings through the end of the 21st century. Anthropogenic greenhouse gas (GHG) emissions (the main drivers for climate change) are mainly driven by population size, economic activity, lifestyle, energy use, land use patterns, technology, and climate policy. The Representative Concentration Pathways (RCPs), which are used for making projections based on these factors, describe four different 21st century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions and land use. The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5) (IPCC 2014).

Projected temperature and precipitation results can be transformed to regional and local scales (a process called downscaling) for use as inputs in precipitation-runoff models (Pytlak, et al. 2016). Downscaling is necessary to add local information (such as terrain elevation, aspect, and slope) to the coarse climate model output to create the higher resolution geospatial datasets to support hydrologic modeling at the subbasin scale. All downscaling methods have relative strengths and weaknesses and inherently introduce uncertainty and error that may require subsequent correction via debias or hybrid methods.

Uncertainty is inherent to projections of temperature and precipitation due to the GCMs, RCPs, downscaling methods, and many assumptions needed to create projections (USGCRP 2017). When applied, precipitation-runoff models introduce an additional layer of uncertainty. However, these methods represent the best available science to predict future hydrologic variables (e.g. precipitation, temperature, & streamflow). Many researchers use multiple GCMs and RCPs in their studies to understand how various model assumptions impact results (Gleckler et al., 2008).

For this assessment, background literature on observed and projected temperature, precipitation and snowpack trends is provided as context for the hydrologic regime and the design/implementation requirements to ensure project viability, reduce risk, maintain durability, and extend service life.

2.1 Temperature

2.1.1 Baseline Temperature Trends

In the twentieth century, all areas of the Pacific Northwest Region became warmer, and spring temperatures increased 1 to 3°C between 1970 and 1998 (Spears et al. 2013). MacDonald (2010) noted that average annual temperatures in the Pacific Northwest for the 2001 to 2009 period were up to 2 standard deviations above the 20th century average (1895 – 2000).

Based on observed temperature records, the annual, average air temperature between 1986 and 2016 for the Northwest has increased by 1.54°F from the 1901-1960 annual average temperature baseline (Vose, et al. 2017). Temperatures from 1895–2011 averaged warming of about 1.3°F. The average present-day (1986– 2016) observed coldest daily temperature for the Pacific Northwest Region is 4.78°F warmer than the average for the first half of the last century (1901–1960). The warmest day of this same comparison is 0.17°F cooler. Temperature extremes across the contiguous United States has also changed. The frequency of cold waves has decreased since early 1900s, and heat wave frequency has increased since mid-1960s. The number of high temperature records set in past two decades far exceeds the number of low temperature records.

Kunkel et al (2013) reported that temperatures in the Pacific Northwest Region have generally been above the 1901–1960 average for the last 25 years, both annually and for all seasons. The report noted that increases in inland temperature of the northwest US were greater than those near the coast. Freeze-free season lengths during 1991–2010 averaged about 11 days longer than during 1961–1990. Since 1990, freeze temperatures have been occurring later in fall and not occurring earlier in spring. The freeze-free period across much of the Pacific Northwest Region increased by 25–35 days with larger increases for the inland northwest. Kunkel et al. also reported on the frequent occurrence of heat waves in the Pacific Northwest Region in recent years, with five of the top 10 years for intense heat occurring in the last two decades. Cold waves have been generally more infrequent since 1990, with all the top ten years for intense cold occurring prior to 1991. This study also predicted an increase in the number of days hotter than 95°F in the southeast portion of the Pacific Northwest region where the Yakima Delta is located. The longest string of days with such high temperatures is simulated to increase by up to 10 days per year.

2.1.2 Projected Future Temperature Trends

Projected future temperatures are expected to be greater for the inland northwest than those near the coast (Kunkel et al 2013). The freeze-free period is estimated to increase by 25–35 days across much of the Pacific Northwest Region, with larger increases on the west of the Cascade Mountains. This study also predicts an increase in the number of days hotter than 95°F in the southeast portion of the region. The longest string of days with such high temperatures was simulated to increase by up to 10 days per year.

Mantua et al (2010) reported that rising water temperatures will thermally stress salmon throughout Washington watersheds, becoming increasingly severe later in the twenty-first century. They indicate that while winter and spring warming may benefit parts of the freshwater life cycle of some salmon populations, the combined effects of warming summertime stream temperatures and altered streamflow will likely reduce the quality and extent of freshwater salmon habitat and increase strain to many salmon populations.

For the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), Mote and Salathé (2010) indicate that climate models which generally reproduce the observed seasonal cycle and twentieth century warming trend of 0.8°C (1.5°F) in the Pacific Northwest Region predict a much greater warming for the next century relative to the average from 1970 to 1999. These models project increases in annual temperature of 1.1°C (2.0°F), on average, by the 2020s, 1.8°C (3.2°F) by the 2040s, and 3.0°C (5.3°F) by the 2080s, averaged across all climate models. Predicted rates of warming range from 0.1°C to 0.6°C (0.2°F to 1.0°F) per decade, with some models projecting an enhanced seasonal cycle trending towards wetter autumns and winters, with drier summers.

Mote and Sharp (2016) indicate that for increasing temperature estimates in the Western United States of 2°– 5° C over the next century, it is likely that losses in snowpack observed up to 2005 will likely continue and even accelerate, with faster losses in milder climates like much of the Cascades and the slowest losses in the higher altitude Rockies and Sierra Nevada.

Pytlak et al. (2018) report that Columbia Basin warming is expected to be greatest (and more locally variable) within the interior, potentially increasing as much as 3 to 6°F over baseline observations by the 2070s if RCP 4.5 emissions pathways are attained as shown in Figure 2-1 below.

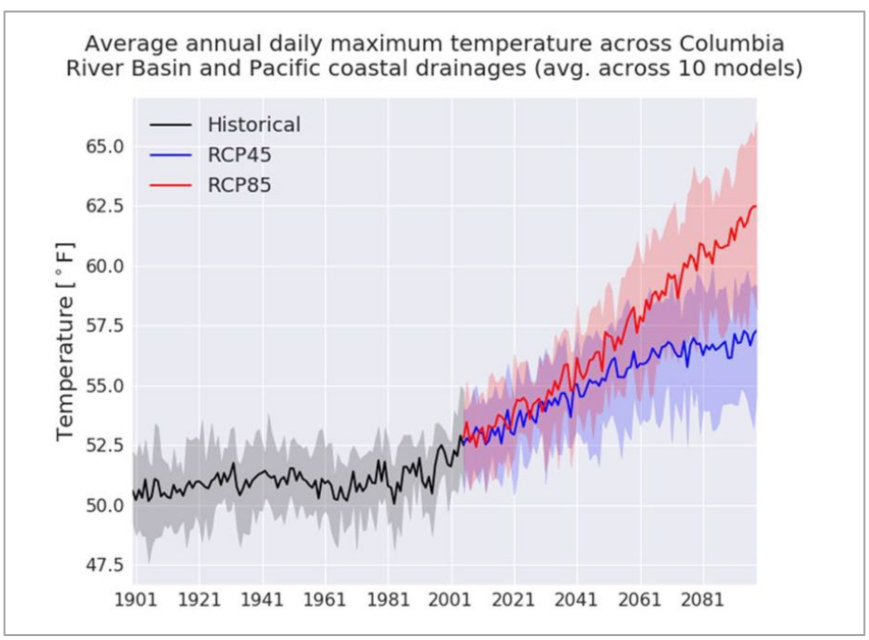


Figure 2-1 Average Annual Daily Maximum Temperatures for the Columbia River Basin and Pacific Coastal Drainages in Washington and Oregon Through 2100 for RCP 4.5 and 8.5 (RMJOC 2018)

2.2 Precipitation and Snowpack

2.2.1 Baseline Trends

Multiple studies have identified increasing trends in average annual precipitation in the Pacific Northwest region for the latter half of the 20th century, especially for the coast areas which are notably distinct from the inland northwest. Observed data indicates that the summer season will become dryer, however, there will be an increase in winter precipitation events. Some studies have conflicting results leading overall precipitation results to be highly variable; these trends are also further variable depending upon location and season.

A precipitation trend analysis by McRoberts et al. (2011) identified widespread positive linear trends of 2-5% for the inland northwest and western Idaho over the 20th century average (1895 – 2009) hydroperiod with a negative trend of 2-5% for southeastern Washington. A similar study by MacDonald (2010) noted a decrease in precipitation within the inland Pacific Northwest Region for the 2001 to 2009 period relative to the 20th century average (1895 – 2000).

Wang et al. (2009) analyzed gridded precipitation data for a historical (1950 – 2000) hydroperiod. Within the inland northwest, slight increasing trends were observed during both the spring and fall and no trend during the summer when precipitation is generally lower.

An analysis of 20th century rainfall data by Pryor et al (2009), identified statistically significant nonlinear trends for the pacific northwest, including: an overall increasing trend in total annual precipitation, a decreasing trend in large precipitation events and intensity (exceeding the 90th percentile) and an increase in the number of precipitation days per year.

Soil moisture is a function of both supply (precipitation) and demand (evapotranspiration). Grundstein (2009) found that soil moisture was slightly decreasing in the eastern portion of the Pacific Northwest based on annual data from 1895 to 2006.

In the twentieth century, some areas of the Pacific Northwest Region received more winter precipitation and experienced a general decline in spring snowpack, reduced snowfall to winter precipitation ratios, and earlier snowmelt runoff between the mid- and late twentieth century (Spears et al. 2013).

In the Western United States, from 1950–1999, there was a general decrease in the fraction of precipitation retained in the spring snowpack. Snow cover extent in North America set record lows in 3 of the 5 years preceding 2012. A study by Kapnick and Hall (2010) found that recent snowpack changes are due to regional- scale warming, which implies a possible future loss of late season snowpack and an earlier melt season. Multiple studies estimated 1°C warmer climate results in a 14.8–20 percent decrease in snow water equivalent (SWE).

Mote and Sharp (2016) reported that both winter and spring temperatures have increased in western North America during the twentieth century, coinciding with spring snowmelt shifting earlier in the year and decreased April 1 snowpack. Carelton and Hsiang (2019) noted that increased Increasing temperatures can accelerate snowmelt and lengthen the frost-free season.

2.2.2 Projected Future Trends

Analyses by Beles et al. (2006) suggested both losses in snowpack in lower altitude mountain ranges and high altitude or high latitude cool season will increase during the twenty-first century.

Kunkel et al (2013) simulated an increase in seasonal mean precipitation for southeast Washington, except for winter, which was projected to experience a 2–4 percent decrease. There is notable uncertainty however associated with the predicted precipitation changes. While the number of wet days (precipitation > 1 in) was forecasted to increase, the changes were found to be statistically significant for only small areas in central Washington and Oregon.

The Washington Climate Change Impacts Assessment (Little et al 2009) projects that April 1 snowpack will decrease by 28 percent across Washington by the 2020s, 40 percent by the 2040s, and 59 percent by the 2080s (relative to the 1916–2006 historical average).

Because global climate models do not have sufficient spatial resolution to represent the atmospheric and land surface processes comprising the unique regional climate of the state of Washington, the regional climate model study by Salathé et al. (2010) is very relevant. The study reports two 100-year regional climate simulations showing large-scale weather patterns simulated by a global model interacting with local terrain. The mesoscale simulations produced regional changes in snow cover, cloudiness, and circulation patterns, which affected temperature and precipitation trends over the region relative to the statistical downscaling of the global model. To illustrate this effect, this study analyzes the changes from the current climate (1970– 1999) to the mid-twenty-first century (2030–2059). Main findings from this analysis were (1) projected loss of snowpack; (2) reduced snowpack and earlier snowmelt will alter timing and amount of river runoff in the summer, though changes in annual runoff will depend on annual precipitation changes, which differ between scenarios; and (3) extreme precipitation frequency increases over the north Cascades and over eastern Washington.

Miles, et al. (2010) assessed regional impacts and adaptation strategies for potential climate change impacts within Washington State. They indicated that the already highly variable water available would be expected to change in the future as temperature increases of 2–3°F by the 2040s and more basins shift towards rain-dominated by mid-century. Summer and fall low flow season would substantially increase in length, exacerbating direct effects of warmer air temperatures on stream temperature. Rising stream temperatures are expected to reduce freshwater salmon habitat. Based on their analysis, they project greater western and far eastern Washington precipitation, but less precipitation in the lower Columbia River Basin. Consistent with multiple other studies reviewed, this study projects decreasing April 1 SWE.

2.3 Hydrology

2.3.1 Baseline Trends

The regional summary from USACE Civil Works Technical Report CWTS-2015-23 reported a mixed consensus of statistically significant decrease in streamflow and April 1 SWE data for the latter half of the twentieth century within the Northwest United States. A synthesis of historical climate trends (Spears, et al. 2013) found that stream runoff was characterized by earlier freshet peak flows at most stations between 1950 and 1999, with significant trends toward earlier runoff in the Pacific Northwest Region.

Stewart et al. (2005) found that the center of mass of streamflow has shifted earlier by 1 to 4 weeks in many of the records. Other studies found runoff earlier by 1 to 3 weeks over most of the Mountain West. Fritze et al. (2011) found that warmer temperatures in snowpack dependent watersheds cause reduced snowpack during winter, increased winter month runoff, and earlier spring freshet flows associated with an earlier snowmelt, resulting in decreased inflow to lower elevation reservoirs relative to historical conditions.

Present work from the River Management Joint Operating Committee, which includes Bonneville Power Administration, USACE, and the U.S. Bureau of Reclamation, considered data for the Columbia River Basin (RMJOC 2018). The study primarily presents updated sets of naturalized streamflow datasets derived from the Coupled Model Intercomparison Project (CMIP) Phase 5 and projections of future conditions. Under this study, a

No Regulation-No Irrigation (NRNI) dataset was developed to best represent streamflows unaffected by human activity in the Columbia River Basin prior to any water resources development for the 1929-2008 hydroperiod. Analysis of the NRNI dataset found that the spatial distribution of identified nonstationarities in annual maximum flows correlated with subbasins where annual peak flows are attributed to spring snowmelt while more rain dominated basins had lower detection rates.

In these areas, nonstationarities were also detected in the 30-day maximum flow, due to the spring snowmelt season, which has lower daily peaks than the rainy season, but higher flows for longer durations during snowmelt season. The authors note that snowmelt flooding is more sensitive to warming temperatures, particularly in regions where average winter temperature is close to freezing and at lower latitudes that experience higher rates of spring warming. Nonstationarities were also detected in the annual minimum weekly mean summer flows and were geographically distributed consistent latitude, topography, and snowmelt signature.

2.3.2 Projected Future Trends

Streamflow for the inland northwest is predicted to decrease in summer, exacerbating increased temperature effect on aquatic habitat. River hydrograph timing is predicted to continue to shift earlier in the year. The combination of increasing temperature and changing hydrology are predicted to result in loss of freshwater salmon habitat and other ecological mismatches.

A study by Elsner et al (2010), notes that the Pacific Northwest Region hydrology is sensitive to temperature change impact on rain/snow balance because of dependency on snowmelt. April 1 SWE is predicted to decrease by 38–46 percent by the 2040s compared with the mean over water years 1917–2006. By the 2080s, seasonal streamflow timing will shift in both snowmelt dominated and rain-snow mixed watersheds. Annual runoff across the state is projected to increase by 2–3 percent by the 2040s, given an increase in winter precipitation.

Hydrologic simulations by Mantua et al (2010) estimated that by the 2080s, the pacific northwest region would experience a complete loss of snowmelt dominant basins within Washington State, with only about ten transient basins (a mix of direct runoff from cold-season rainfall and springtime snowmelt) remaining in the north Cascades. These transient basins were found to be most sensitive to climate change, with historically transient runoff watersheds (such as the Yakima River) shifting towards rainfall-dominant behavior, with more severe summer low-flow periods and more frequent days with intense winter flooding that could reduce salmonid egg-to-fry survival rates.

Modeling by USBR (2011) of three Columbia-Snake River subbasins, was used to simulate hydroclimate response from an ensemble of downscaled CMIP3 models that were run through a Variable Infiltration Capacity model (Liang et al., 1994). As enumerated in Table 2-1, the ensemble changes suggest that these basins will experience increasing mean-annual temperature and precipitation during the 21st century, accompanied by decreasing trend in spring SWE, decreasing trend in April - July runoff volume, and increasing trends in December - March and annual runoff volumes.

Table 2-1 Summary of Simulated Changes in Decade-Mean Hydroclimate in the Columbia River Basin

Hydroclimate Metric (Change from 1990s)	2020s	2050s	2070s
Columbia River at The Dalles			
Mean Annual Temperature (°F)	1.4	3.2	4.6
Mean Annual Precipitation (%)	3.4	6.2	8.5
Mean April 1 SWE (%)	-1.0	-3.1	-6.7
Mean Annual Runoff (%)	2.3	3.7	7.5

Hydroclimate Metric (Change from 1990s)	2020s	2050s	2070s
Columbia River at The Dalles			
Mean December–March Runoff (%)	9.8	18.5	27.3
Mean April–July Runoff (%)	2.2	4.1	2.4
Mean Annual Maximum Week Runoff (%)	3.5	4.0	5.5
Mean Annual Minimum Week Runoff (%)	-1.5	-5.9	-8.5
Snake River at Brownlee Dam			
Mean Annual Temperature (°F)	1.6	3.6	5.0
Mean Annual Precipitation (%)	2.3	3.9	6.6
Mean April 1 SWE (%)	-5.0	-12.0	-16.0
Mean Annual Runoff (%)	-0.1	1.2	3.4
Mean December–March Runoff (%)	5.6	13.7	21.0
Mean April–July Runoff (%)	-1.3	-2.0	-0.9
Mean Annual Maximum Week Runoff (%)	2.4	3.5	5.8
Mean Annual Minimum Week Runoff (%)	-3.0	-4.3	-5.9
Yakima River at Parker			
Mean Annual Temperature (°F)	1.3	2.9	4.2
Mean Annual Precipitation (%)	3.7	5.7	7.7
Mean April 1 SWE (%)	-10.3	-19.6	-28.7
Mean Annual Runoff (%)	3.8	3.7	5.6
Mean December–March Runoff (%)	19.6	39.9	56.9
Mean April–July Runoff (%)	-2.0	-9.5	-17.0
Mean Annual Maximum Week Runoff (%)	2.7	4.2	6.7
Mean Annual Minimum Week Runoff (%)	-4.0	-10.6	-14.2

Hydrologic predictions from the River Management Joint Operating Committee (RMJOC) reported by Pytlak et al. (2018), indicate that future increases in temperature, with decreases in winter snowpack and summer precipitation will manifest as significantly higher average fall and winter river flows, earlier peak spring runoff, and longer periods of low summer flows starting as early as the 2030s.

2.4 Summary

The consensus from the literature supports evidence that temperature and precipitation have increased, while streamflows have decreased over the observed period of record within the inland Northwest regions of the Columbia River basin, with notable departures in recent decades relative to 20th century normals.

The Columbia River System Operations Environmental Impact Statement (USACE 2020) heavily relies on the studies performed by the RMJOC, and therefore supports several studies listed in this assessment. Future forecasts of temperature, precipitation, and hydrologic response in the Pacific Northwest are uncertain and variable, but in general can be characterized as wet regions and seasons becoming wetter, dry regions and seasons becoming drier, and reduced snow depth, density, and extent. Regional temperatures of the inland northwest are projected to increase by varying amounts, on the order of 3.5–9° F over the next century. An increased freeze-free period and loss of April 1 snowpack follows from this prediction and is also discussed in the literature. Streamflow is predicted to decrease in summer, exacerbating increased temperature effect on aquatic habitat. River hydrograph timing is predicted to continue to shift earlier in the year. The combination of increasing temperature and changing hydrology are predicted to result in loss of freshwater salmon habitat and other ecological mismatches.

Using the most recent data from CMIP5/IPCC-5, two recent climate assessments (USBR 2016 and Department of Energy 2017) reached similar conclusions regarding the future hydroclimate of the Columbia River Basin. More specifically, they agreed that temperatures in the Columbia River Basin will almost certainly continue to rise over the next several decades, which will impact snowpack and subsequent seasonal runoff. Both reports also indicated that a signal may be emerging in the temperature and precipitation datasets produced by the GCMs and their downscaled counterparts that wetter autumns and winters may develop over time in the Columbia Basin, which would correspond to higher annual precipitation despite a possible, partially offsetting emerging trend for already dry summers to turn drier in parts of the basin.

These findings are further supported by the Pacific Northwest region-specific USACE Climate Change Assessment CWTS-2015-23 (USACE 2015), which found that there is a moderate consensus that air temperatures will increase over the next century in the Pacific Northwest Region, and a strong consensus that the region could experience an increase in maximum temperature extremes on the order of 5–15 °F. A strong consensus is also noted that intensity and frequency of extreme storm events will increase. Future minimum temperature, average annual precipitation, and streamflow show varied trends, which may be due to physiographic variability within the greater pacific Northwest Region. Literature review trends from CWTS- 2015-23 are summarized in Figure 2-2.

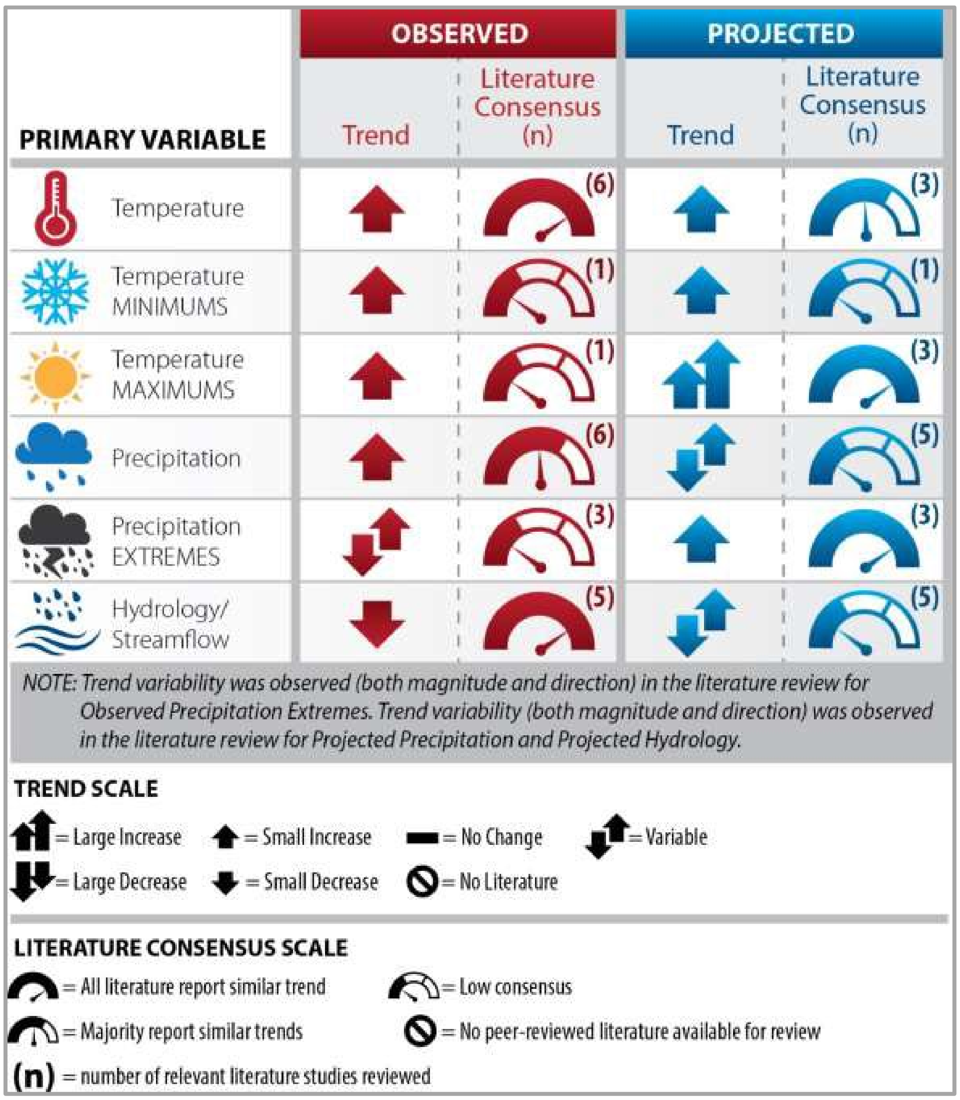


Figure 2-2 Literature review trends from CWTS-2015-23

2.5 Identification of Relevant Climate Variables

Construction of McNary Dam and Tri-Cities Levees has degraded the Yakima Delta ecosystem by creating poor habitat conditions for native fish and reducing biodiversity (USACE 2021). Impoundment of Lake Wallula (the run of the river reservoir upstream of McNary Dam) has inundated the Yakima River up to 2 miles from the delta. This inundation has created ideal habitat for non-native predatory fish and invasive plants inside the southern part of the delta and promoted localized sediment deposition. The degradation has been compounded by the reduction in flow, increased stream temperatures and sediment buildup caused by the Bateman Island causeway. These changes to the ecosystem have caused delays to upstream migration and contribute to increased straying (diverting from normal migration pathway), diminished health, and lower reproductive success in adult salmonids and the possible increase in predation on smolts. The Yakima Delta 1135 TSP will alleviate detrimental ecosystem conditions by increasing stream flow (due to removal of the causeway currently blocking flow around Bateman Island) and lowering mean stream temperatures (improved by increased mixing of cooler Columbia River flows with the much warmer Yakima River flows).

The relevant climate variables measuring TSP performance are annual air temperatures, mean annual stream flow and annual precipitation. Increases in air and water temperatures are expected to continue to delay adult salmon migrations. Physiological consequences of migrating through elevated temperatures may result in a failure to survive to complete spawning in adult salmon (Farrell et al. 2008). As water temperatures rise, the thermal barrier at the Yakima delta is expected to become more severe, possibly leading to a shift in migration passage. Salmon migrate to freshwater tributaries during the summer months for either spawning, rearing, or seaward smolt migrations. Summertime stock migrations are expected to be most impacted by the increasing annual water temperatures caused by climate change. These include summer-run steelhead, sockeye, and summer Chinook populations in the Columbia Basin. Because of the earlier timing of snowmelt and increased evaporation, most of Washington's river basins, including the Yakima River, are projected to experience reduced streamflow in summer and early fall that results in an extended period of summer low flows. In combination with increased summertime stream temperatures, reduced flow is likely to limit rearing habitat for salmon with stream-type life histories (wherein juveniles rear in freshwater for one or more years) and increase mortality rates during spawning migrations for summer-run adults (Madtua, et al. 2010).

For this assessment, indicator variables within the three categories identified as relevant for assessing potential climate impacts to the Yakima Delta restoration project include:

Temperature variables:

- Annual maximum 1-day temperature as an indicator of heat waves
- Annual minimum 1-day temperature as an indicator of winter warming
- Monthly seasonal temperature trends

Precipitation variables:

- Annual accumulated precipitation as indicator of wetter or dryer years.
- Monthly seasonal precipitation trends
- Annual maximum of number of consecutive dry days as an indicator of drought conditions

Hydrologic variables:

- Annual maximum stream temperature
- Annual peak streamflow as an indicator of flashy (potentially rain-driven) peaks.
- Annual and maximum monthly flow as an indicator of runoff associated with snowmelt.

- Annual summer volume as an indicator of relatively wetter or dryer years.
- Mean annual and monthly flows to identify seasonality trends that could impact the TSP.
- Minimum annual and monthly streamflow as an indicator of low flow conditions & trends.
- Monthly seasonal flow trends.

3 Hydrologic Time Series Nonstationarities & Trends

This portion of the climate assessment focuses on carrying out first order statistical analyses of streamflow records in the study area using the USACE Time Series Toolbox (TST).

3.1 Time Series Data

Initially, two USGS stream gages were used to analyze trends at the project site. These included the Yakima River at Kiona, WA (USGS 12510500) and the Columbia River below Priest Rapids Dam (USGS 12472800) gages. Peak streamflow records were used from water years 1934 through 2022 for the Yakima gage and 1960 through 2022 for the Columbia gage. While both gages have data collected pervious to these start dates, these data were excluded due to large amounts of missing data (more than five years). However, it was determined through reference to the gages' USGS Water-Year Summaries that both are affected by significant irrigation withdrawals upstream and the Columbia gage is impacted by 10 dams upstream. The Yakima River at Kiona gage has significant upstream diversions for the irrigation of about 424,000 acres. The Kennewick Canal has also been diverting about 96,000 acre-feet of flow above the gage since August 1956 (USGS, 2023a). The Columbia River below Priest Rapids Dam has significant upstream diversions for irrigation of about 600,000 acres and flow regulation by 10 major reservoirs and numerous smaller reservoirs and powerplants (USGS, 2023b).

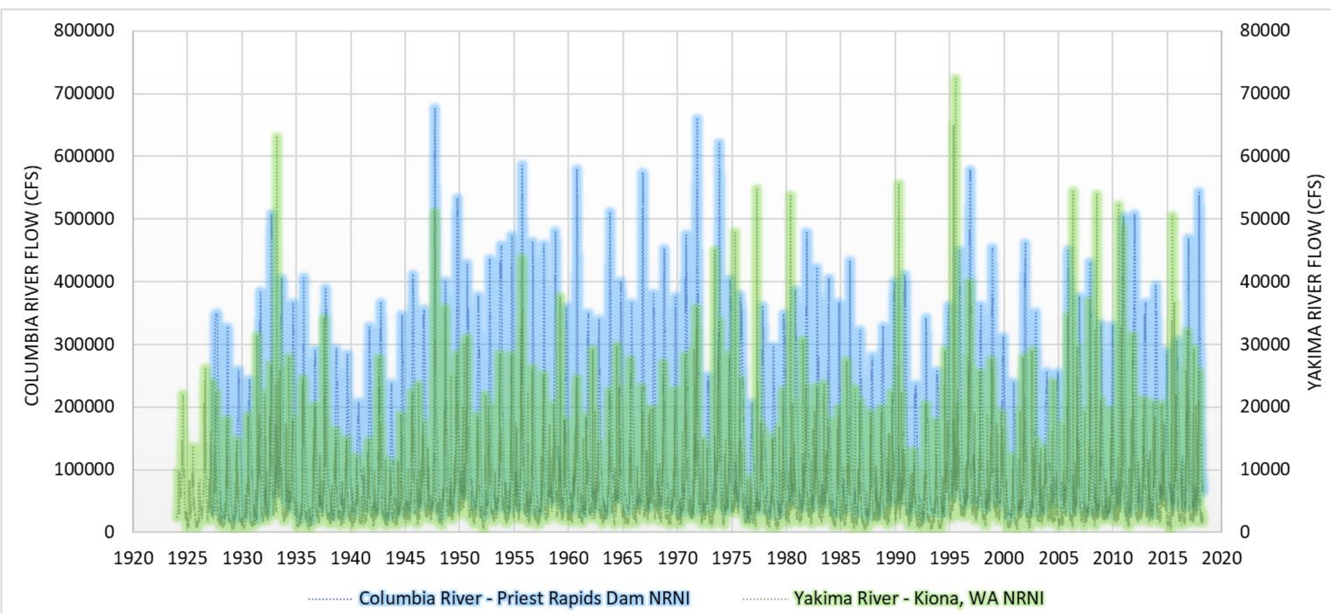


Figure 3-1 NRNI Period of Record Daily Flow for Yakima River at Kiona and Columbia River at Priest Rapids Dam. (The axis for the Yakima River gage is scaled down a tenth of the Columbia River gage flows)

The purpose of the nonstationarity and trend analysis on observed streamflow is to help determine if climate change is affecting streamflow at the project site. Because these two gages have significant irrigation diversions and regulation upstream, their trends are likely due to changes in regulations and diversions and not reflective of climate change. Due to this, analysis was completed on a no regulation no irrigation (NRNI) streamflow dataset at

Kiona on the Yakima River and at Priest Rapids Dam on the Columbia River with a focus on what was learned in the analysis on the gage record with regulation and irrigation. The NRNI dataset is shown in Figure 3-1 above and the NRNI annual peaks are shown in Figure 3-2 below. See Appendix A for nonstationarity and trend analysis results on the regulated data for the same locations.

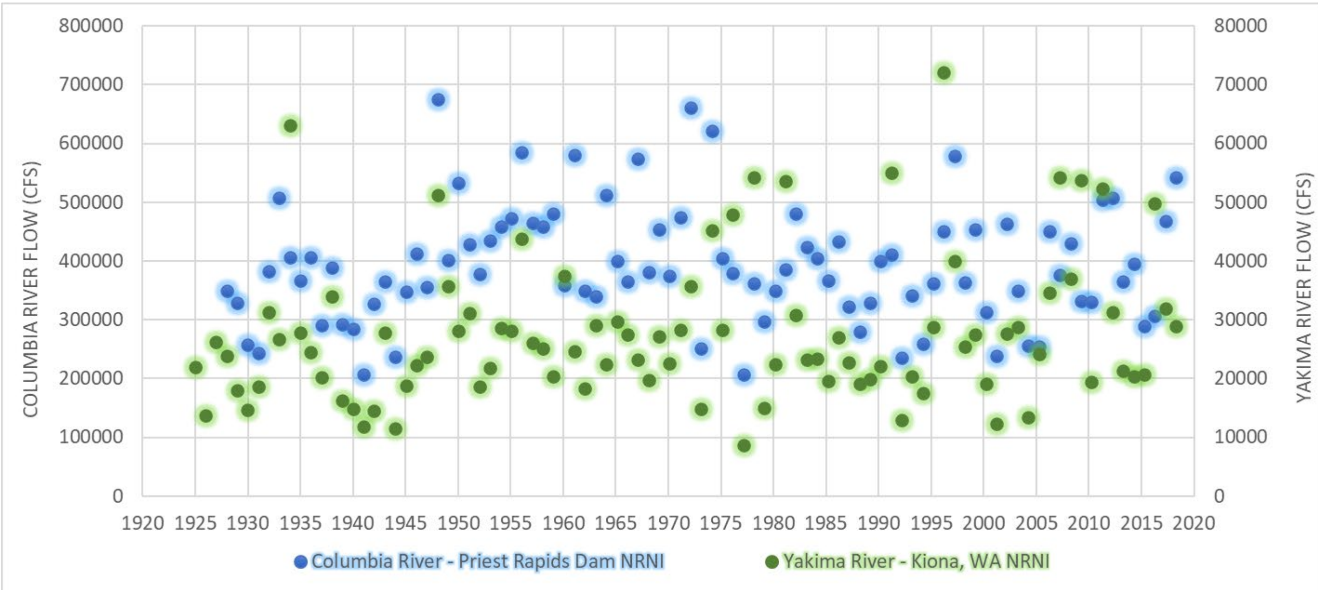


Figure 3-2 NRNI annual peak flow for Yakima River near Kiona and the Columbia River at Priest Rapids Dam. (The axis for the Yakima River gage is scaled down a tenth of the Columbia River gage flows)

3.2 Nonstationarity Detection

The assumption that the statistical characteristics of hydrological time series are constant through time (stationarity) has been a foundational assumption for hydrologic assessment and forecasting (Milly et al., 2008). This assumption has enabled the use of well-accepted statistical methods in hydrologic analyses that rely primarily on the observed record and assume that the first and second order statistical moments (i.e., mean and variance) do not vary within a particular timescale of interest. Statistical tests can be used to test this assumption using techniques outlined in Engineering Technical Letter (ETL) 1100-2-3. Over short-term timescales (e.g., daily, monthly, annual), hydrologic timeseries frequently include nonstationarities that can be corrected for such as seasonality or deterministic flow regulation. Over longer timescales however, hydrologic nonstationarity can be present due to random or uncertain processes (such as climatic drivers) that can be difficult to identify without a sufficiently long period of record.

Nonstationary in hydrologic records can result from multiple spatial and temporal factors. This includes changes in watershed land cover or land use, changes in upstream water supply such as hydro-regulation, diversions for water supply or irrigation, and larger scale changes in meteorology and climate. Systemic changes in hydrologic response can be temporally abrupt or gradual and vary by catchment and stream network.

Climate change has the potential to undermine the stationarity assumption by introducing nonstationary into both meteorological trends and hydrologic response. USACE civil works policy guidance includes methodologies for the detection of nonstationarities in streamflow in support of USACE project planning, design, construction, operations, and maintenance (ECB 2016-25, USACE, 2016; ETL 1100-2-3, USACE, 2017).

The TST includes both breakpoint and nonstationarity detection tools. The breakpoint detection utilizes linear regression models of segmented data, while the nonstationary detection tool identifies statistically significant changes in the mean, variance, and distribution of a time series dataset using a suite of both parametric and nonparametric statistical methods. The TST nonstationarity detection approach applies 12 statistical tests to detect trends in the data, five of which are change point models, a Bayesian change point, smooth and abrupt Lombard methods, the energy divisive method, and the Pettitt test. All datasets were initially analyzed with the default NSD sensitivity parameters enumerated in Table 3-1. In some cases, the default parameters were adjusted to test the sensitivities of detected nonstationarities.

Table 3-1 Default Sensitivity Parameters for TST Tool Nonstationary Detection methods

NSD Test Method	Default Sensitivity Parameters
CPM Methods Burn-In Period	20
CPM Methods Sensitivity	1,000
Bayesian Posterior Threshold	0.5
Energy Divisive Method Sensitivity	0.5
Pettitt Sensitivity	0.05
Bayesian Prior Likelihood	0.2
Lombard Smooth Methods Sensitivity	0.05

3.3 Observed Record Strong Nonstationarity and Trend Analysis Results

Table 3-2 below summarizes the hydrologic records of interest selected to inform the feasibility of the Yakima Delta ecosystem restoration project and which TST tests were evaluated. Analyses of climate change trends within the Yakima Delta study area is complicated by the variety of uses that both rivers have. Streamflow magnitude can be influenced by changes in irrigation use, hydroregulation and seasonality. These factors can make it difficult to determine the role of climate change in affecting the hydrologic signal at the project scale. The relevant question of interest at the project scale is whether there has been, or will be, a change that affects conditions in the study area and how this change would impact the resilience of the TSP. The selection of the time series datasets considered aligns with the hydrologic records rationale for of relevant climate variables as previously discussed in Section 2.5 above.

Table 3-2 Summary of hydrologic timeseries analyzed in the TST

Dataset	Rationale
Annual Peak Flows and Maximum Flows	Peak/maximum flows could indicate a lower April 1st SWE value which would impact TSP performance since the project area is in a snow driven basin and the project relies heavily on the mixing of the Yakima and Columbia Rivers.
June – August Volumetric Yield	Decreasing trends in annual summer volume could significantly impact TSP performance since there would be less stream volume available for mixing inside the project area.
Mean Flows	The seasonality trends in mean annual and monthly flows are of interest because reduced summer flows could potentially impact various measures of the ecosystem restoration TSP.
Minimum Flows	The study area frequently experiences low flows, especially during the summer months, which could impact project performance by increasing temperatures inside the Yakima Delta.
Annual Maximum Stream Temperature	Increasing maximum stream temperatures could significantly impact TSP performance since the project requires lower stream temperatures to support aquatic species habitats.

3.3.1 Annual Maximum Stream Temperature Results with Statistical Significance and Detected Strong Nonstationarities

Annual maximum stream temperature values were analyzed in the project area. Average and minimum values were unable to be analyzed due to the lack of data available in the project area. Annual maximums were aggregated from instantaneous values for the Yakima River at Kiona, WA gage; for the Columbia River Below Priest Rapids Dam gage, hourly data was aggregated to yearly values.

No significant trends or strong nonstationarities were found for either data set. The Columbia River gage exhibited one breakpoint in 1997.

Table 3-3 Annual Maximum Stream Temperatures

Dataset	Trends	Breakpoints	Strong Nonstationarities
Yakima River at Kiona, WA (12510500)			
Yakima River at Kiona, WA (#12510500) – Maximum Annual Temperature (2003 – 2022)	Traditional Slope =0.03925 Sen's Slope = 0.04802 <u>Significance</u> t-test = 0.70742 Mann-Kendall = 0.72052 Spearman Rank-Order = 0.72836	None detected	None detected
Dataset	**Trends**	**Breakpoints**	**Strong Nonstationarities**
Columbia River Below Priest Rapids Dam (12472800)			
Columbia River Below Priest Rapids Dam (#12472800) – Maximum Annual Temperature (1994 – 2023)	Traditional Slope = -0.083737 Sen's Slope = -0.023529 <u>Significance</u> t-test = 0.11003 Mann-Kendall = 0.6296 Spearman Rank-Order = 0.61972	1 Breakpoint Detected <u>1997-09-30</u>	None detected

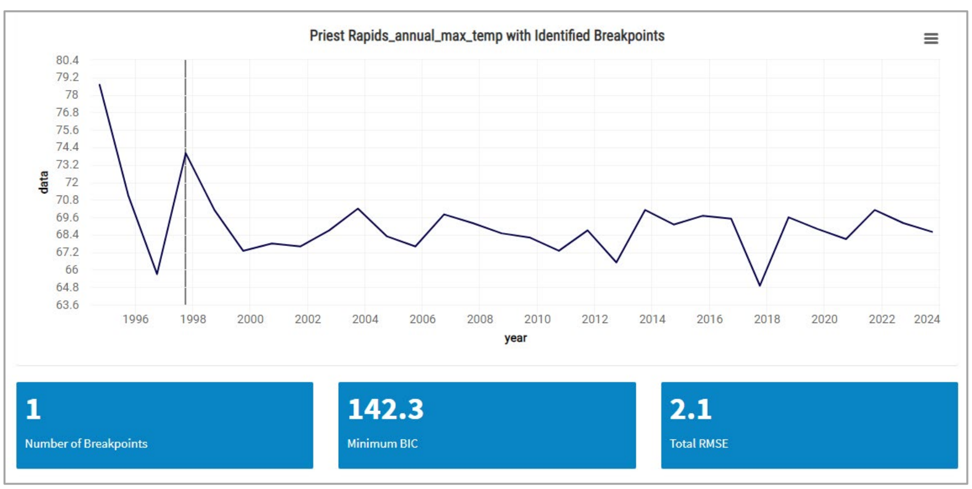


Figure 3-3 Columbia River – Priest Rapids Dam Annual maximum temperature BA

3.3.2 NRNI Peak Flow Results with Statistical Significance and Detected Strong Nonstationarities

Trend results for annual peak flows at both gages indicate a slightly positive near-zero trend. Only one test detected a significant trend below the α = 0.05 threshold for the Yakima River gage. The Columbia River gage detected no significant trends.

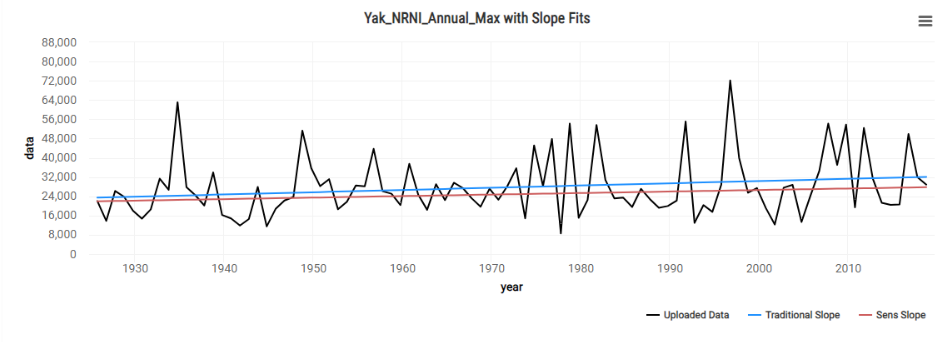
Annual peak flows for both the Yakima River and the Columbia River resulted in a strong nonstationarity detected within five years of each other (1945 and 1947 respectively). The Columbia River NRNI data also detected a strong nonstationarity in 1975, which corresponds to a similar nonstationarity found in the regulated datasets.

Two breakpoints were found the in Columbia River annual peak dataset located within the same period as the strong nonstationarities. No breakpoints were detected for either Yakima River peak datasets.

Table 3-4 Peak Flow Nonstationarity and Trend Analysis Results

Hydrologic Dataset	Trends	Breakpoints	Strong Nonstationarities
NRNI Yakima River at Kiona, WA (12510500)			
Yakima River at Kiona, WA (#12510500) – Annual Peak Flows (1925 – 2018)	Traditional Slope = 93 Sen's Slope = 63 Significance **t-test = 0.047903** Mann-Kendall = 0.057306 Spearman Rank-Order = 0.054927	None detected	**One strong nonstationarity detected around 1945 (2 mean tests, 3 smoothing tests)**
Yakima River at Kiona, WA (#12510500) – Annual July Peak Values (1925 – 2018)	Traditional Slope = -14 Sen's Slope = -12 Significance t-test = 0.3309 Mann-Kendall = 0.29592 Spearman Rank-Order = 0.30468	None Detected	None Detected
Hydrologic Dataset	**Trends**	**Breakpoints**	**Strong Nonstationarities**
NRNI Columbia River Below Priest Rapids Dam (12472800)			
Columbia River Below Priest Rapids Dam (#12472800) – Annual Peak Flows (1929 – 2018)	Traditional Slope = 50 Sen's Slope = 80 Significance t-test = 0.90102 Mann-Kendall = 0.821 Spearman Rank-Order = 0.86519	2 Breakpoints Detected 1947-09-30 1974-09-30	**Two strong nonstationarities detected around 1947 (3 distribution tests, 1 mean tests) and 1975 (2 distribution tests, 1 mean tests)**
Columbia River Below Priest Rapids Dam (#12472800) – Annual July Peak Values (1929 – 2018)	Traditional Slope = -24 Sen's Slope = -30 Significance t-test = 0.94778 Mann-Kendall = 0.92353 Spearman Rank-Order = 0.92837	None Detected	None Detected

Yakima River Results



Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Positive	93	-155523
Sen's Slope	Positive	63	-99188

Trend Hypothesis Test

Test	P-Value
t-Test	0.047903
Mann-Kendall	0.057306
Spearman Rank-Order	0.054927

Figure 3-4 NRNI Yakima River - Kiona, WA Annual Peaks Trend Analysis

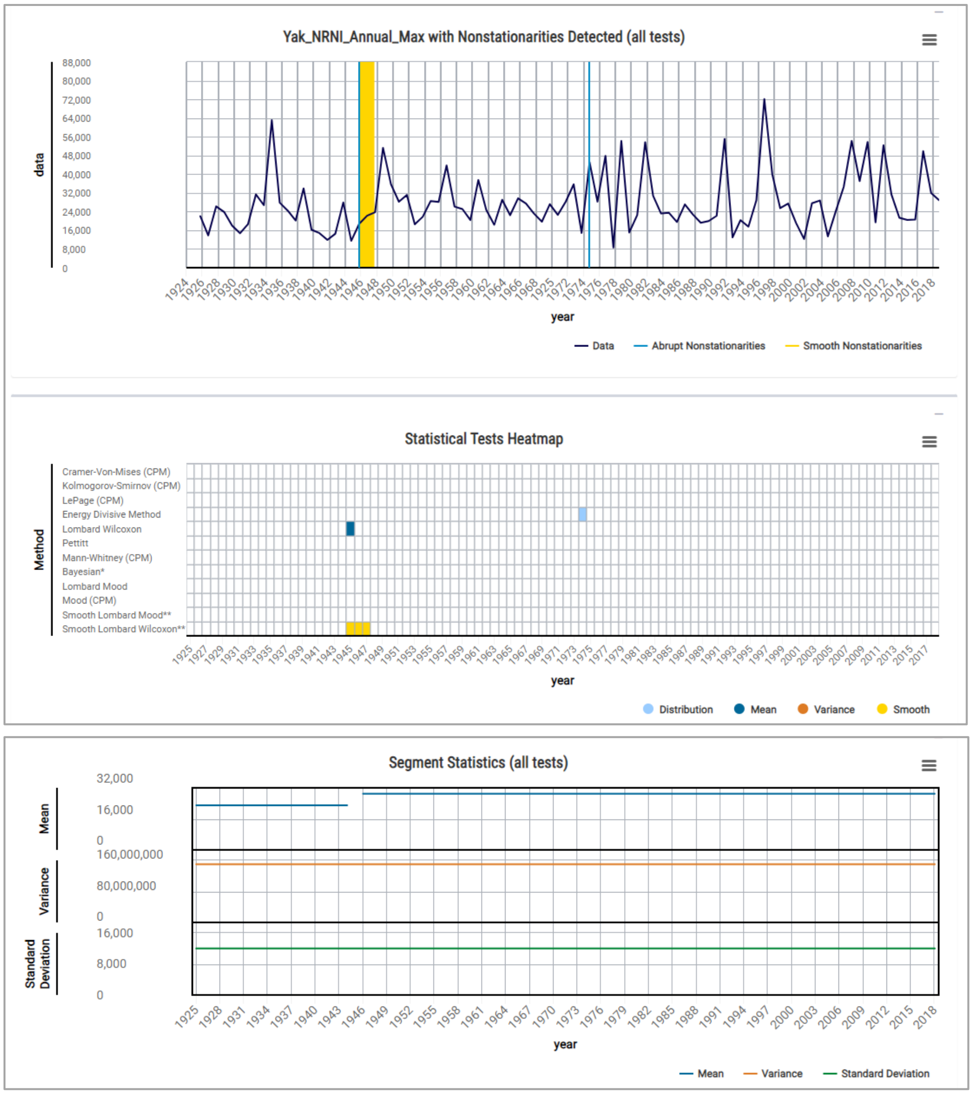


Figure 3-5 NRNI Yakima River - Kiona, WA Annual Peaks NSD

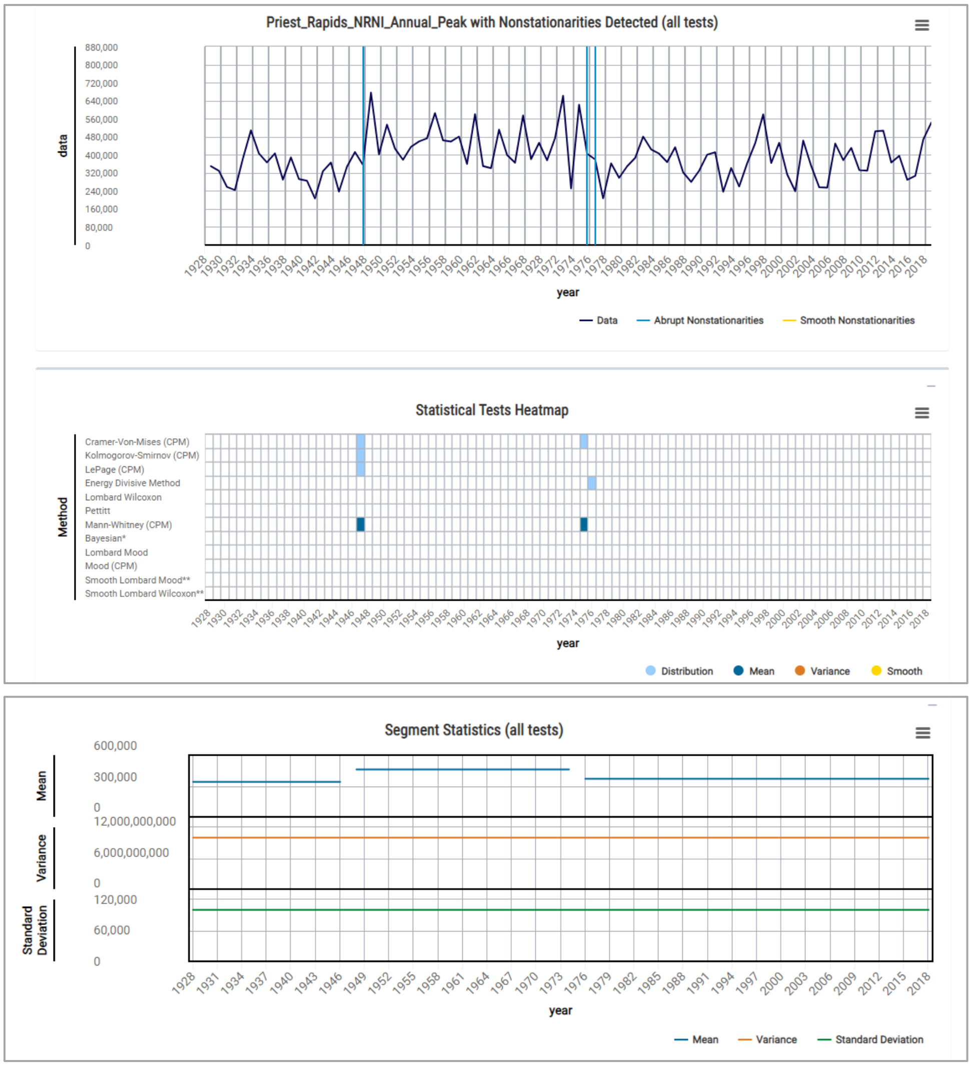


Figure 3-6 NRNI Columba River - Priest Rapids Dam Annual Peak NSD

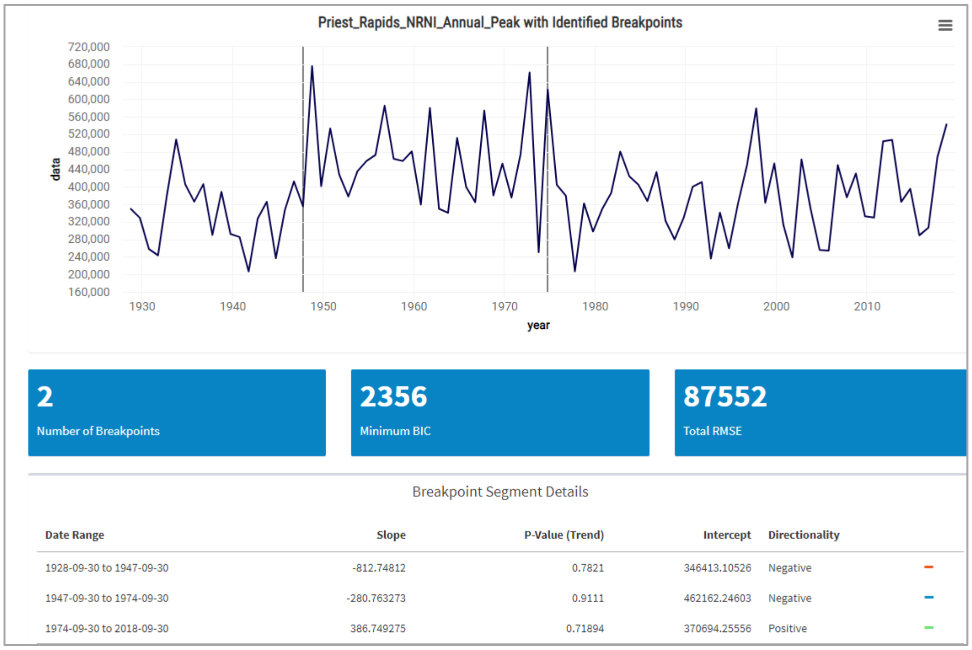


Figure 3-7 NRNI Columbia River - Priest Rapids Dam Annual Peaks BA

<u>3.3.2 NRNI Daily Flow Results with Statistical Significance and Detected Strong Nonstationarities</u>

One strong trend was detected for the Columbia River annual minimum flows as summarized in Table 3-5 below. One strong nonstationarity was detected in both the Yakima River annual and July minimum datasets during 1976. For the Columbia River datasets, a strong nonstationarity was found during 1946 for the annual minimum flows and the summer volume. There was a second strong nonstationarity found in the Columbia River summer accumulated volume during 1976.

No breakpoints were detected in the Yakima River datasets. The Columbia River datasets detected breakpoint in both the summer volume and the annual minimum flow during 1945 and 1946 respectively. The Columbia River gage accumulated summer volume also detected at breakpoint in 1976; the June – August volume breakpoint analysis shows a clear increase in the mean between 1945 and 1976.

Table 3-5 NRNI Daily Average Flow Nonstationarity and Trend Analysis Results.

Hydrologic Dataset	**Trends**	**Breakpoints**	**Strong Nonstationarities**
NRNI Yakima River at Kiona, WA (12510500)			
Yakima River at Kiona, WA (#12510500) – Annual June-August Accumulated Volume (1926 – 2018)	Traditional Slope = -1715 Sen's Slope = -1586 <u>Significance</u> t-test = 0.32786 Mann-Kendall = 0.38975 Spearman Rank-Order = 0.40824	None Detected	None Detected
Yakima River at Kiona, WA (#12510500) – Annual Mean Flow (1925 – 2018)	Traditional Slope = 2 Sen's Slope = 2 <u>Significance</u> t-test = 0. 69758 Mann-Kendall = 0. 75882 Spearman Rank-Order = 0.76803	None Detected	None Detected

Yakima River at Kiona, WA (#12510500) – July Mean Flow (1925 – 2018)	Traditional Slope = -9 Sen's Slope = -8 <u>Significance</u> t-test = 0.31735 Mann-Kendall = 0.22831 Spearman Rank-Order = 0.22668	None Detected	None Detected
Yakima River at Kiona, WA (#12510500) – Annual Minimum Flow (1925 – 2018)	Traditional Slope = -1 Sen's Slope = -1 <u>Significance</u> t-test = 0.57091 Mann-Kendall = 0.4331 Spearman Rank-Order = 0.46687	None Detected	**One strong nonstationarity around 1976 (3 mean tests, 1 distribution test, 3 smoothing tests)**
Yakima River at Kiona, WA (#12510500) – July Minimum Flow (1925 – 2018)	Traditional Slope = -5 Sen's Slope = -6 <u>Significance</u> t-test = 0. 30923 Mann-Kendall = 0.12079 Spearman Rank-Order = 0.11185	None Detected	**One strong nonstationarity around 1976 (2 mean tests, 1 distribution test)**

Hydrologic Dataset	Trends	Breakpoints	Strong Nonstationarities
Columbia River Below Priest Rapids Dam (12472800)			
Columbia River Below Priest Rapids Dam (#12472800) – Annual June-August Accumulated Volume (1929 – 2018)	Traditional Slope = -11627 Sen's Slope = -10485 Significance t-test = 0.78353 Mann-Kendall = 0.83992 Spearman Rank-Order = 0.76929	2 Breakpoints Detected 1945-09-30 1976-09-30	**Two strong nonstationarities around 1945 (1 mean tests, 2 distribution tests) and 1976 (1 mean test, 1 distribution test, 3 smoothing tests)**
Columbia River Below Priest Rapids Dam (#12472800) – Annual Mean Flow (1928 – 2018)	Traditional Slope = 62 Sen's Slope = 48 Significance t-test = 0. 48432 Mann-Kendall = 0.60709 Spearman Rank-Order = 0.60621	None Detected	None Detected
Columbia River Below Priest Rapids Dam (#12472800) – July Mean Flow (1928 – 2018)	Traditional Slope = -84 Sen's Slope = -98 Significance t-test = 0. 76424 Mann-Kendall = 0.73269 Spearman Rank-Order = 0.65772	None Detected	None Detected
Columbia River Below Priest Rapids Dam (#12472800) – Annual Minimum Flow (1928 – 2018)	Traditional Slope = 83 Sen's Slope = 92 Significance **t-test = 0. 015998** **Mann-Kendall = 0.013836** **Spearman Rank-Order = 0.012202**	1 Breakpoint detected 1946-09-30	**One strong nonstationarity detected around 1946 (1 distribution test, 2 mean tests, 3 smoothing tests)**
Columbia River Below Priest Rapids Dam (#12472800) – July Minimum Flow (1928 – 2018)	Traditional Slope = -167 Sen's Slope = -164 Significance t-test = 0. 35646 Mann-Kendall = 0.29101 Spearman Rank-Order = 0.23172	None Detected	None Detected

Yakima River – Significant Results

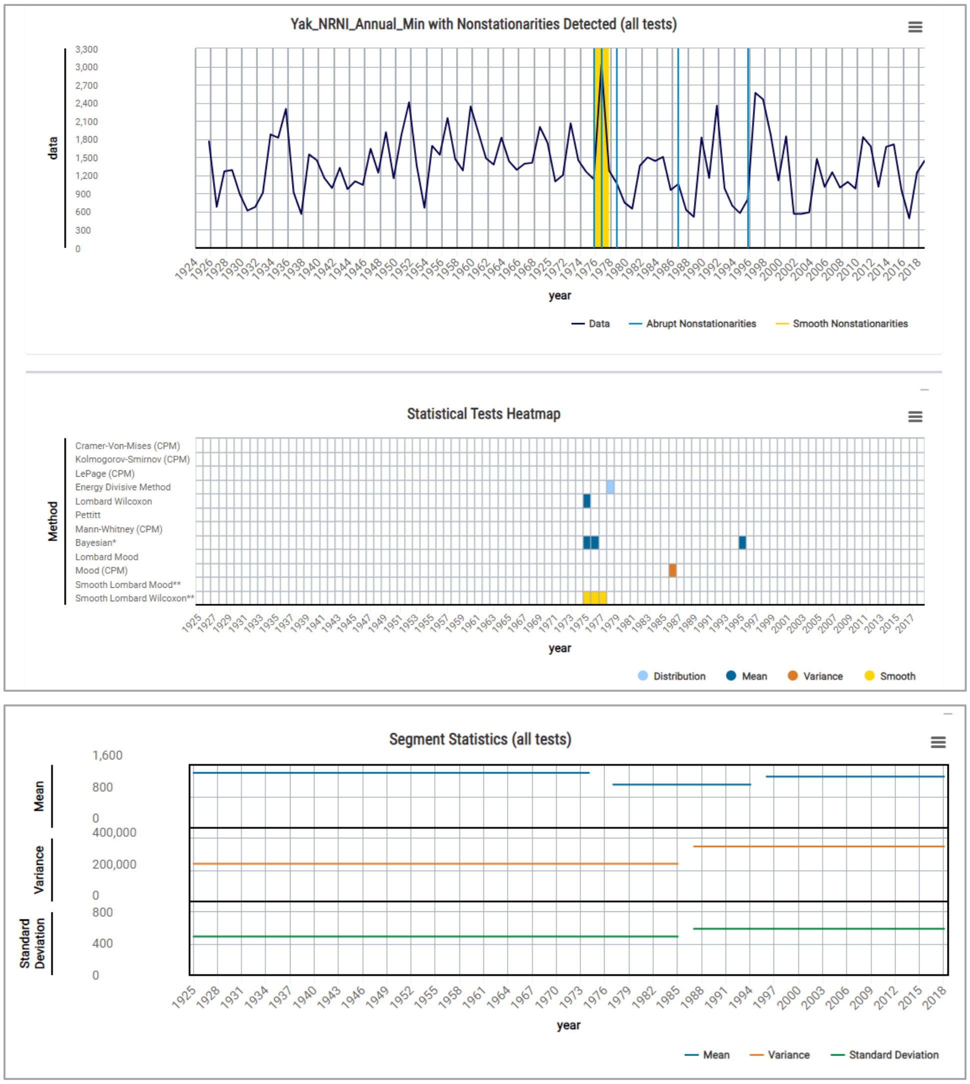


Figure 3-8 NRNI Yakima River - Kiona, WA Annual Minimum NSD

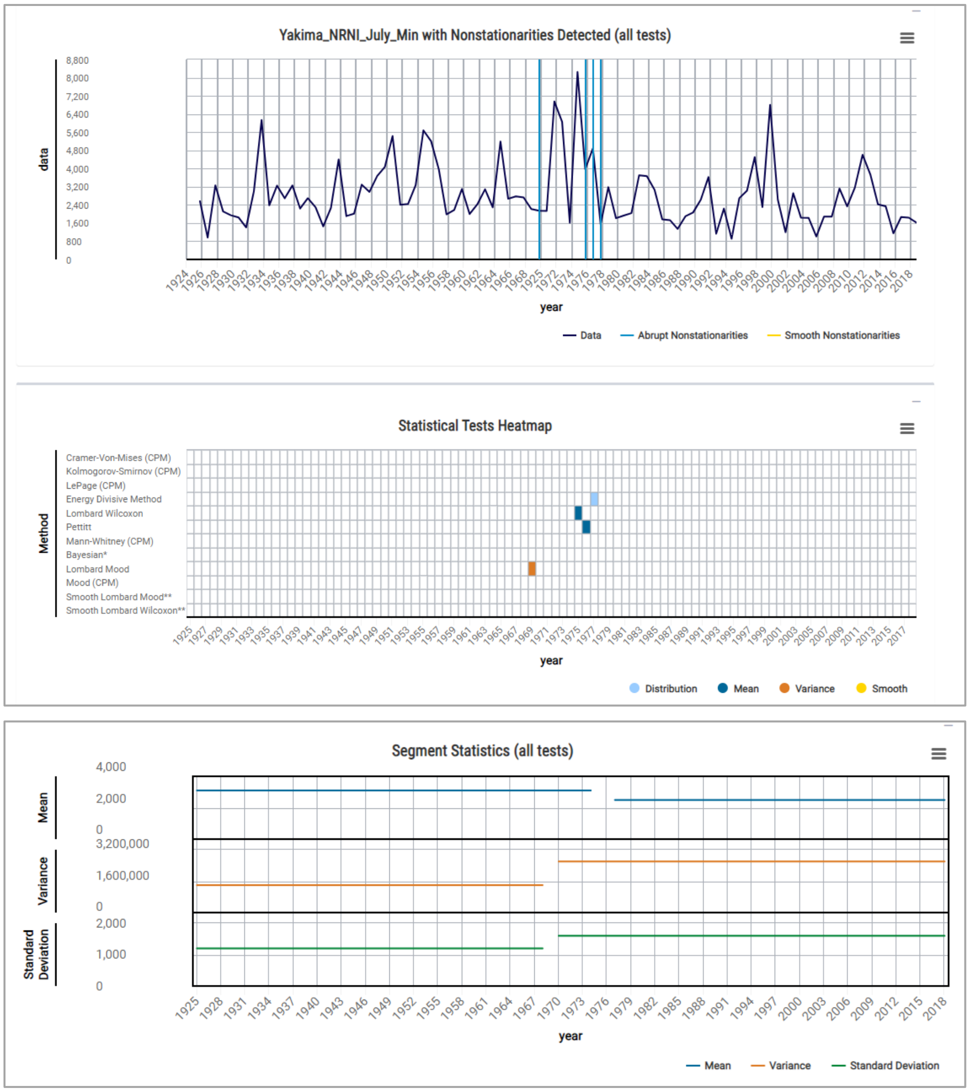


Figure 3-9 NRNI Yakima River - Kiona, WA July Minimum NSD

Columbia River – Significant Results

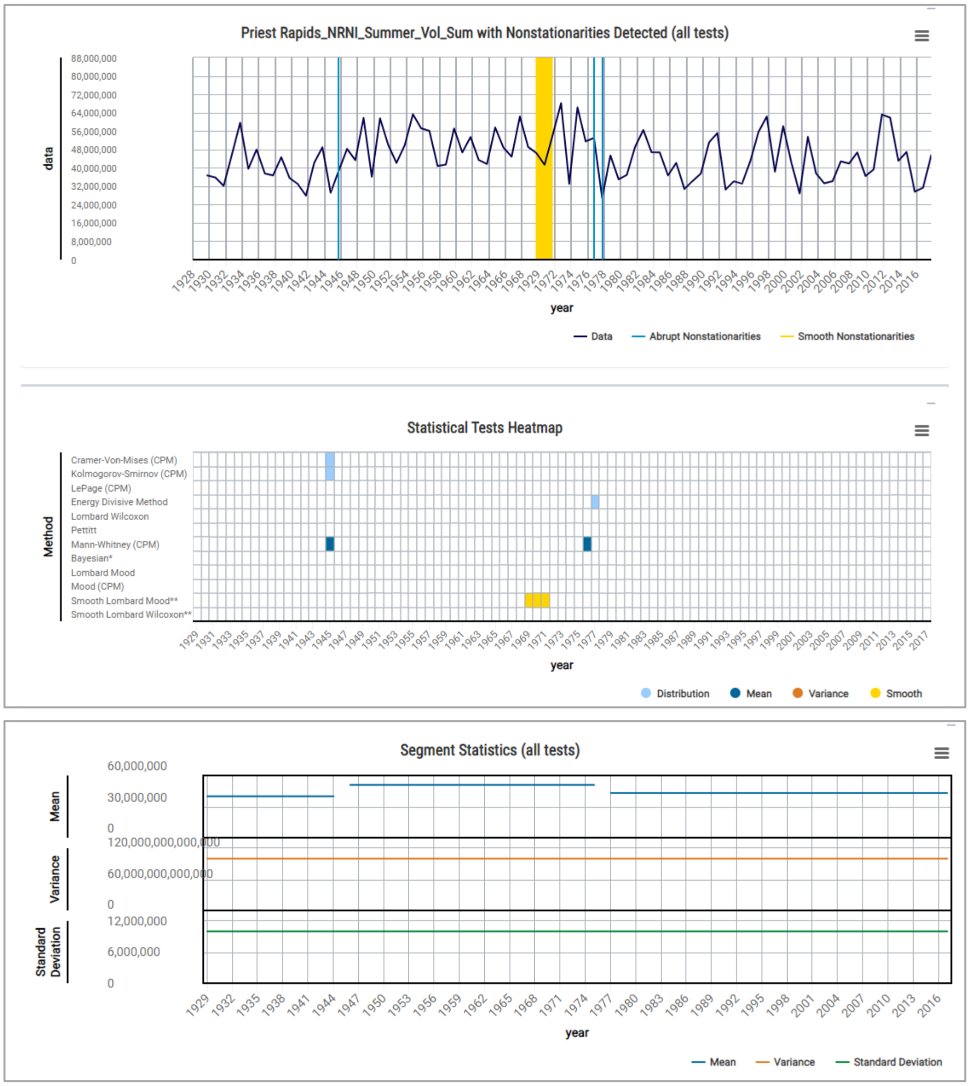
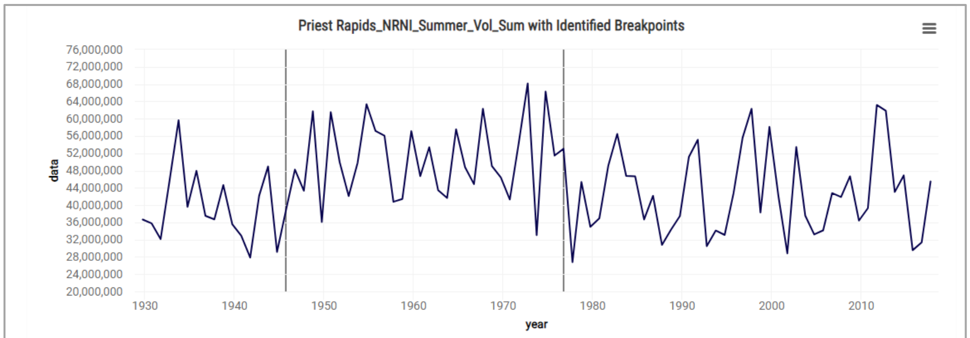


Figure 3-10 NRNI Columbia River – Priest Rapids Dam June - August Volume NSD



2 Number of Breakpoints

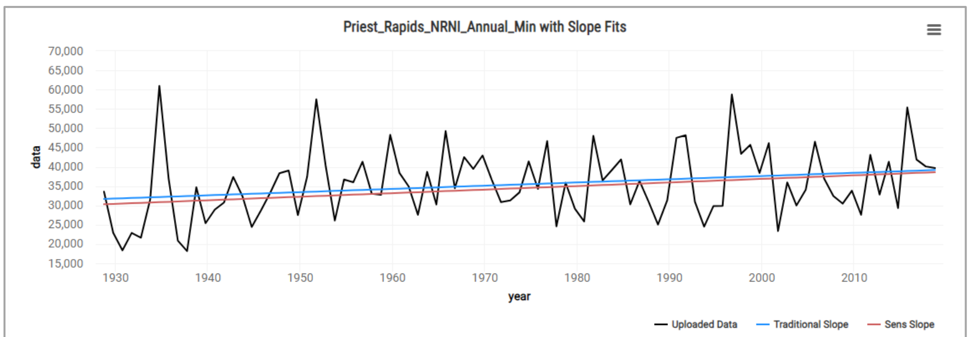
3132 Minimum BIC

9089736 Total RMSE

Breakpoint Segment Details

Date Range	Slope	P-Value (Trend)	Intercept	Directionality
1929-09-30 to 1945-09-30	-271035.686275	0.51227	41948025.76471	Negative
1945-09-30 to 1976-09-30	145241.789223	0.41152	47885113.29032	Positive
1976-09-30 to 2017-09-30	30921.110283	0.80971	42095466.46225	Positive

Figure 3-11 NRNI Columbia River – Priest Rapids Dam June - August Volume BA



Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Positive	83	-128866
Sen's Slope	Positive	92	-147550

Trend Hypothesis Test

Test	P-Value
t-Test	0.015998
Mann-Kendall	0.013836
Spearman Rank-Order	0.012202

Figure 3-12 NRNI Columbia River - Priest Rapids Dam Annual Minimum Trend Analysis

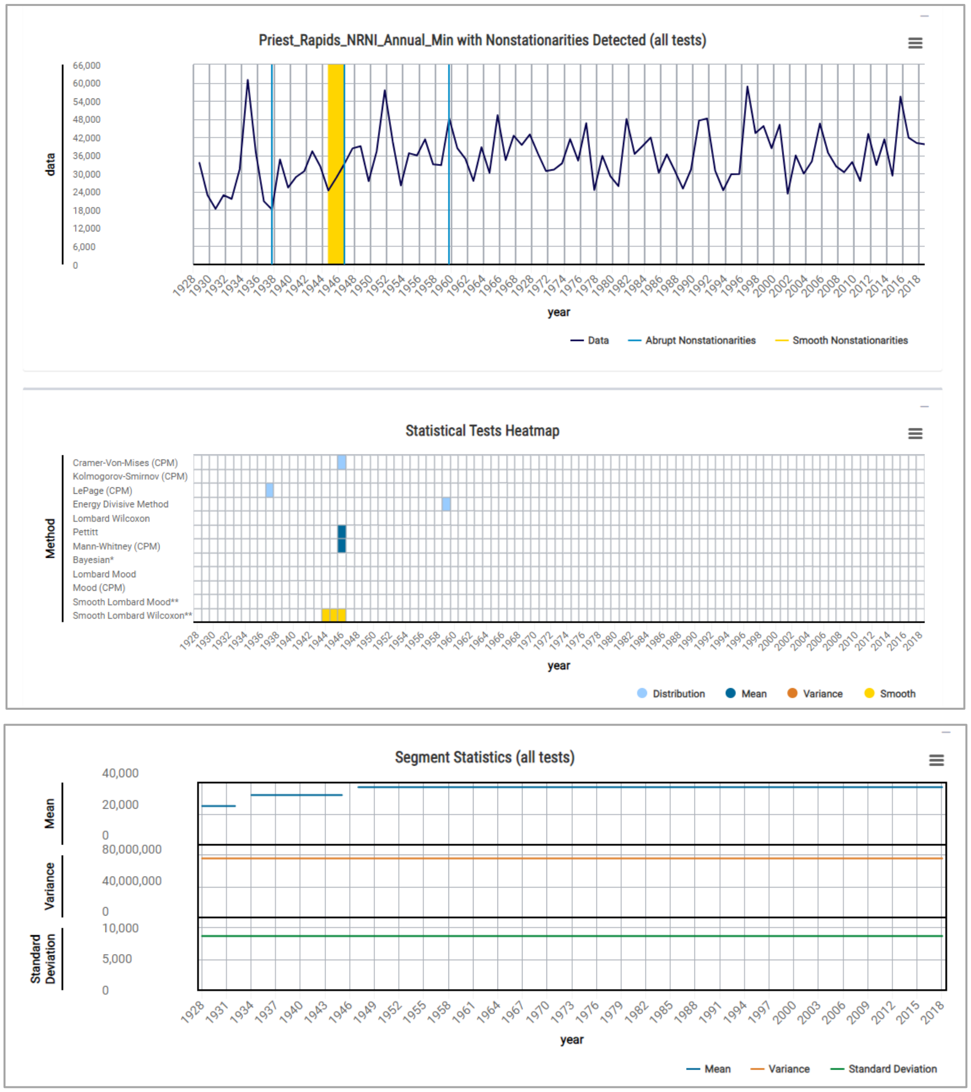
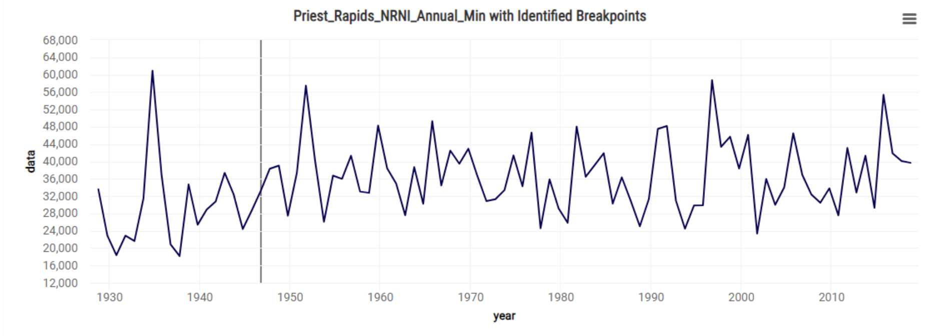


Figure 3-13 NRNI Columbia River - Priest Rapids Dam Annual Minimum NSD



1
Number of Breakpoints

1916
Minimum BIC

8163
Total RMSE

Breakpoint Segment Details

Date Range	Slope	P-Value (Trend)	Intercept	Directionality
1928-09-30 to 1946-09-30	197.963158	0.64002	27689.63158	Positive
1946-09-30 to 2018-09-30	8.39581	0.84791	36583.99886	Positive

Figure 3-14 NRNI Columbia River - Priest Rapids Dam Annual Minimum BA

4 Climate Hydrology Assessment Tool (CHAT)

The USACE Climate Hydrology Assessment Tool (CHAT) can be used to assess projected, future changes to streamflow in the watershed. Projections are at the spatial scale of a HUC8 watershed, with flows generated using a Variable Infiltration Capacity (VIC) model from temperature and precipitation data statistically downscaled from GCMs using the Bias Corrected, Spatially Disaggregated (BCSD) method. The VIC model is setup to simulate unregulated basin conditions. The CHAT displays various simulated historic and future, climate-changed streamflow, temperature, and precipitation outputs derived from 32 Global Climate Models (GCMs). The CHAT uses Coupled Model Intercomparison Project Phase 5 (CMIP5) GCM meteorological data outputs that have been statistically downscaled using the Localized Constructed Analogs (LOCA) method. GCMs rely on scenarios representing different pathways to a given atmospheric concentration of greenhouse gas emissions (GHG) referred to as representative concentration pathways (RCPs).

To analyze runoff, LOCA-downscaled GCM outputs are used to force an unregulated Variable Infiltration Capacity (VIC) hydrologic model (Liang et al., 1994). Areal runoff from VIC is then routed through a stream network using mizuRoute. Outputs represent the daily in-channel routed runoff (i.e., streamflow) for each stream segment – valid at the stream segment endpoint. Since runoff is routed, the streamflow value associated with each stream segment is a representation of the cumulative flow, including all upstream runoff, as well as the local runoff contributions to that specific segment. For this scenario, the project specific location is the Lower Yakima watershed (HUC 17030003), stream segment 17000574.

The HUC 17030003 Lower Yakima contains the project site. The Upper Columbia watershed (HUC 17020016) stream segment 17005214 upstream of the project area was also analyzed due to the mixing that occurs between the two segments. Figure 4-1 below depicts the Lower Yakima watershed shaded in dark gray with the specific stream segment highlighted in yellow which is also the terminal segment for the HUC8 watershed. Figure 4-2 depicts the Upper Columbia watershed shaded in dark gray with the specific stream segment highlighted in yellow. Note that all the results produced by the CHAT model are modeled and not observed results.

Figure 4-3 and the results of the following section show the range of output derived from 32 Global Climate Models (GCMs) and representative concentration pathways (RCP) of greenhouse gas emissions applied to the generate climate-changed hydrology using the VIC model. The range of data is indicative of the uncertainty associated with projected, climate-changed hydrology.

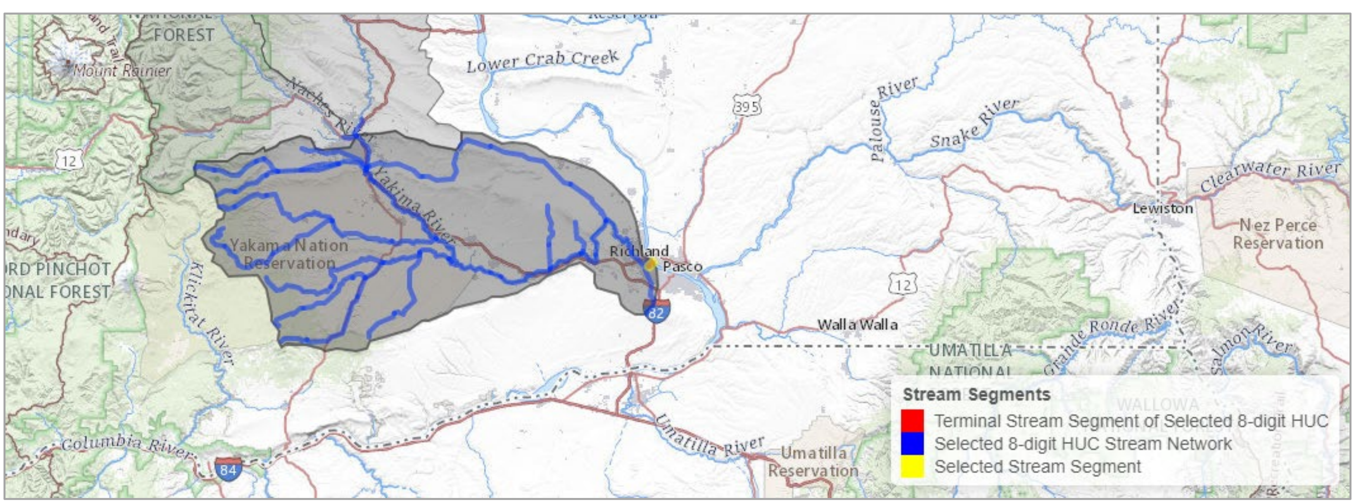


Figure 4-1 Lower Yakima River watershed with project stream segment selected

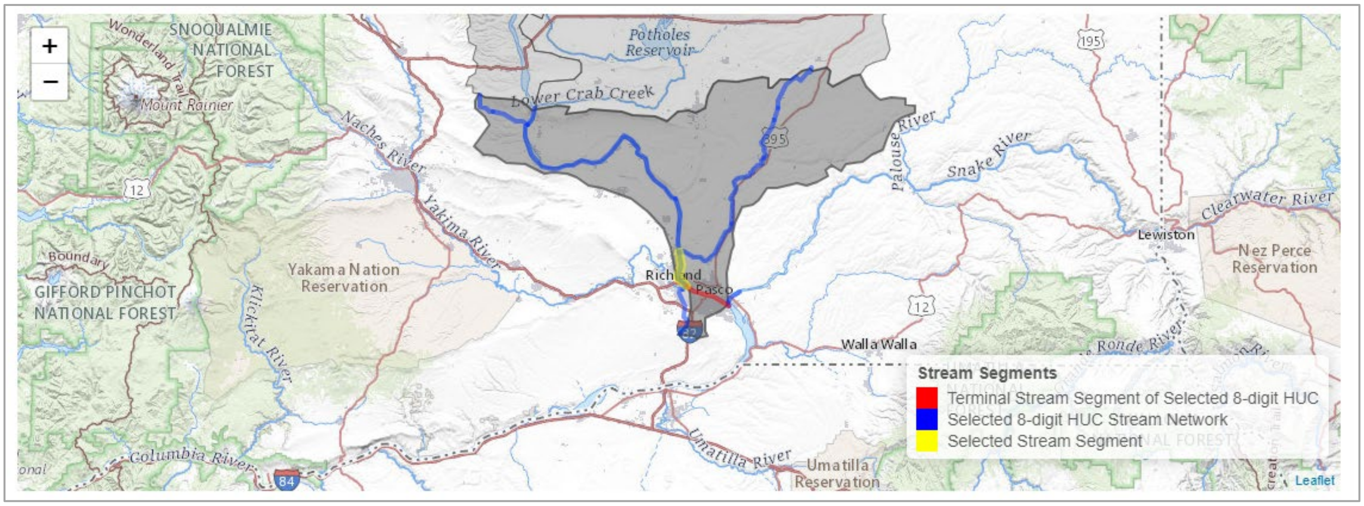


Figure 4-2 Upper Columbia watershed with upstream segment selected

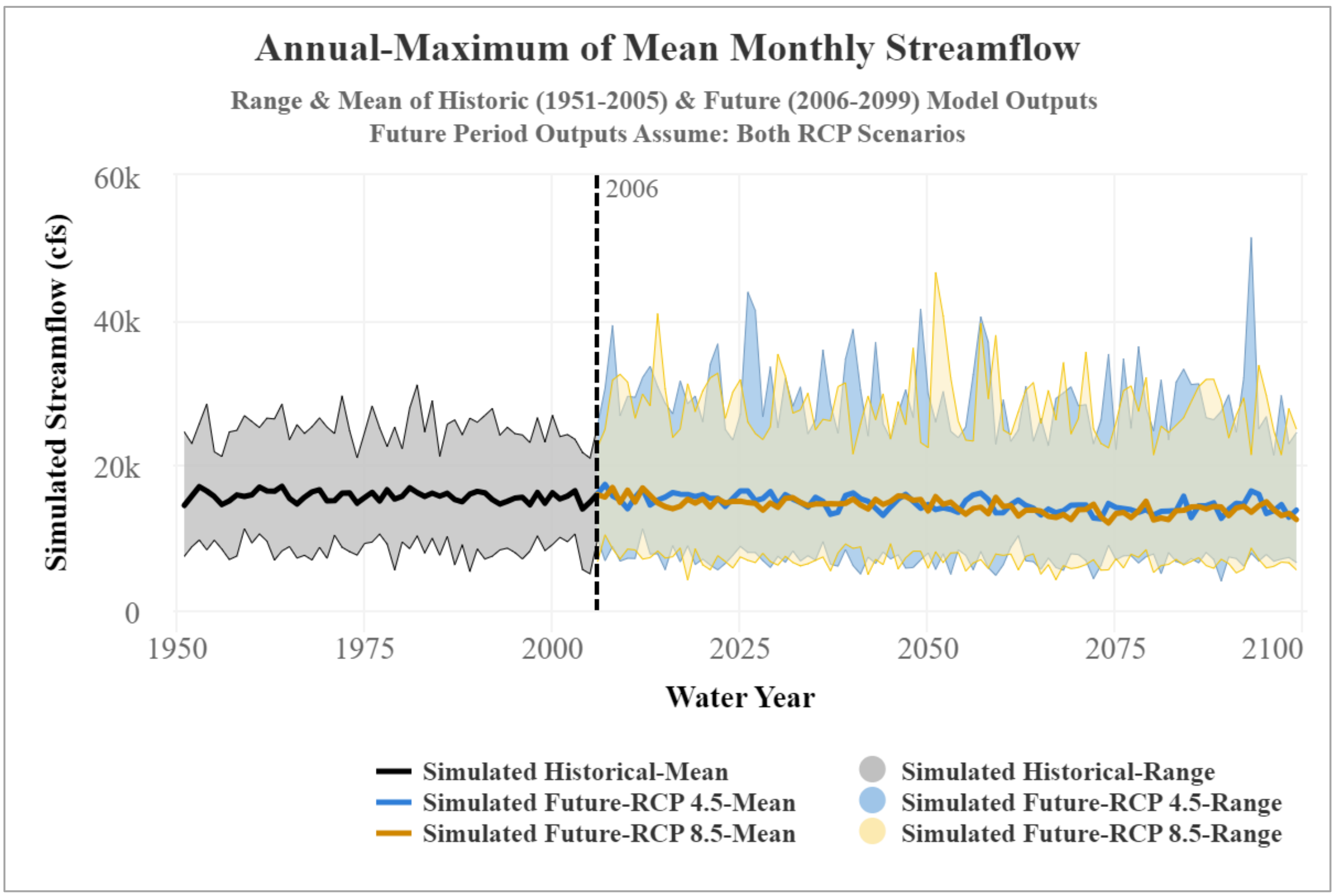


Figure 4-3 Range of 32 Climate-Changed Hydrology Model Output for Lower Yakima (HUC 17030003)

4.1 CHAT Assessment Results

4.1.1 Temperature

Historical and projected trends from the 32 GCM simulations were analyzed in the CHAT for the annual maximum and minimum 1-day temperature. Both gages showed similar results, but specific differences will be discussed. The temperature range for the projected future (2006-2099) shows statistically significant increase for in both maximum and minimum annual temperatures as illustrated in Figure 4-4 and Figure 4-9. While the RCP 4.5 scenario trends indicate an increase in the projected range of temperatures, they are not as extreme as RCP 8.5.

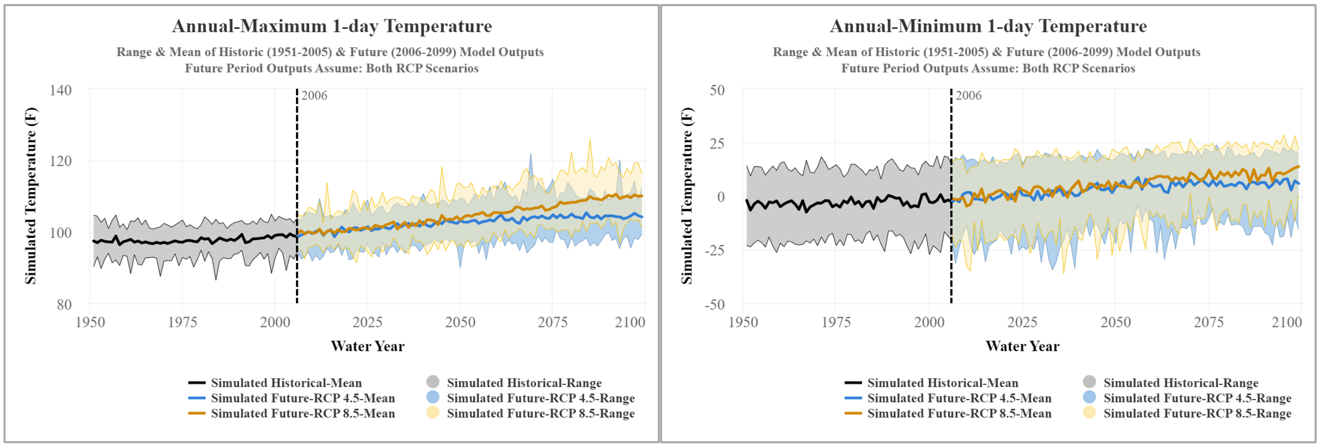


Figure 4-4 Simulated historic and future 1-day temperature values for RCP 4.5 and 8.5 scenarios (Lower Yakima)

As depicted in Figure 4-3 and Figure 4-8, the CHAT analysis indicates that historical temperatures have been increasing during the second half of the 20th century, with future forecasts that indicate a statistically significant positive trend in both maximum and minimum annual temperatures.

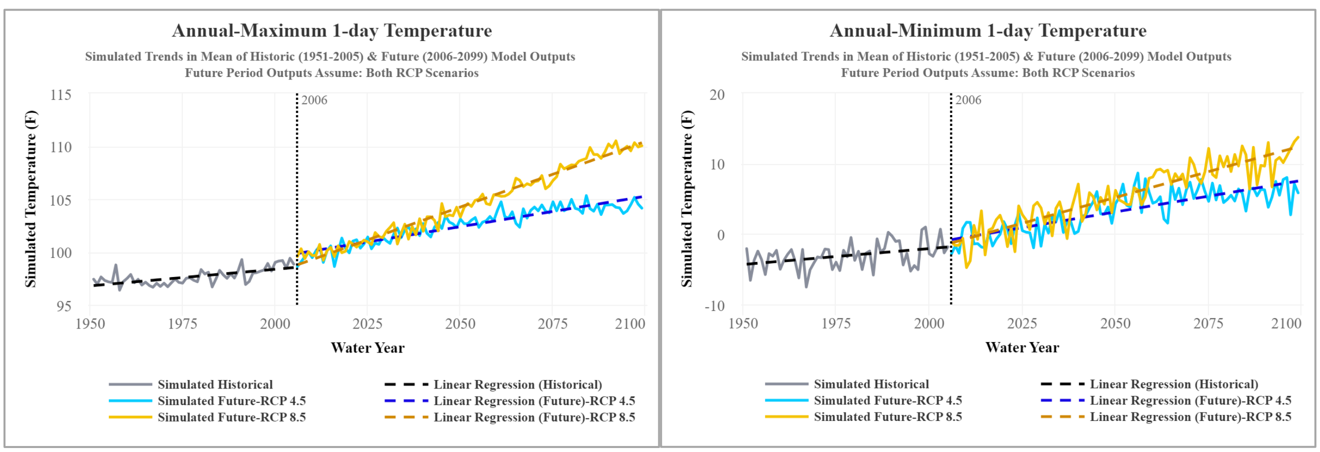


Figure 4-5 Simulated historic and future 1-day temperature trends for RCP 4.5 and 8.5 scenarios (Lower Yakima)

Increasing temperatures pose an issue for proposed project riparian and aquatic habitat features especially if combined with longer periods of drought indicated by the CHAT. As summarized in Figure 4-5, Figure 4-6 and Figure 4-9, the positive trend in both historical and future annual temperatures is significant, based on near-zero P values across both parametric and non-parametric tests. Based on the trend lines all tests indicate a strong level of consensus and exhibit robust statistical significance that historic temperatures have been increasing and the future rate of temperature increase will be larger, especially under the RCP 8.5 scenario. Slope comparison indicates that historical annual minimum temperatures have been rising faster than historical annual maximum temperatures. For the Lower Yakima watershed future RCP 4.5 values are predicted to increase by 1.83 times for maximum values and 1.98 times for minimum values when compared to historical values. For the future RCP 8.5 scenario the rate of change in projected minimum annual temperature is about three times higher than historical values and four times higher for maximum values.

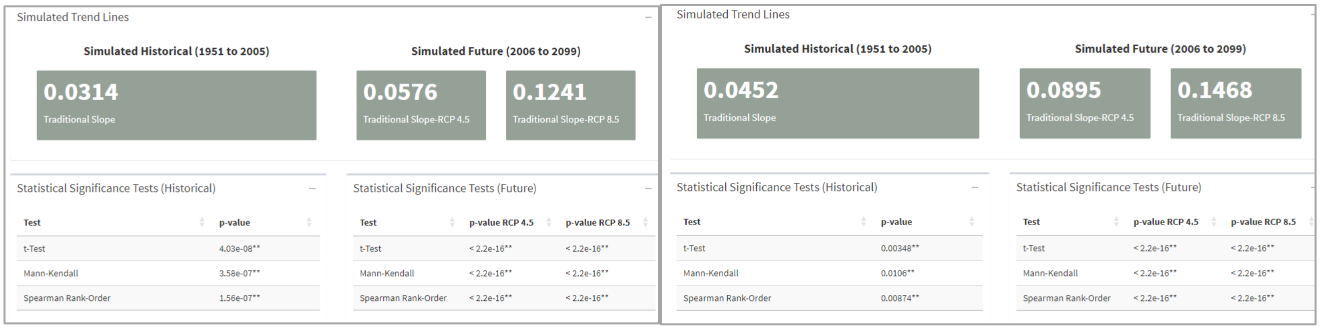


Figure 4-6 Annual Maximum (left) and Minimum (right) 1-day Temperatures Trends (Lower Yakima)

Box plots depicting the distribution of the change in monthly temperature extremes were included from the CHAT as illustrated in Figure 4-7, Figure 4-8, Figure 4-10 and Figure 4-11. RCP 4.5 scenario is represented by red box plots and RCP 8.5 is represented by blue box plots. The figures show simulated changes in temperature (deg. F) from the Base Epoch (1976-2005) to the Mid-Century Epoch (2035-2064) and from the Base Epoch to End-Century Epoch (2070- 2099).

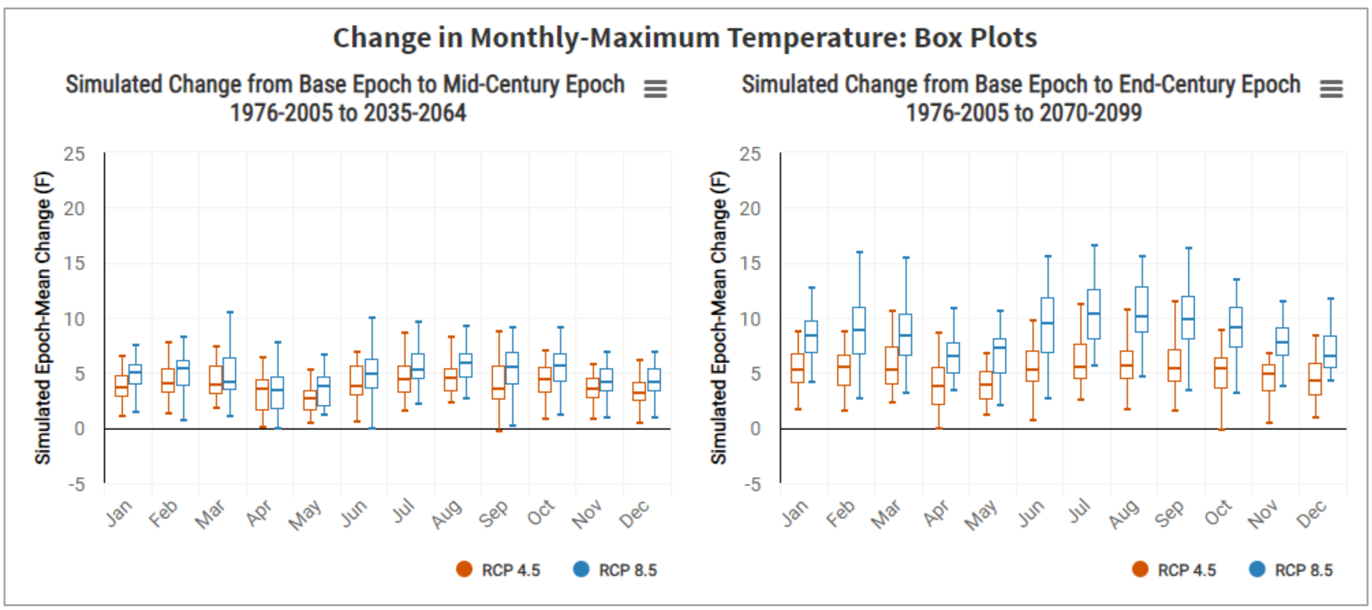


Figure 4-7 Change in Monthly-Maximum Epoch box plots (Lower Yakima)

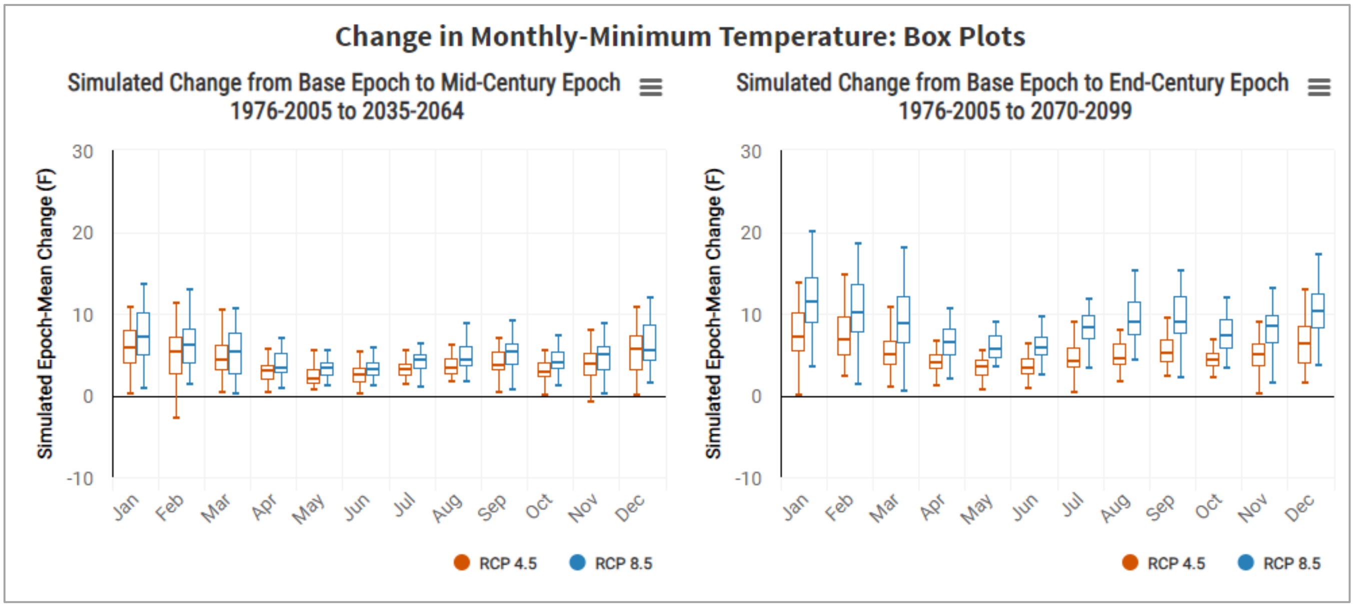


Figure 4-8 Change in Monthly-Minimum Epoch box plots (Lower Yakima)

As illustrated in Figure 4-7 and Figure 4-8, changes in monthly maximum and minimum temperature show increasing trends for all months of the year for both Epochs. Monthly maximum values tend to increase more in the summer while the monthly minimum value tend to increase more in the winter months for both RCP scenarios. This matches literature consensus that summer maximum temperatures will continue to rise, and winter months will become warmer. The spread between upper and lower quartiles for RCP 4.5 and 8.5 for Mid-Century are small with minimal variation. The simulated change from base epoch to end-century epoch has a slightly larger increases in median values for RCP 4.5 from mid-century epoch values and significantly larger medians and larger variability between upper and lower quartiles for RCP 8.5. However, it is consistent across all months that temperature changes are projected to increase through the next century.

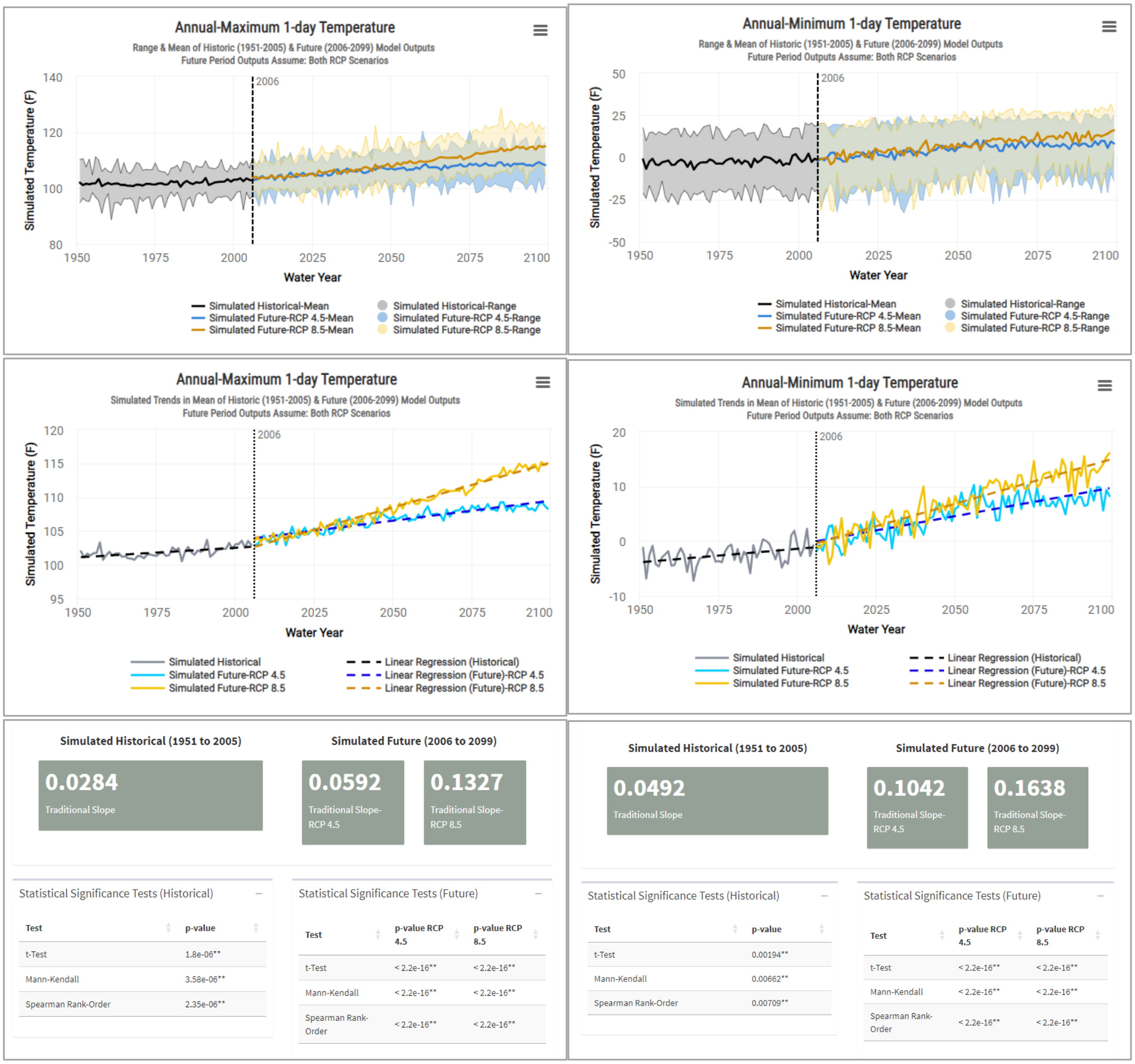


Figure 4-9 Simulated historic and future 1-day temperature trends for RCP 4.5 and 8.5 scenarios (Upper Columbia)

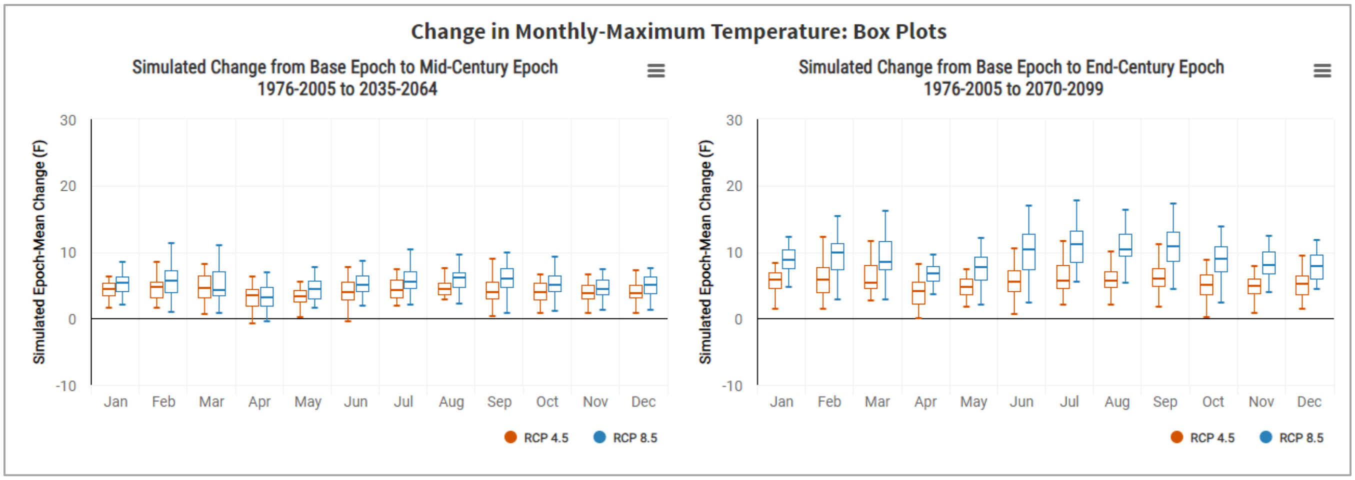


Figure 4-10 Change in Monthly-Maximum Epoch box plots (Upper Columbia)

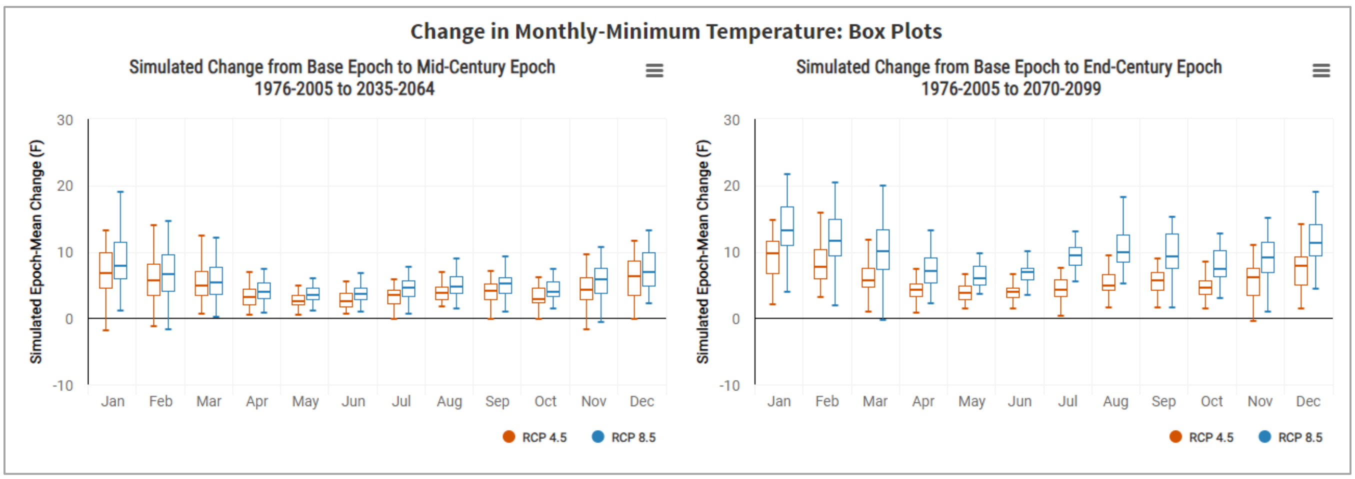


Figure 4-11 Change in Monthly-Minimum Epoch box plots (Upper Columbia)

4.1.2 Precipitation

Based on the Climate Literature Synthesis, there is a wide agreement that precipitation events will become more frequent and with larger intensities. The CHAT was used to evaluate projected future precipitation conditions forecasted by the GCMs for the Lower Yakima (Figure 4-12) and Upper Columbia (Figure 4-15) watersheds. The slope of the model is not distinctively increasing or decreasing; increasingly dry summer and wetter winters would cause this result. The simulated RCP 4.5 shows higher variability in annual precipitation while the RCP 8.5 shows a similar trend with less variability. The amount of precipitation over the project area would have a large variability from year to year between wet and dry years, and as literature states this can vary widely with project location.

Another climate aspect that is relevant to the project in the number of consecutive dry days as this could have a significant impact on aquatic and riparian habitats. The CHAT generated future projections of increasing number or dry days for periods 2006 to 2099 (Figure 4-13). Historically consecutive dry days show a mean span of about 32-34 days. Future conditions for RCP 4.5 and 8.5 show an increasing trend and considerable increases in range for consecutive days without precipitation with mean spans of approximately 40-45 days.

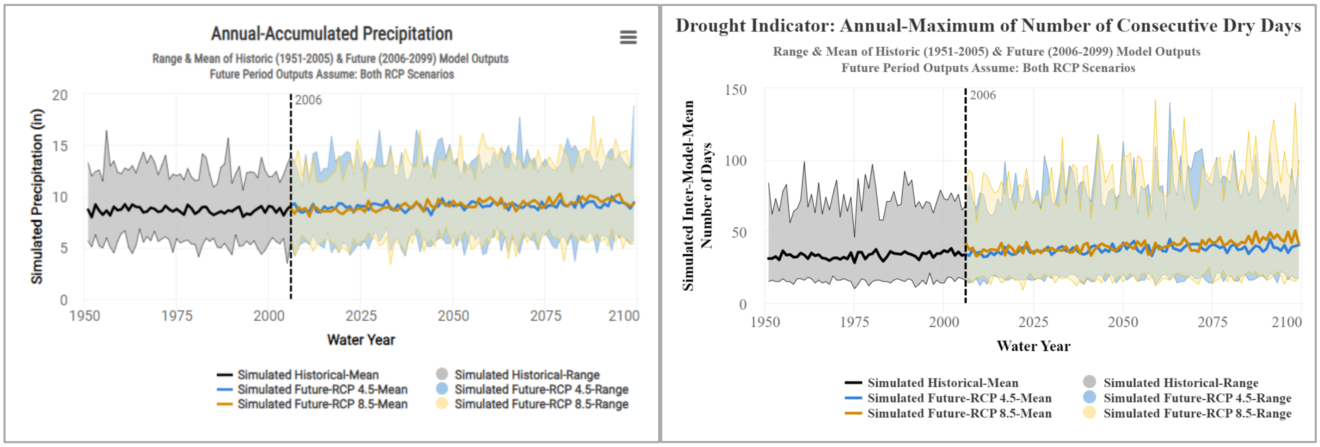


Figure 4-12 Annual accumulated precipitation and maximum of number of consecutive dry days (Lower Yakima)

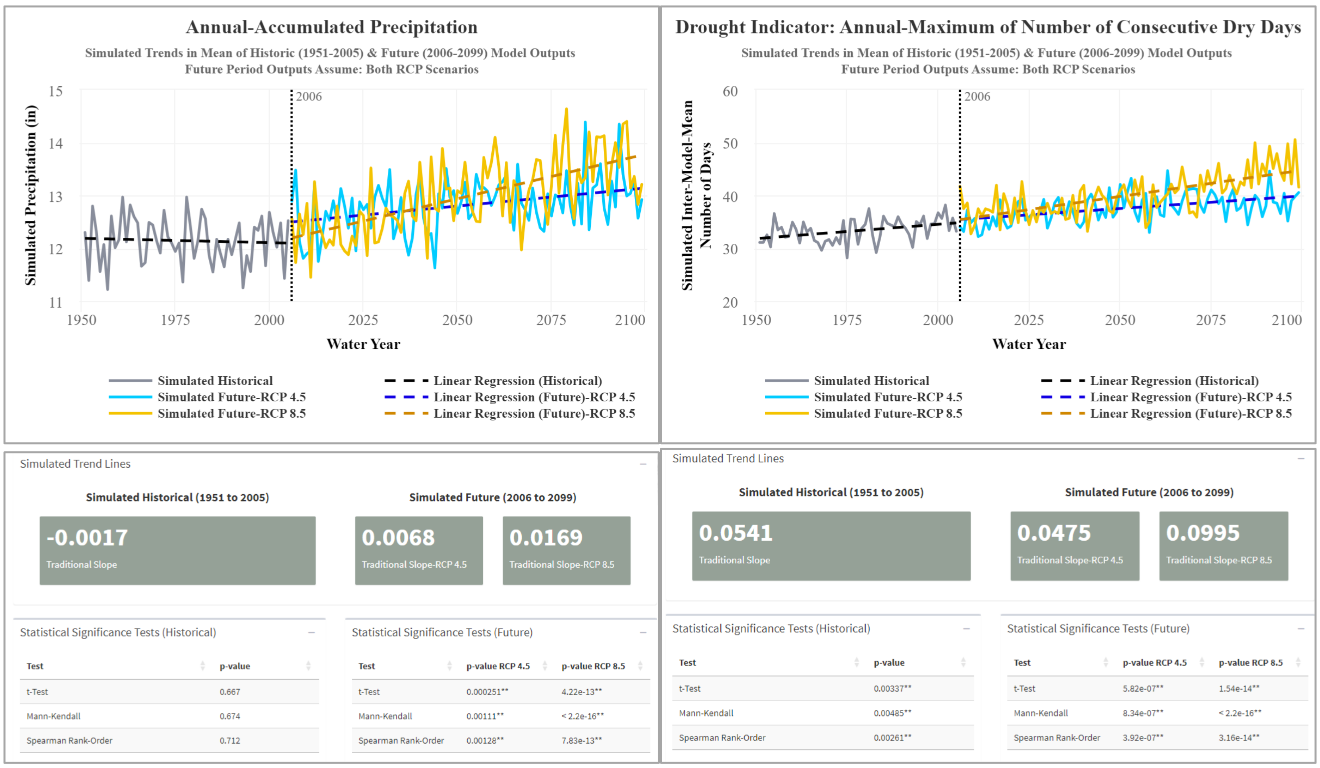


Figure 4-13 Trend analysis for annual accumulated precipitation and annual maximum of number of consecutive dry days (Lower Yakima)

Historical trend lines for annual accumulated precipitation did not show a statistical significance (P values above 0.05) and the trend line slope is approximately equal to zero meaning historical annual precipitation values were not showing increasing or decreasing trends. When evaluating the projected future trend lines, both RCP 4.5 and 8.5 scenarios had all three statistical trend analysis test return P values approximately equal to zero indicating robust statistical significance of the increase. Both scenarios project an increasing trend in annual precipitation however RCP 8.5 has a steeper trend slope line. Increased annual precipitation could be of benefit for the restoration project providing a greater annual supply of water to the area. However, even though annual precipitation amounts are projected to increase, the timing of these events are not accounted for with an annual accumulation value.

For number of consecutive dry days all three trend tests returned P values of less than 0.05 for Historic, RCP 4.5, and RCP 8.5 trendlines. This indicates all trends exhibit robust statistical significance. The RCP 8.5 scenario shows a stronger increasing trend in the number of dry days. Typically, this area receives the most amount of consecutive dry days during the summer and longer spans of dry days could have significant impacts to aquatic and riparian habitat.

Box plots for monthly changes in accumulated precipitation were included from the CHAT. The box plots show simulated changes from the Base Epoch (1976-2005) to the Mid-Century Epoch (2035-2064) and from the Base Epoch to End-Century Epoch (2070-2099). The Mid-Century Epoch changes in monthly accumulated precipitation for both RCP scenarios (4.5 and 8.5) project slight increases for months October through April.

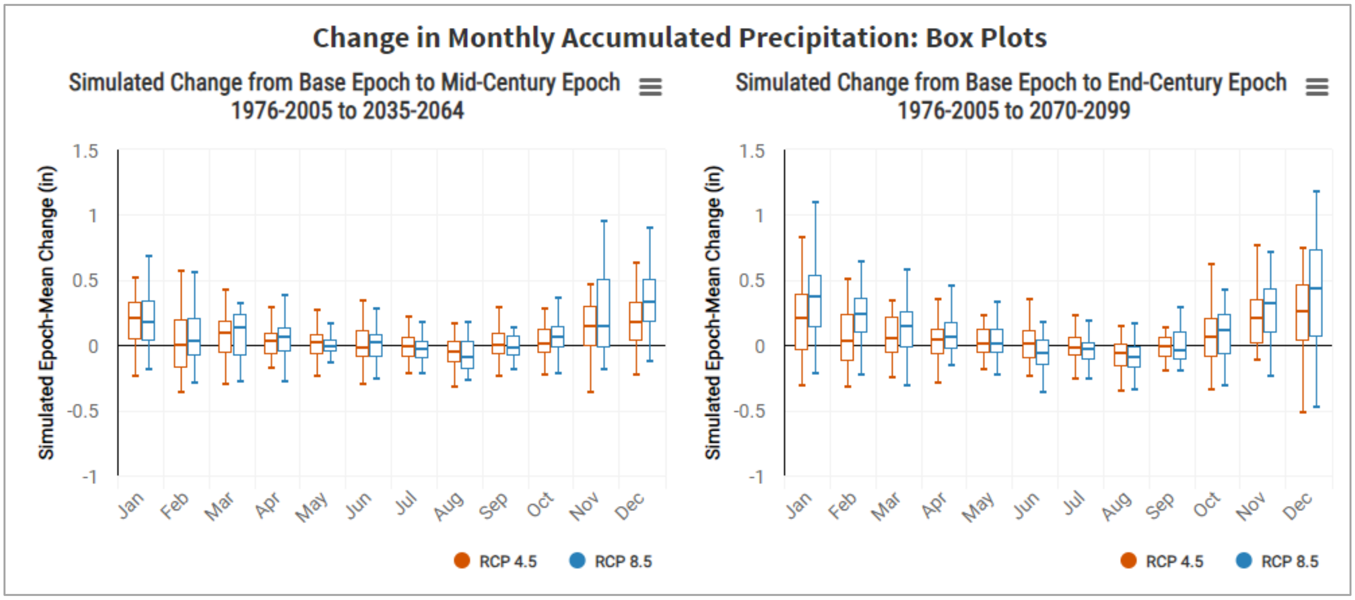


Figure 4-14 Change in monthly accumulated precipitation Epoch plots (Lower Yakima)

The Epoch box plots for both watersheds show an increase in accumulated precipitation during the winter months and a slight decrease in monthly precipitation in summer months. The end century Epoch values show a much higher magnitude of change in the winter months with a larger amount of variability. Both the Yakima River and the Columbia River show similar trends in monthly accumulated precipitation.

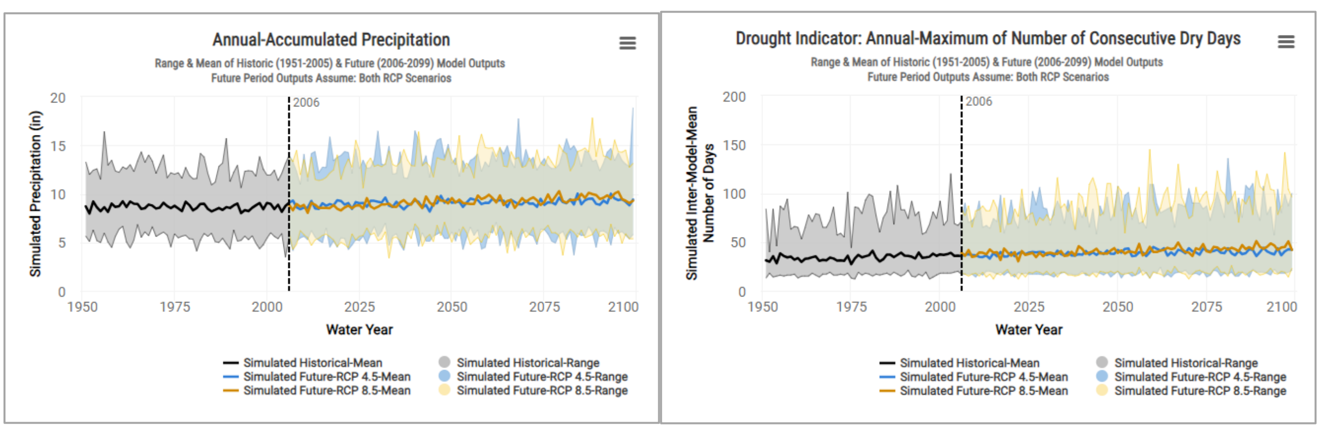


Figure 4-15 Annual accumulated precipitation and annual maximum of number of consecutive dry days (Upper Columbia)

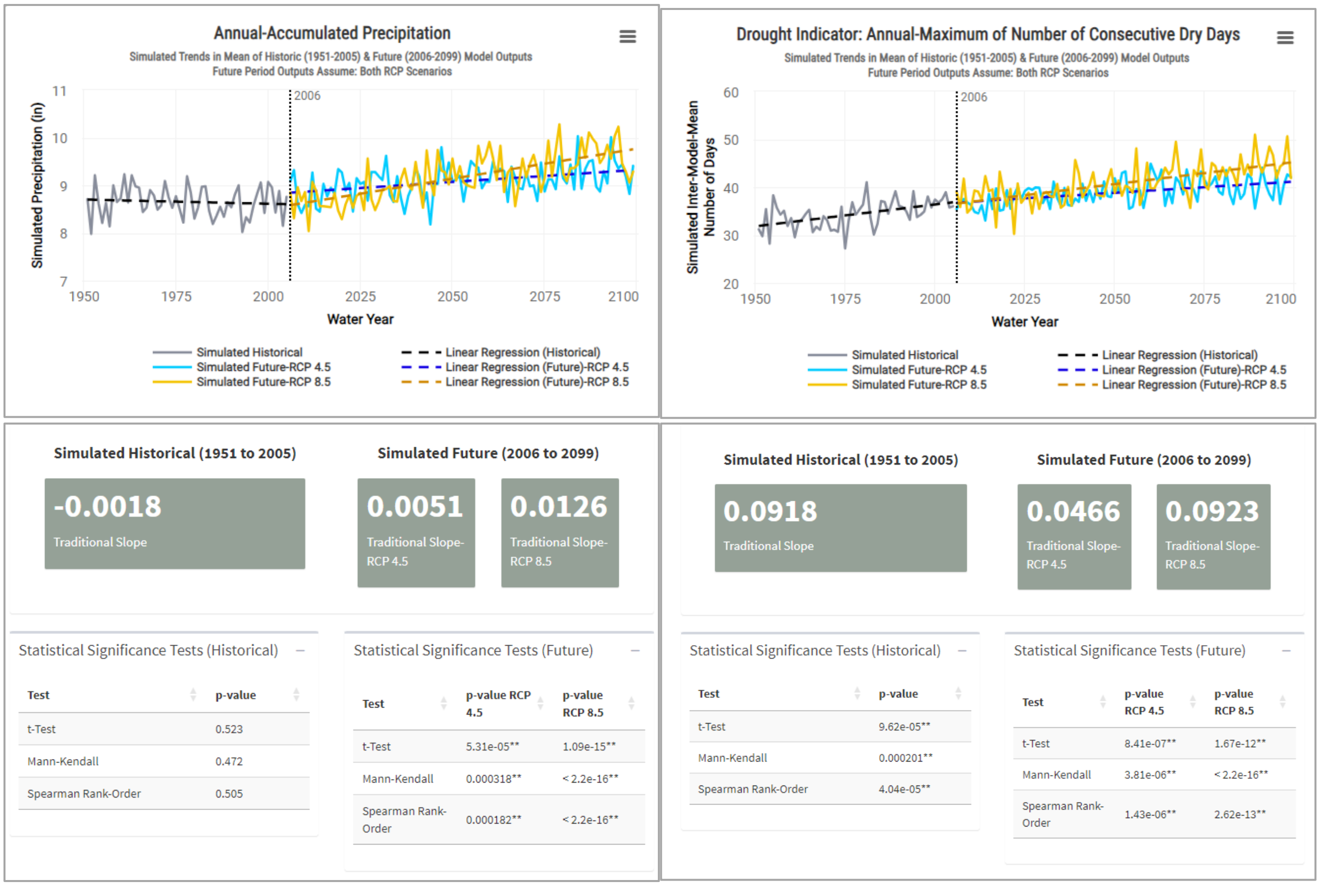


Figure 4-16 Trend analysis for annual accumulated precipitation and annual maximum of number of consecutive dry days (Upper Columbia)

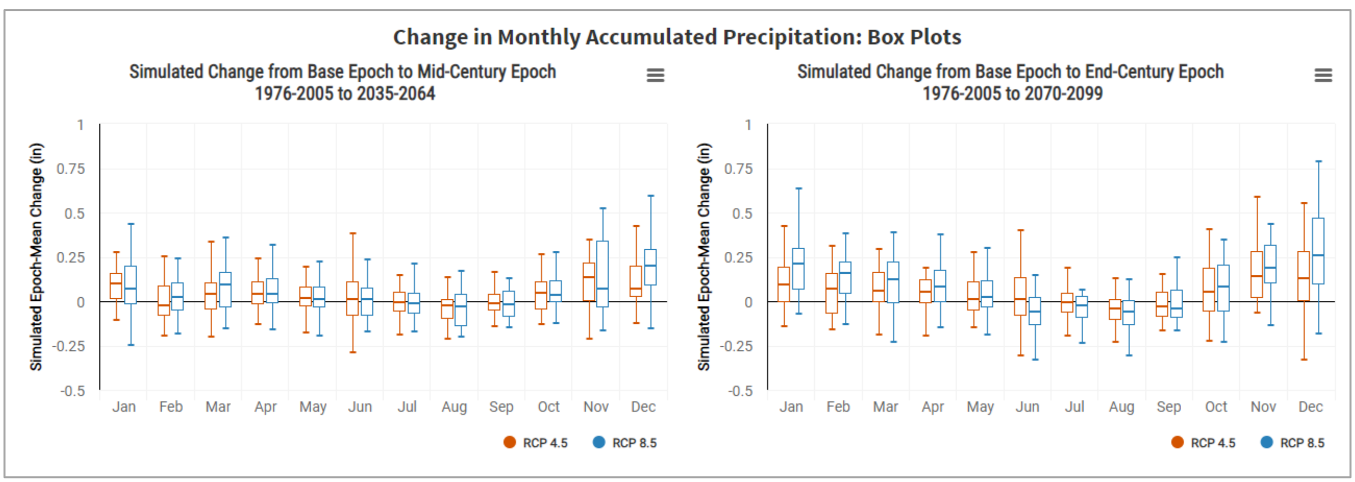
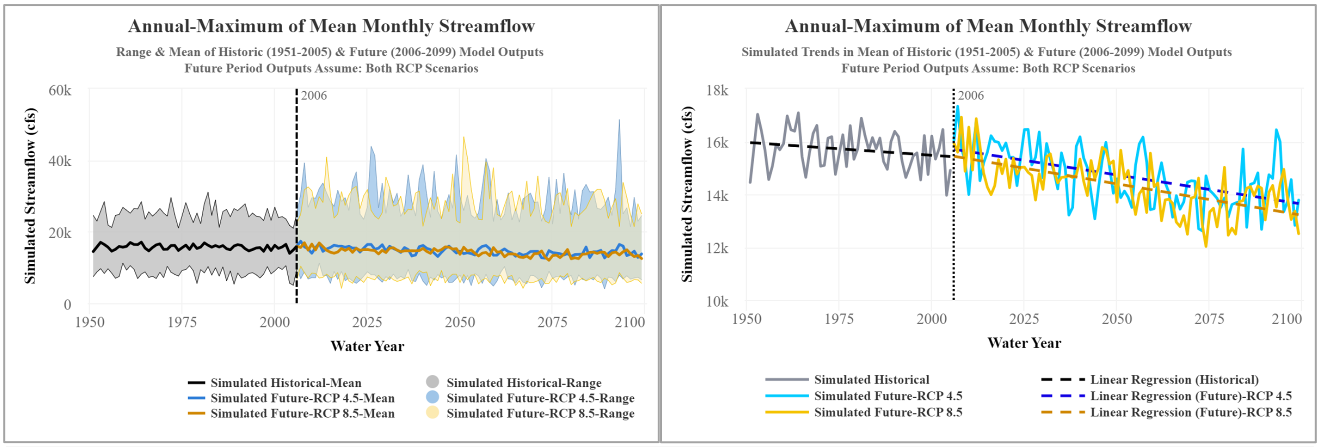


Figure 4-17 Change in monthly accumulated precipitation Epoch plots (Upper Columbia)

4.1.3 Streamflow

CHAT analysis of historical and projected mean monthly streamflow output from the 32 GCM simulations is illustrated in Figure 4-18 below which depict the range of results and corresponding trendlines for RCP 4.5 and 8.5 scenarios. The RCP 4.5 scenario is represented by blue and RCP 8.5 scenario is represented by yellow in all figures. As expected for this type of analysis, there is considerable, but consistent spread in the projected annual maximum monthly flows. The spread in the projected annual maximum monthly flows is indicative of the high degree of uncertainty associated with projected, climate changed hydrology. The maximum of mean monthly streamflow exhibits a downward trend from 2006 to 2099 but the ranges for both RCP 4.5 and 8.5 have large variabilities.



Simulated Trend Lines

Simulated Historical (1951 to 2005)

-9.8
Traditional Slope

Simulated Future (2006 to 2099)

-22.068
Traditional Slope-RCP 4.5

-23.768
Traditional Slope-RCP 8.5

Statistical Significance Tests (Historical)

Test	p-value
t-Test	0.116
Mann-Kendall	0.151
Spearman Rank-Order	0.149

Statistical Significance Tests (Future)

Test	p-value RCP 4.5	p-value RCP 8.5
t-Test	5.33e-09**	1.63e-12**
Mann-Kendall	1.54e-08**	1.09e-10**
Spearman Rank-Order	6.76e-09**	1.05e-12**

Figure 4-18 Annual maximum of mean monthly flow trend analysis (Lower Yakima)

Trendlines for both historical and future annual maximum streamflow conditions indicate downward direction, however P values for the historical trendline do not indicate a statistical significance. All statistical tests for both the RCP 4.5 and RCP 8.5 future trend lines have P-values less than 0.05 indicating statistical significance.

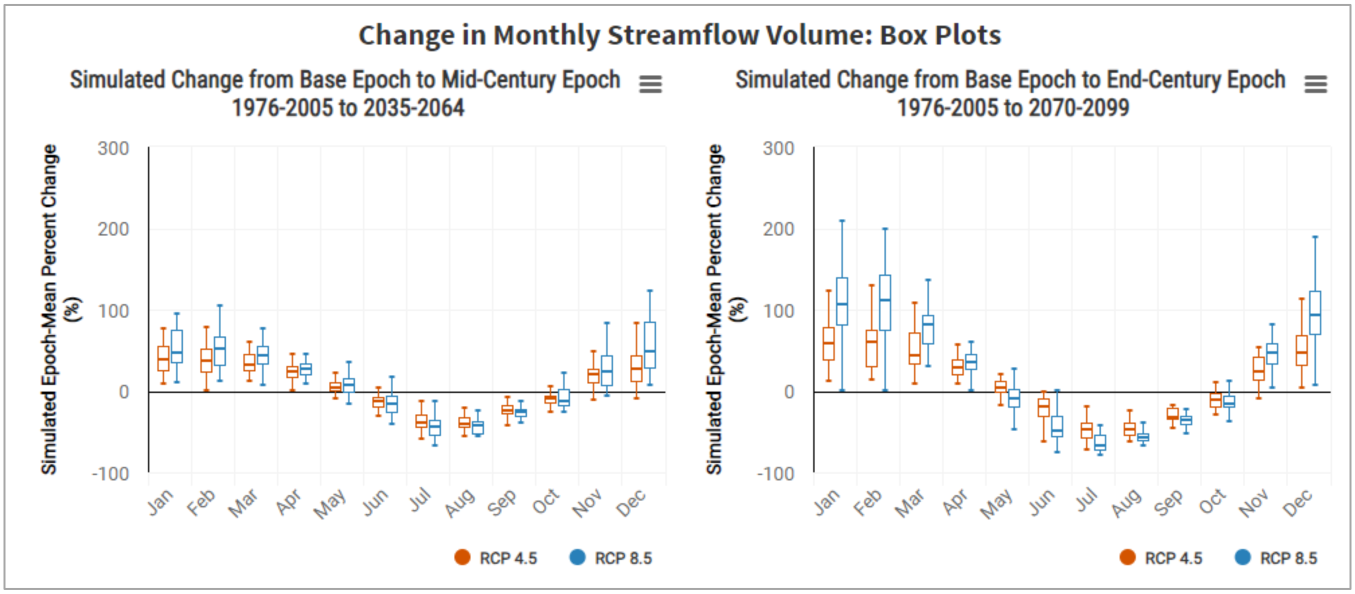


Figure 4-19 Monthly streamflow volume epochs for RCP 4.5 and 8.5 (Lower Yakima)

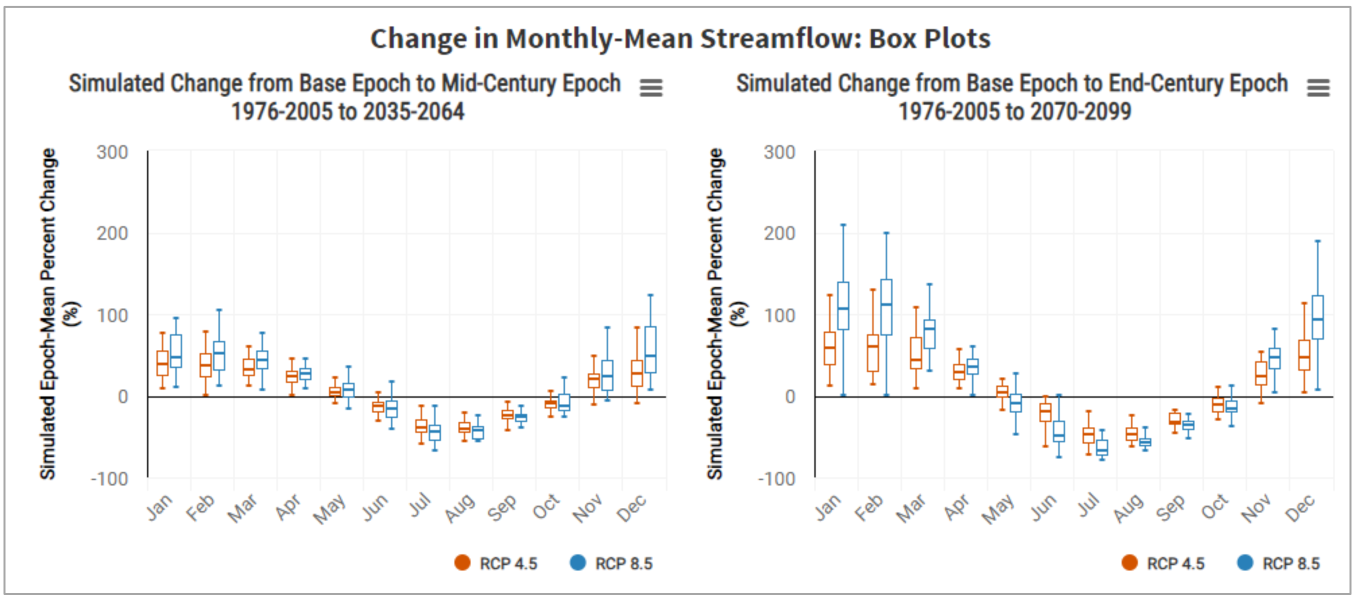
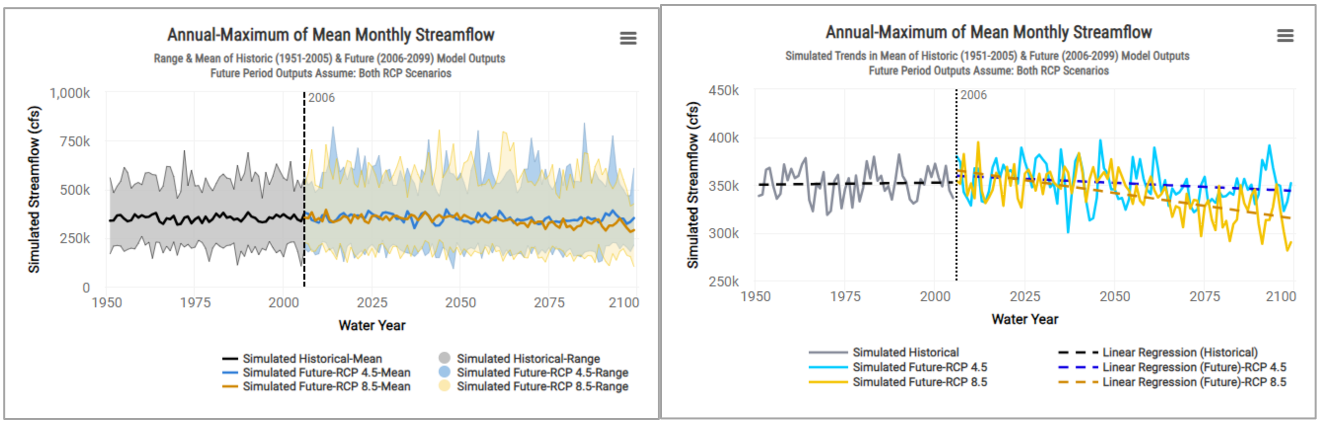


Figure 4-20 Monthly mean streamflow epochs for RCP 4.5 and 8.5 (Lower Yakima)

Monthly streamflow volume and monthly mean streamflow follow similar trends. While the overall trend of Mean of Monthly Streamflow is predicted to decrease, the future seasonal change can be evaluated by comparing boxplots of the distribution as plotted in Figure 4-19 and Figure 4-20. The simulated change from the Base Epoch to Mid Century Epoch (1976-2005 to 2035-2064) for both RCP scenarios shows an increase in streamflow in winter months November through April and a significant decrease in spring and summer stream flows from May to October.

Simulated Changes from the Base Epoch to the End-Century Epoch follow the trends described for the Mid-Century Epoch however, the variability between the upper and lower quartiles for each month is greater and more extreme. Both epochs show a significant decrease in flows in the month of July and August and significant increases from November to March.



Simulated Historical (1951 to 2005)

41.555
Traditional Slope

Simulated Future (2006 to 2099)

-167.26
Traditional Slope-RCP 4.5

-536.51
Traditional Slope-RCP 8.5

Statistical Significance Tests (Historical)

Test	p-value
t-Test	0.759
Mann-Kendall	0.816
Spearman Rank-Order	0.87

Statistical Significance Tests (Future)

Test	p-value RCP 4.5	p-value RCP 8.5
t-Test	0.0253**	2.1e-12**
Mann-Kendall	0.0246**	1.74e-10**
Spearman Rank-Order	0.0152**	1.45e-11**

Figure 4-21 Annual maximum of mean monthly flow (Upper Columbia)

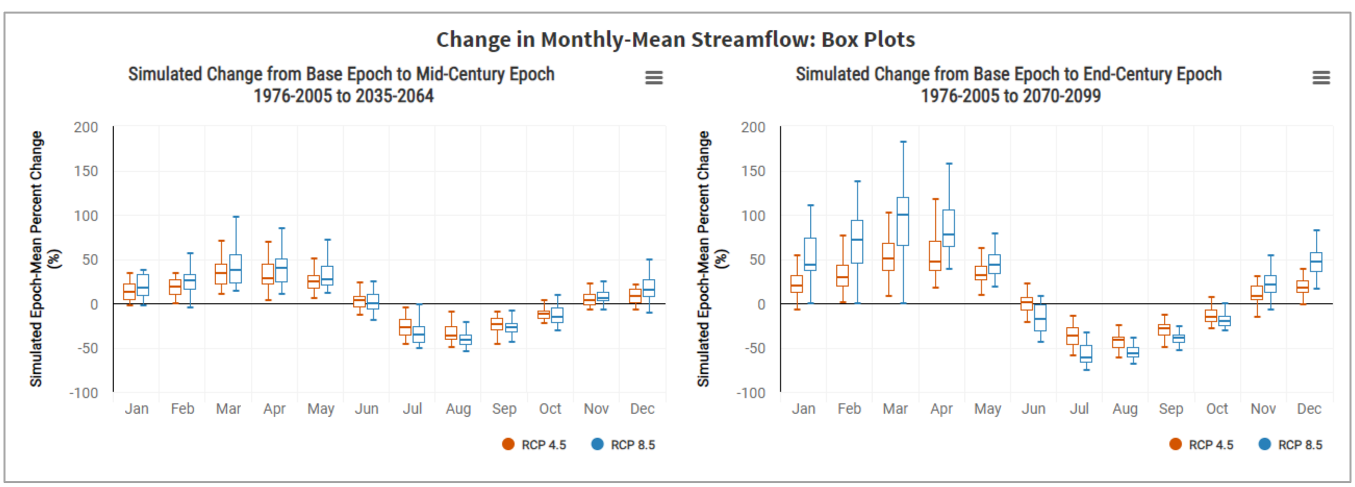


Figure 4-22 Change in monthly-mean streamflow Epoch Plots

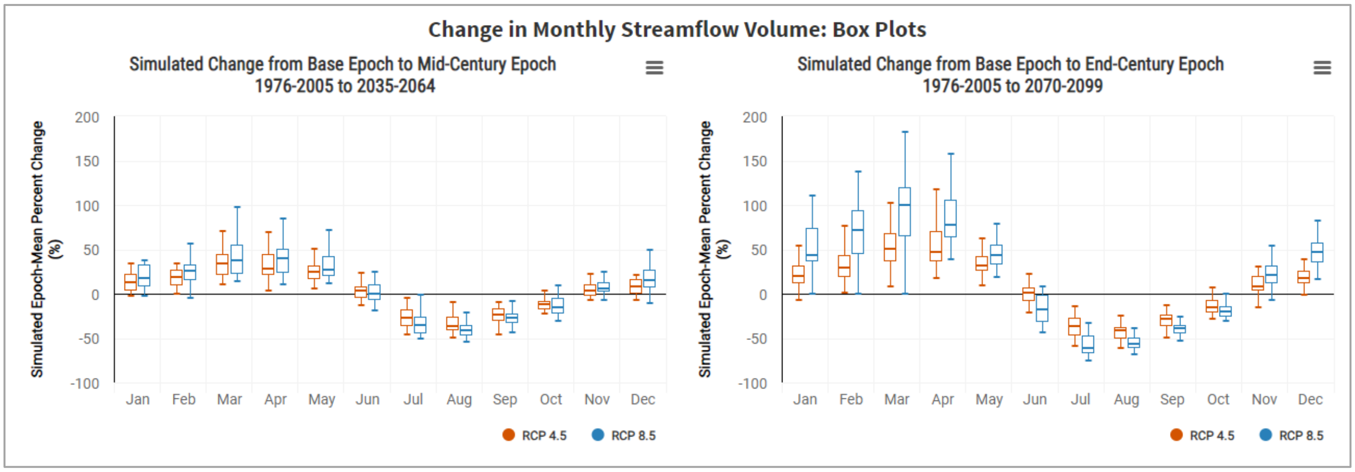


Figure 4-23 Change in monthly streamflow volume Epoch Plots (Upper Columbia)

The Yakima and Columbia Rivers show similar trends however the Columbia River shows the most variability between Jan – Apr while the Yakima River shows more variability between December – March. This difference in timing between watersheds can be attributed to the fact that the Lower Yakima watershed tends to be a flashy subbasin while the Upper Columbia is a snow driven basin.

5 Vulnerability Assessment

The USACE Watershed Climate Vulnerability Assessment (VA) Tool facilitates a screening-level, comparative assessment of the vulnerability of a given business line and HUC-4 watershed to the impacts of climate change, relative to the other HUC-4 watersheds within the continental United States (CONUS). It uses the Coupled Model Intercomparison Project (CMIP5) GCM-BCSD-VIC dataset (2014) to define projected hydrometeorological inputs, combined with other data types, to define a series of indicator variables to define a vulnerability score.

Vulnerabilities are represented by a weighted-order, weighted-average (WOWA) score generated for two subsets of simulations (wet—top 50% of cumulative runoff projections; and dry—bottom 50% cumulative runoff projections). Data are available for three epochs. The epochs include the current time period (“Base”) and two 30-year, future epochs (centered on 2050 and 2085). The Base epoch is not based on projections and so it is not split into different scenarios. For this application, the tool was applied using its default, National Standards Settings. In the context of the VA Tool, there is some uncertainty in all of the inputs to the vulnerability assessments. Some of this uncertainty is already accounted for in that the tool presents separate results for each of the scenario-epoch combinations rather than presenting a single aggregate result.

Table 5-1 and Table 5-2 show indicator scores across the business lines in the VA tool for the Yakima and Upper Columbia HUCs. Figure 5-1 through Figure 5-3 show the Upper Columbia (1702) and Yakima (HUC 1703) are not considered vulnerable under USACE criteria for either the dry or wet scenarios for either of the Ecosystem Restoration, Water Supply, or Emergency Management business lines. This is true for both the wet and dry scenarios and both the 2050 and 2085 epochs. All these business lines were documented because they include indicators important to the project. For example, the Emergency Management business line was investigated because the removal of the causeway will make fire-fighting more difficult on the island. However, results should be interpreted with care because the VA tool applies to a significantly large area (HUC4 level) and if not focused on the project site. National Standard settings were used in the tool.

Dominant climate indicators driving risk across the business lines include freshwater plant communities at risk of extinction (indicator 8), sedimentation (indicator 1560), the high variability in the monthly runoff within a year (indicator 221C, Monthly COV), low flow reduction (indicator 700C), the percentage of people who are disabled in the HUC (indicator 447), and the percentage of people in poverty (indicator 443). At risk freshwater plants is the percentage of wetland and riparian plant communities that are at risk of extinction, based on remaining number and condition, remaining acreage, threat severity, etc. Sediment is the ratio of the change in sediment load in the future to the present. Monthly COV is a measure of short-term variability in the region's hydrology based on runoff variance and mean. Low flow reduction is the change in low runoff, or monthly runoff exceeded 90 percent of the time.

The Vulnerability Assessment WOWA scores for select business lines for the Yakima (HUC 1703) and the Columbia (HUC 1702) are summarized in Table 5-1 and Table 5-2 below.

Table 5-1 HUC 1703 – Yakima VA WOWA Indicator Scores for select USACE business lines.

Business Line	Indicator	Base	2050 Dry	2050 Wet	2085 Dry	2085 Wet	Avg	Std	CV
Ecosystem Restoration	Freshwater Plants	29.06	29.18	29.04	29.18	29.04	29.10	0.07	0.00
	Monthly Runoff COV	11.86	11.01	11.02	10.96	10.98	11.17	0.39	0.03
	Mean Annual Runoff	8.11	8.17	8.04	8.16	8.03	8.10	0.07	0.01
	Runoff Precipitation	3.93	5.48	5.81	6.10	6.00	5.46	0.89	0.16
	Macroinvertebrate	5.25	4.06	4.04	4.06	4.04	4.29	0.54	0.13
	Low Flow Reduction	2.72	2.98	2.15	3.07	2.23	2.63	0.42	0.16
	Sediment	2.04	1.92	2.92	1.96	2.99	2.37	0.54	0.23
	Flood Magnification (cum)	1.56	1.39	1.60	1.42	1.64	1.52	0.11	0.07
	Flood Magnification (local)	0.80	0.71	0.82	0.73	0.84	0.78	0.06	0.07
	Ecosystem Restoration Total	62.14	63.68	62.74	64.79	63.56	63.38	1.00	0.01
Water Supply	Sediment	29.63	26.87	32.68	27.61	33.58	30.08	2.98	0.10
	Runoff Precipitation	5.82	9.44	10.05	10.49	10.38	9.24	1.95	0.21
	Monthly Runoff COV	9.67	5.71	5.74	5.68	5.72	6.50	1.77	0.27
	Annual Runoff COV	2.58	2.49	2.53	2.67	2.63	2.58	0.07	0.03
	Drought Severity	0.00	0.93	0.50	1.68	1.36	0.89	0.67	0.75
	Water Supply Total	47.71	45.45	51.51	48.14	53.66	49.29	3.27	0.07
Regulatory	Freshwater Plants	25.60	25.61	25.78	25.65	25.73	25.67	0.08	0.00
	Low Flow Reduction	6.89	11.68	8.88	12.03	11.45	10.19	2.23	0.22
	Mean Annual Runoff (cum)	11.16	9.00	11.17	9.00	8.95	9.86	1.20	0.12
	Monthly Runoff COV	8.77	6.52	6.60	6.49	6.55	6.99	1.00	0.14
	Mean Annual Runoff (local)	5.03	5.05	5.02	5.05	5.01	5.03	0.02	0.00
	Macroinvertebrate	2.46	3.06	1.99	3.06	1.98	2.51	0.54	0.21
	Flood Magnification (cum)	3.07	2.18	2.55	1.80	2.61	2.44	0.48	0.19
	Sediment	1.87	1.75	3.22	1.44	3.28	2.31	0.87	0.38
	Runoff Precipitation	1.22	1.31	1.40	2.26	1.45	1.53	0.42	0.27
	Flood Magnification (local)	0.88	0.78	0.91	0.64	0.93	0.83	0.12	0.14
	Annual Runoff COV	0.63	0.62	0.64	0.83	0.66	0.68	0.09	0.13
	Regulatory Total	67.57	67.56	68.15	68.26	68.60	68.03	67.57	0.01

Table 5-2 HUC 1702 – Upper Columbia VA WOWA Indicator Scores for select USACE business lines.

Business Line	Indicator	Base	2050 Dry	2050 Wet	2085 Dry	2085 Wet	Avg	Std	CV
Ecosystem Restoration	Freshwater Plants	28.55	28.16	28.55	28.29	28.45	28.4	0.17	0.01
	Monthly Runoff CV	11.39	11.46	11.05	11.31	11.82	11.41	0.28	0.02
	Macroinvertebrate	7.45	7.35	7.45	7.39	7.43	7.41	0.05	0.01
	Runoff Precipitation	5.18	4.89	5.49	5.52	4.78	5.17	0.34	0.07
	Low Flow Reduction	3.72	2.04	3.77	2.74	2.66	2.99	0.75	0.25
	Sediment	1.9	2.81	1.91	3.76	2	2.48	0.81	0.33
	Mean Annual Runoff	2.7	1.56	2.7	1.57	3.5	2.4	0.83	0.35
	Flood Magnification (cum)	1.43	3.65	1.41	2.09	1.53	2.02	0.95	0.47
	Flood Magnification (local)	0.77	0.85	0.76	0.85	0.78	0.8	0.04	0.06
	Ecosystem Restoration Total	63.10	62.77	63.09	63.51	62.94	63.08	0.28	0.00
Water Supply	Sediment	27.79	32.9	27.12	33.34	29.63	30.16	2.86	0.09
	Monthly COV	9.45	9.64	5.79	6.05	9.84	8.15	2.05	0.25
	Runoff Precipitation	6.02	5.77	9.55	9.8	5.57	7.34	2.14	0.29
	Annual COV	2.2	2.25	1.47	2.29	2.24	2.09	0.35	0.17
	Drought Severity	1	0.72	3	1.19	0	1.18	1.11	0.94
	Water Supply Total	46.46	51.28	46.91	52.66	47.29	48.92	2.84	0.06
Recreation	Low Flow Reduction	21.34	20.31	21.25	20.72	20.23	20.77	0.51	0.02
	10% Exceedance (cum)	13.64	13.94	13.39	13.78	13.83	13.72	0.21	0.02
	90% Exceedance (local)	8.48	6.48	8.36	8.41	6.50	7.65	1.06	0.14
	Monthly Runoff CV	6.39	8.55	6.10	6.41	8.73	7.24	1.29	0.18
	Flood Magnification (cum)	4.03	4.79	3.90	4.57	4.35	4.33	0.37	0.09
	Sediment	1.34	2.63	1.02	2.68	2.41	2.02	0.78	0.39
	Runoff Precipitation	2.41	1.38	2.51	1.54	1.33	1.83	0.58	0.31
	Flood Magnification (local)	1.79	2.01	1.33	2.00	1.84	1.79	0.28	0.15
	Drought Severity	0.56	0.40	1.85	0.67	0.00	0.70	0.69	1.00
	Recreation Total	59.99	60.50	59.70	60.77	59.22	60.03	0.62	0.01

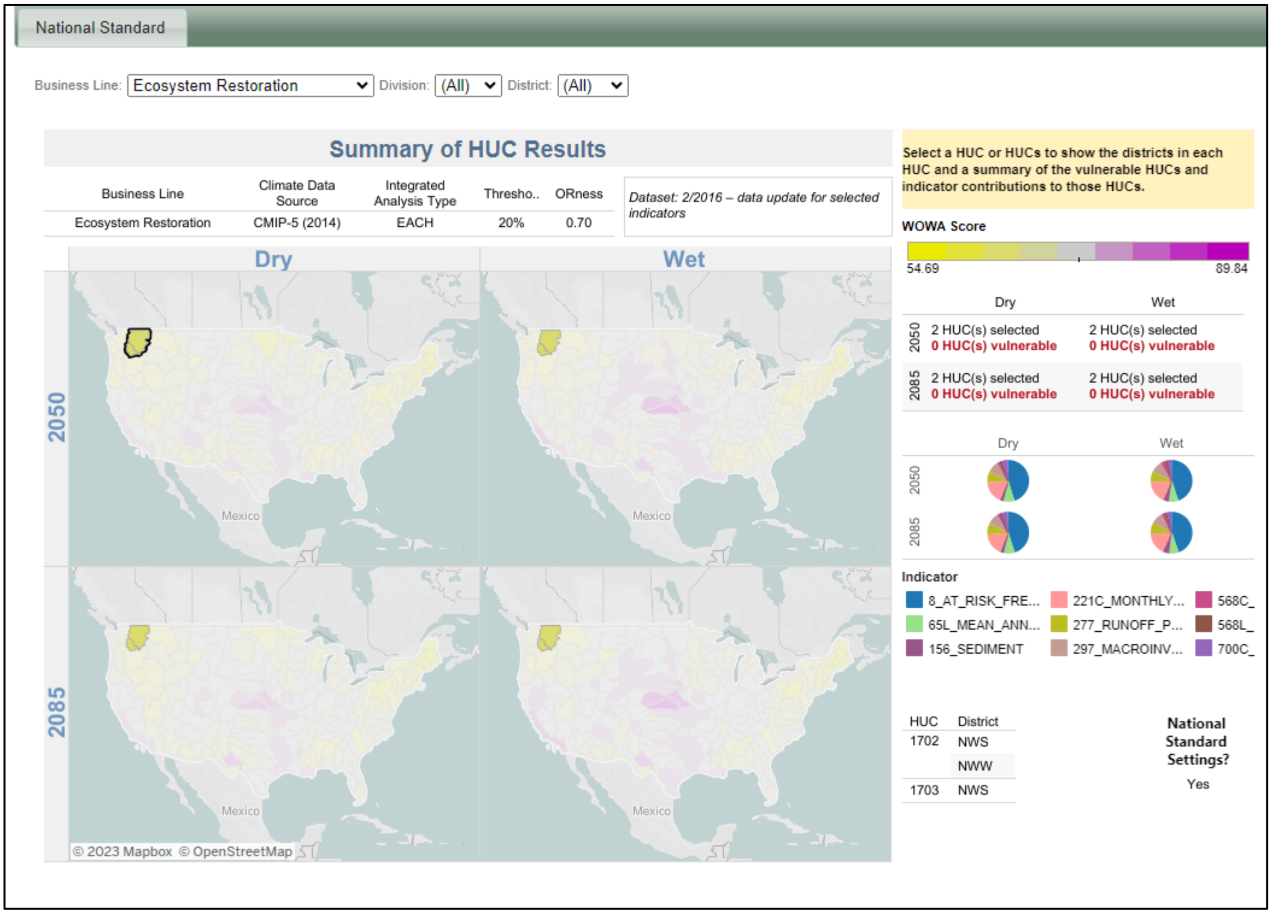


Figure 5-1. Vulnerability Assessment Tool Ecosystem Restoration Results

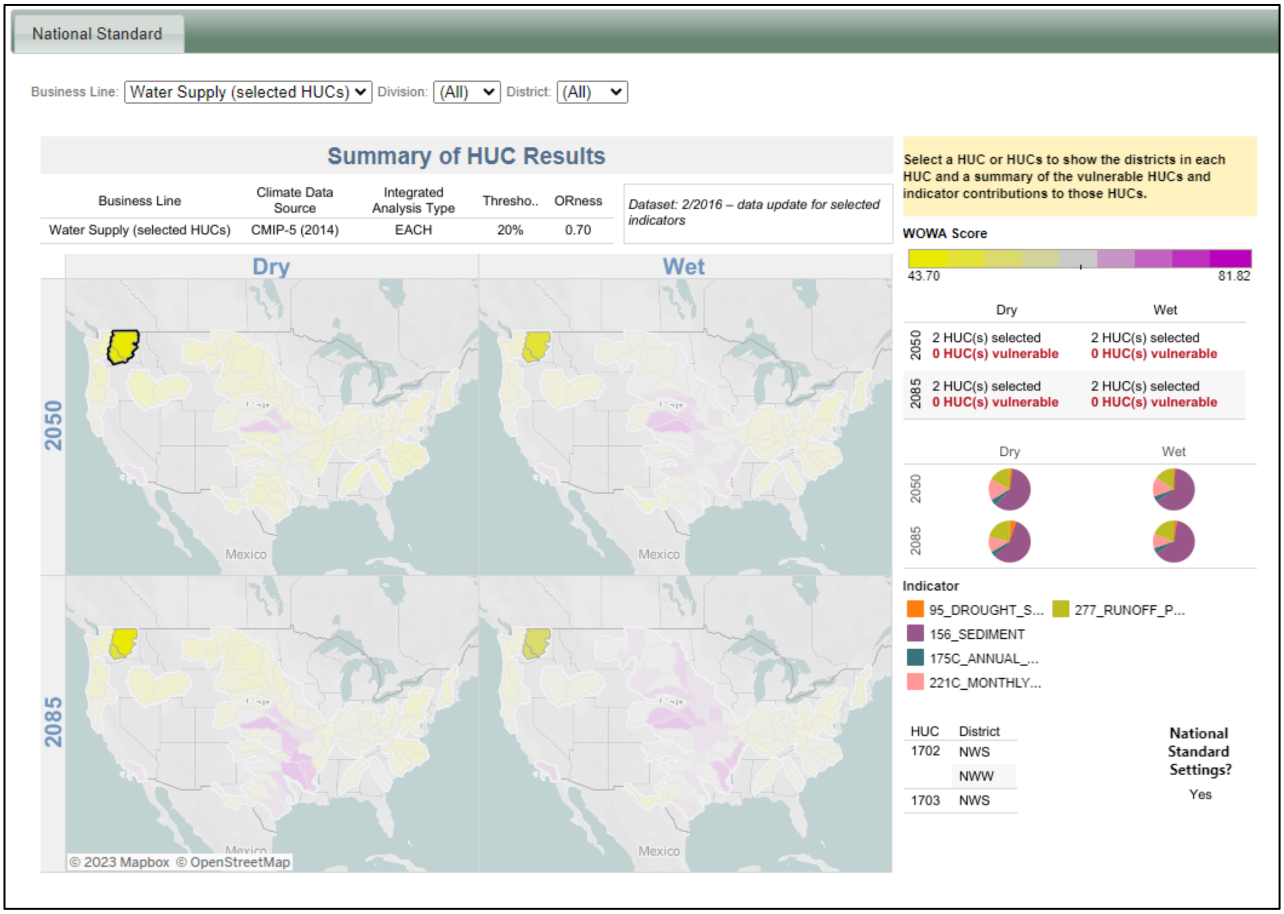


Figure 5-2.. Vulnerability Assessment Tool Water Supply Results

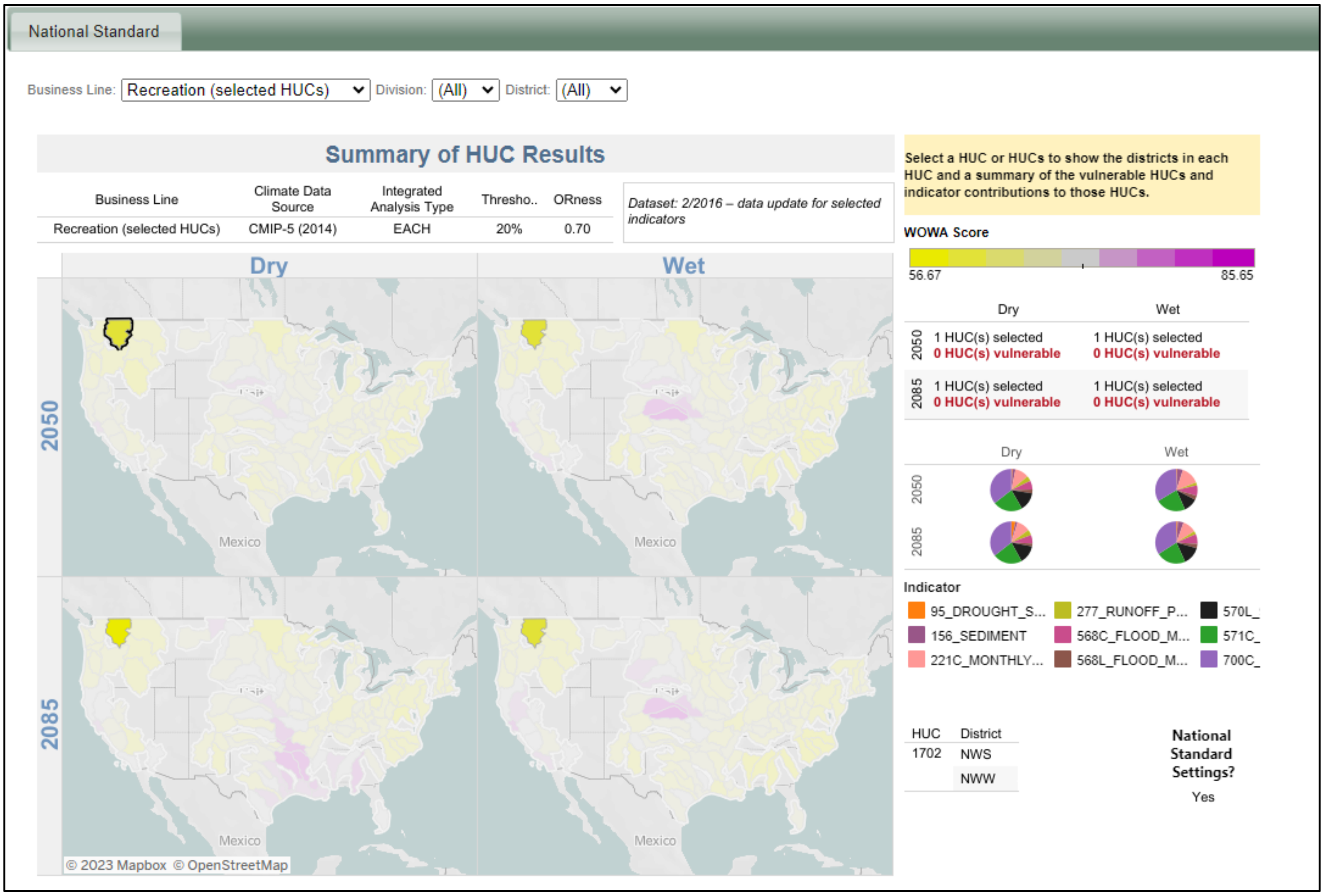


Figure 5-3. Vulnerability Assessment Tool Recreation Business Line

6 Conclusion

The proposed Yakima Delta 1135 TSP is the complete removal of the Bateman Island causeway and the construction of riparian habitat features. This plan is intended to increase the mixing of Columbia and Yakima River flows to the West of Bateman Island to reduce water temperatures and improve aquatic habitat relative to baseline conditions as detailed in the main report. This climate assessment reviewed baseline literature and evaluated both historic, observed hydrometeorological data and projected, climate-changed hydrometeorological data to identify significant trends that could influence the performance of the proposed restoration plan.

Analysis of select period of record hydrologic NRNI datasets for the Yakima River at Kiona, WA gage identified weak trends and two main strong nonstationarities. All TST analyses for the Yakima River indicated a near-zero slope and non-significant trend. One significance test resulted in a slight positive trend for the Yakima River annual peaks. A strong trend was identified for the Columbia River annual minimum flows which produced significant trends for all three tests with a positive near-zero slope. The Yakima River and Columbia River detected multiple nonstationarities around 1947 and the early 1970’s. The 1947 nonstationary can be attributed to the 1948 Columbia River Flood and the nonstationarity in the early 1970’s can be attributed to the completion of the Mica Dam located in British Columbia.

There is a weight of evidence that climactic change during future epochs would manifest as notable changes in meteorological trends such as temperature and precipitation. This in-turn is expected to influence the hydrologic regime, although how future trends will manifest at the local project scale is less certain. Residual risk to the Yakima Delta 1135 TSP due to climate change and proposed adaptive measures are summarized in Table 6-1.

Table 6-1 Residual risks to Yakima Delta 1135 TSP due to climate change

Triggers	Hazard	Harm	Qualitative Likelihood (Low, Moderate, High)	Qualitative Justification for Likelihood Rating
1. Increased summer air temperatures. 2. Decreased summer precipitation accumulation. 3. Increased duration between precipitation events.	Increases in summer air temperatures combined with decreases in summer precipitation could result in decreased soil moisture and impact riparian vegetation features of the TSP.	A reduction in riparian vegetation around Bateman Island could allow invasive vegetation to continue to dominate the biome and cause detrimental impacts to the project environment. Reducing vegetation could also increase localized erosion around Bateman Island and the shoreline of the mainland.	Low to Moderate	Riparian habitat features of the TSP will be designed and implemented to function over a wide elevation range spanning from below reservoir pool to upper benches on Bateman Island. Transitional and upper bench vegetation will be implemented to ensure continued access groundwater at or below the reservoir pool level. In addition, the adaptive management and monitoring plan will allow project stakeholders and agency co-managers to monitor and offset observed detrimental effects.
Decreased summer flows.	A decrease in summer flows could reduce residual pool depth and thermal inertia of upstream reaches and increase water temperatures. This effect is expected to be much greater on the Yakima River.	Warm water temperatures would be associated with decreased dissolved oxygen levels, and effect other water quality parameters, impacting native aquatic species.	Low to Moderate	Removing the causeway allows increased mixing of the Columbia and Yakima Rivers resulting in a net increase of thermal inertia of the Yakima Delta and lowering water temperatures.
Sediment	Increased sediment as primary indicator to water supply in Yakima and Columbia River watersheds as indicated by VA assessment	Increased erosion due to causeway removal and short-term sediment mobilization following spring freshet events.	Low to Moderate	Removing the causeway could help reduce sediment buildup in the Yakima Delta west of Bateman Island There may be moderate adverse effects in the near-term following removal of the causeway as legacy sediment deposition behind the causeway is more readily eroded. Long term effects are expected to diminish due to new areas forming inside the delta

Within the literature, baseline trends of the Pacific Northwest region identified strong consensus of observed increases in temperature and low consensus that minimum and maximum temperature extremes have been increasing relative to 20th century normals. There was also strong consensus of notable decreases in observed streamflow and April 1 SWE across the PNW region for the latter half of the 20th century. There was moderate consensus that average annual precipitation has been increasing in the PNW, including some inland regions where the seasonal response varied with location. The frequency of extreme storms during the 20th century has been variable with low consensus of a consistent trend owing in part to the volatility of atmospheric river systems responsible for such events.

Future forecasts of temperature, precipitation, and hydrologic response in the Pacific Northwest are uncertain and variable, but in general can be characterized as wet regions and seasons becoming wetter, dry regions and seasons becoming drier, and reduced snow depth, density, and extent. Continued future reduction of April 1 SWE is also predicted within the literature. Reduced summer streamflows are also predicted, which would be expected to coincide with increased water temperatures. Impacts to river temperatures are expected to be greater on the Yakima River than the Columbia River as significant irrigation withdrawals coincide with baseflow conditions extending over tens of river miles and thus more vulnerable to diurnal heating effects. Further, reduced water yield in future years could impact aquatic life in the Yakima River upstream of the Yakima delta. Conversely as a much larger volume system, the Columbia River is expected to have more thermal inertia, due in part to snowmelt dominated Canadian headwaters and hydroregulation operations at Grand Coulee Dam. River hydrograph timing for both rivers is predicted to continue to shift earlier in the year coincident with an expansion of the annual frost-free period.

Future projections through the end of the 21st century from the CHAT indicate statistically significant increases in temperature and annual precipitation accumulation. Temperature trends were up across all months, while the precipitation signal was characterized by minor seasonal deviations. The CHAT climate projections of having warmer winter temperatures and more winter precipitation events would likely cause a reduction in the amount of spring snowmelt runoff, however aquatic habitats may benefit from milder temperatures and increased precipitation. CHAT Streamflow projections indicate a significant decrease in flows between June and October. While a reduction in future flows do have some potential to impact the Yakima Delta 1135 TSP, the increased volumetric mixing of cooler Columbia River water following removal of the Bateman Island causeway is expected to reduce these effects in the Yakima Delta.

The National Standard settings of the Vulnerability Assessment indicate that for the Lower Yakima (HUC 1703) and Upper Columbia (HUC 1702) watersheds, all seven USACE business lines were below the 20% threshold score of 70.0, and thus not considered vulnerable relative to the other 202 HUC-4 CONUS watersheds. The primary indicator for both watersheds in the ecosystem restoration business line is at risk freshwater plants for both the 2050 and 2085 Epochs. The primary indicator for water supply in both watersheds is sediment loading. Low flow reduction was the primary indicator for the recreation business line in the Upper Columbia watershed. The final business line considered was the regulatory business line in the Lower Yakima watershed; at risk freshwater plants was the primary indicator for both Epochs.

7 References

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1 Appendix A. Nonstationarity and trend Analysis on Regulated Gages

A. Hydrologic Time Series Nonstationarities & Trends

While this nonstationarity and trend analysis does not clearly provide information on climate trends and changes in stream flow statistics due to climate change due to significant upstream regulation and irrigation withdrawals, it is included to support the need for an environmental restoration study in the project area.

A1. Time Series Data

Two USGS stream gages were used to analyze trends at the project site. These included the Yakima River at Kiona, WA (USGS 12510500) and the Columbia River below Priest Rapids Dam (USGS 12472800) gages. Peak streamflow records were used from water years 1960 through 2022 for both gages although the period of record for the Yakima gage was expanded to include 1934-1960. While both gages have data collected previous to the 1930s, these data were excluded due to large amounts of missing data (more than five years). Figure A-1-1 displays mean daily flow over the period of records for both gages which were used to inform the trend analysis. Figure A-1-2 shows a plot of peak flow data at both gages. Note that the axis of the Figures is scaled down on two separate axes to show correlation between the gages.

Both gages are affected by significant irrigation withdrawals upstream and the Columbia gage is impacted by 10 dams upstream. The Yakima River at Kiona gage has significant upstream diversions for the irrigation of about 424,000 acres. The Kennewick Canal has also been diverting about 96,000 acre-feet of flow above the gage since August 1956 (USGS, 2023a). The Columbia River below Priest Rapids Dam has significant upstream diversions for irrigation of about 600,000 acres and flow regulation by 10 major reservoirs and numerous smaller reservoirs and power plants (USGS, 2023b).

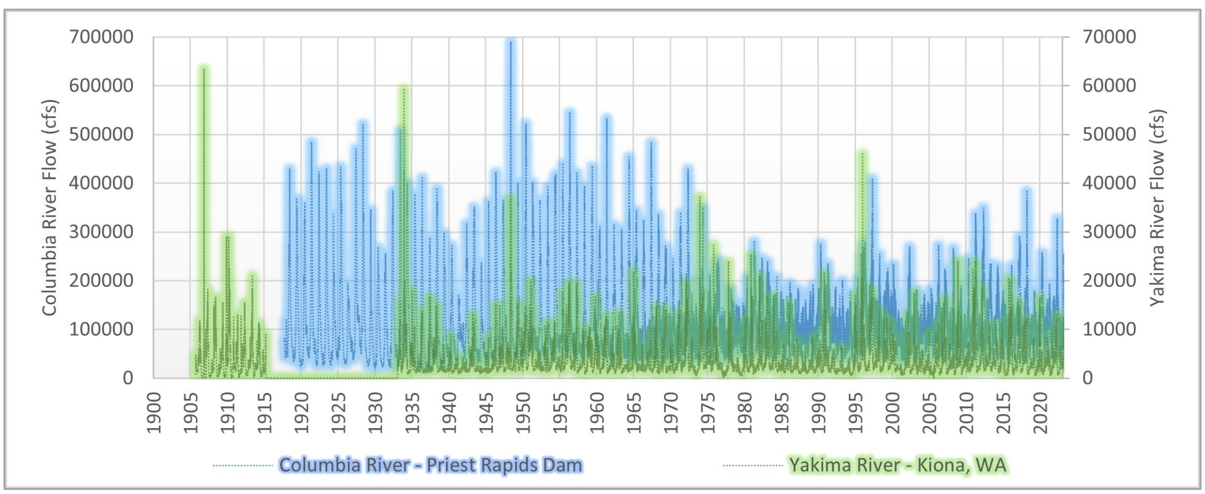


Figure A-1-1 Period of Record Daily Flow for USGS 12520500 and USGS 12472800 gage
(The axis for the Yakima River gage is scaled down a tenth of the Columbia River gage flows)

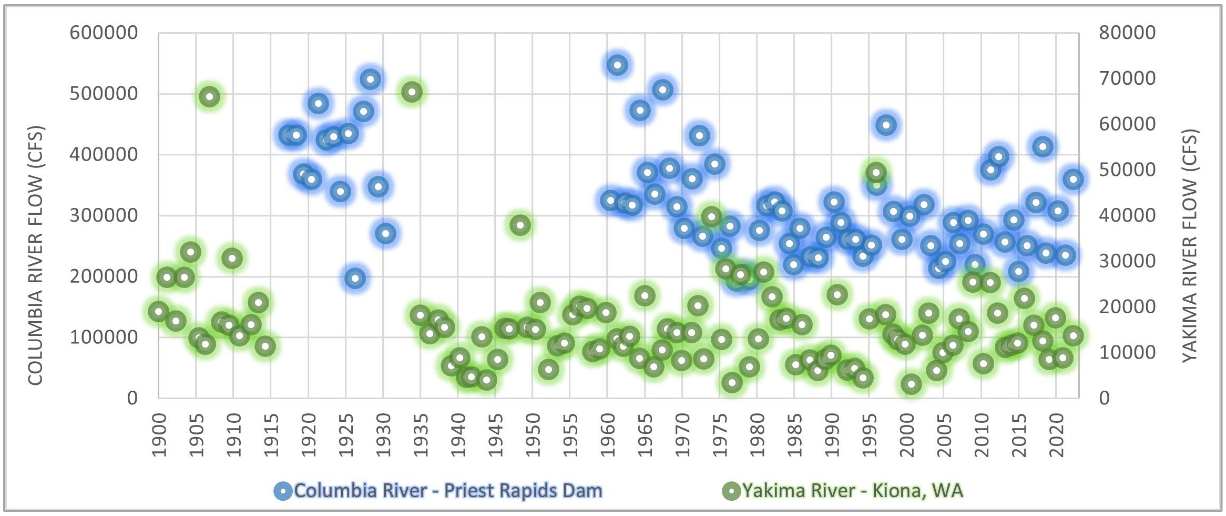


Figure A-1-2 Measured annual peak flow for Columbia and Yakima Rivers
(Yakima River is downscaled from Columbia River flows)

Table A-1 below summarizes the hydrologic records of interest selected to inform the feasibility of the Yakima Delta ecosystem restoration project and which TST tests were evaluated. Analyses of climate change trends within the Yakima Delta study area is complicated by the variety of uses that both rivers have. Streamflow magnitude can be influenced by changes in irrigation use, hydroregulation and seasonality. These factors can make it difficult to determine the role of climate change in affecting the hydrologic signal at the project scale. The relevant question of interest at the project scale is whether there has been, or will be, a change that affects conditions in the study area and how this change would impact the resilience of the TSP. The selection of the time series datasets considered aligns with the hydrologic records rationale for of relevant climate variables as previously discussed in Section 2.5 above.

Table A-1 Summary of hydrologic timeseries analyzed in the TST

Dataset	Rationale
Annual Peak Flows and Maximum Flows	Peak/maximum flows could indicate a lower April 1st SWE value which would impact TSP performance since the project area is in a snow driven basin and the project relies heavily on the mixing of the Yakima and Columbia Rivers.
June – August Volumetric Yield	Decreasing trends in annual summer volume could significantly impact TSP performance since there would be less stream volume available for mixing inside the project area.
Mean Flows	The seasonality trends in mean annual and monthly flows are of interest because reduced summer flows could potentially impact various measures of the ecosystem restoration TSP.
Minimum Flows	The study area frequently experiences low flows, especially during the summer months, which could impact project performance by increasing temperatures inside the Yakima Delta.

A.1.1 Daily Average Flow Results

Table A-2 summarizes the trends, breakpoints, and nonstationarity detection results from the TST for results using the average daily flow series. In general, the Yakima River at Kiona did not display strong trends from 1934-2022 in the annual hydrologic datasets considered. Monthly summer volume and annual minimum flows detected significant near-zero trends. Overall, TST results for the Yakima River gage indicate possible nonstationarities in 1940-1975, 1990-1994 and 2013-2014. The Yakima River gage exhibited breakpoints in 1976 and 2000 for during the period examined.

The Columbia River Below Priest Rapids gage had statistically significant trends in accumulated June-August volume. Multiple tests indicated a breakpoint in the data in 1972; annual minimum flows resulted in a breakpoint in 2000. Several nonstationarities resulted from 1960-1975 and it is important to note that decreasing the period evaluated to 1980-2020 reduced the number of nonstationarities in the data significantly.

The nonstationarity detected in1972 could have been caused by the completion and filling of Mica Dam located in British Columbia, Canada; the dam became operational in March of 1973.

Table A-2 Daily Average Flow Nonstationarity and Trend Analysis Results.

Hydrologic Dataset	Trends	Breakpoints	Strong Nonstationarities
Yakima River at Kiona, WA (12510500)			
Yakima River at Kiona, WA (#12510500) – Annual June-August Accumulated Volume	Traditional Slope = -2520 Sen's Slope = -2159 Significance **t-test = 0.014936** **Mann-Kendall = 0.020275** **Spearman Rank-Order = 0.017504**	1 Breakpoint Detected 1976-09-30	**One strong nonstationarity around 1976 (2 mean tests, 1 distribution test)**
Yakima River at Kiona, WA (#12510500) – Annual Mean Flow	Traditional Slope = -0.74843469 Sen's Slope = -1 Significance t-test = 0. 61363 Mann-Kendall = 0. 74708 Spearman Rank-Order = 0.81297	None Detected	**None Detected**
Yakima River at Kiona, WA (#12510500) – July Mean Flow	Traditional Slope = -9 Sen's Slope = -8 Significance t-test = 0.0.028023 Mann-Kendall = 0.0027166 Spearman Rank-Order = 0.0022837	None Detected	**One strong nonstationarity around 2014 (2 mean tests, 2 distribution tests)**
Yakima River at Kiona, WA (#12510500) – Annual Minimum Flow	Traditional Slope = -4 Sen's Slope = -5 Significance **t-test = 0.00075802** **Mann-Kendall = 0.00092731** **Spearman Rank-Order = 0.00054508**	1 Breakpoint detected 2000-09-30	**Three strong nonstationarities detected around 1945 (2 distribution tests, 1 mean), 1956 (2 distribution tests, 2 mean tests), and 2000 (3 distribution, 5 mean tests)**
Yakima River at Kiona, WA (#12510500) – July Minimum Flow	Traditional Slope = -6 Sen's Slope = -6 Significance t-test = 0. 0004385 Mann-Kendall = 0.000090544 Spearman Rank-Order = 0.000034043	1 Breakpoint detected 2000-09-30	**Three strong nonstationarities detected around 1945 (3 distribution tests, 1 mean), 1956 (3 distribution tests, 1 mean tests), and 2000 (2 distribution, 3 mean tests)**

Hydrologic Dataset	Trends	Breakpoints	Strong Nonstationarities
Columbia River Below Priest Rapids Dam (12472800)			
Columbia River Below Priest Rapids Dam (#12472800) – Annual June-August Accumulated Volume	Traditional Slope = -180542 Sen's Slope = -170975 Significance **t-test = 0.0034933** **Mann-Kendall = 0.032261** **Spearman Rank-Order = 0.018416**	1 Breakpoint Detected 1972-09-30	**One strong nonstationarity around 1972 (2 mean tests, 2 distribution tests, 5 smoothing tests)**
Columbia River Below Priest Rapids Dam (#12472800) – Annual Mean Flow	Traditional Slope = -101 Sen's Slope = -101 Significance t-test = 0. 49067 Mann-Kendall = 0.56277 Spearman Rank-Order = 0.49853	None Detected	**None Detected**
Columbia River Below Priest Rapids Dam (#12472800) – July Mean Flow	Traditional Slope = -1230 Sen's Slope = -1206 Significance **t-test = 0. 0017302** **Mann-Kendall = 0.0078796** **Spearman Rank-Order = 0.0056327**	1 Breakpoint detected 1972-09-30	**One strong nonstationarity around 2014 (1 mean test, 2 distribution tests)**
Columbia River Below Priest Rapids Dam (#12472800) – Annual Minimum Flow	Traditional Slope = 22 Sen's Slope = 25 Significance t-test = 0. 61794 Mann-Kendall = 0.37864 Spearman Rank-Order = 0.32791	2 Breakpoints detected 1978-09-30 2000-09-30	**Two strong nonstationarities detected around 1978 (3 distribution tests, 2 mean tests), and 2000 (1 distribution test, 1 mean test, 1 smoothing test)**
Columbia River Below Priest Rapids Dam (#12472800) – July Minimum Flow	Traditional Slope = -524 Sen's Slope = -540 Significance t-test = 0. 071901 Mann-Kendall = 0.13203 Spearman Rank-Order = 0.096768	1 Breakpoint detected 1972-09-30	**One strong nonstationarity detected around 1972 (3 distribution tests, 2 mean tests)**

A.1.2 Instantaneous Flow Results

As summarized in Table A-3 the annual peak flows for both gages had a negative slope trend of small magnitude by both the Traditional and Sen's methods. The three hypothesis tests (T-test, Mann-Kendall, and Spearman Rank Order) did not identify this negative trend as significant at the α = 0.05 threshold for the Yakima River. The Columbia River gage showed a significant trend with all three hypothesis tests below the α = 0.05 threshold. It is important to note that since the Columbia River has a much larger magnitude of flow compared to the Yakima River, the slope value does not directly relate to a stronger trend relative to the Kiona gage. Decreasing trends in annual peak flow could suggest that peak streamflow magnitude has been slowly decreasing, which would agree with climate literature findings (see section 2.2) that flow magnitudes have been declining over recent years.

Annual monthly peak flows for the months of June, July and August were chosen to identify trends in peak flows during summer months with each month analyzed separately. For both gages the month of July provided the best data for observing climate trends based on the variables established in section 2.5.

Two of the three hypothesis tests detected a significant near-zero trend for the Yakima River peak July flows. Peak July flows at both the Columbia River Below Priest Rapids Dam gages did not exhibit any significant trends with near-zero to mildly negative slopes. During NSD tests, both gages resulted in smoothing nonstationarities, which is most likely due to the tests not working well with small changes in magnitude between years.

The Yakima River gage did not result in nonstationarities or breakpoints for the annual peak flows. The annual monthly peak flows for the month of July resulted in four nonstationarities. These nonstationarities will not impact the record length used in the project study. A nonstationarity in 1970 was found using the Lombard Mood test (a variance-based test); as previously stated this state is sensitive to small changes in magnitude. Decreasing the period from 1934-2022 to 1980-2022 resulted in no nonstationarities.

Evaluation of the Columbia River gage resulted in a nonstationarity in 1991 by the energy-divisive method. Lowering the NSD parameter for the energy-divisive method to 0.23 removed the nonstationarity from the results. The sensitivity of the parameter is meant to account for repeated tests across all subsets of the period, and the default parameter setting of 0.5 is set to ensure the method regularly returns at least one nonstationarity.

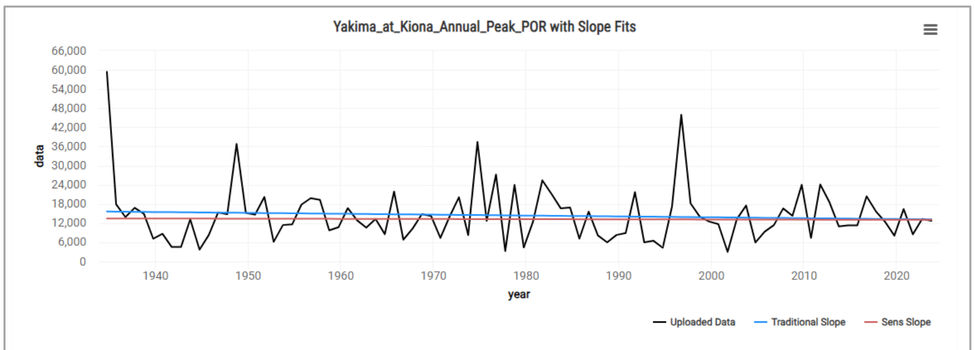
Multiple tests resulted in a nonstationarity in 1972. Possible changes in hydroregulation operations at or above Priest Rapids Dam could have altered the trend of data during that time. Later test results also indicate that there was a change in data statistics during this time.

Table A-3 Instantaneous Nonstationarity and Trend Analysis Results

Gage - Variable	Trends	Breakpoints	Strong Nonstationarities
Yakima River at Kiona, WA (#12510500) – Annual Peak Flows Observed (POR 1934-2022)	Traditional Slope = -28 Sen's Slope = -5 <u>Significance</u> t-test = 0.44421 Mann-Kendall = 0.79109 Spearman Rank-Order = 0.84317	None detected	None detected
Yakima River at Kiona, WA (#12510500) – Annual July Peak Values (POR 1934-2022)	Traditional Slope = -16 Sen's Slope = -9 <u>Significance</u> t-test = 0.084296 **Mann-Kendall = 0.036508** **Spearman Rank-Order = 0.023369**	None Detected	None Detected

Columbia River Below Priest Rapids Dam (#12472800) – Annual Peak Flows Observed (POR 1960-2022)	Traditional Slope = -1358 Sen's Slope = -1098 Significance **t-test = 0.01189** **Mann-Kendall = 0.023859** **Spearman Rank-Order = 0.020562**	1 Breakpoint Detected 1972-01-01	**One strong nonstationarity detected around 1974 (2 tests distribution, 2 tests mean)**
Columbia River Below Priest Rapids Dam (#12472800) – Annual July Peak Values (POR 1960-2022)	Traditional Slope = -1715 Sen's Slope = -1372 Significance **t-test = 0.0013934** **Mann-Kendall = 0.010712** **Spearman Rank-Order = 0.0050614**	1 Breakpoint Detected 1974-09-30	**One strong nonstationarity detected around 1974 (3 tests distribution, 2 tests mean)**

Yakima River Results



Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-28	68879
Sen's Slope	Negative	-5	23142

Trend Hypothesis Test

Test	P-Value
t-Test	0.44421
Mann-Kendall	0.79109
Spearman Rank-Order	0.84317

Figure A-1-3 Yakima Annual Peak Flow

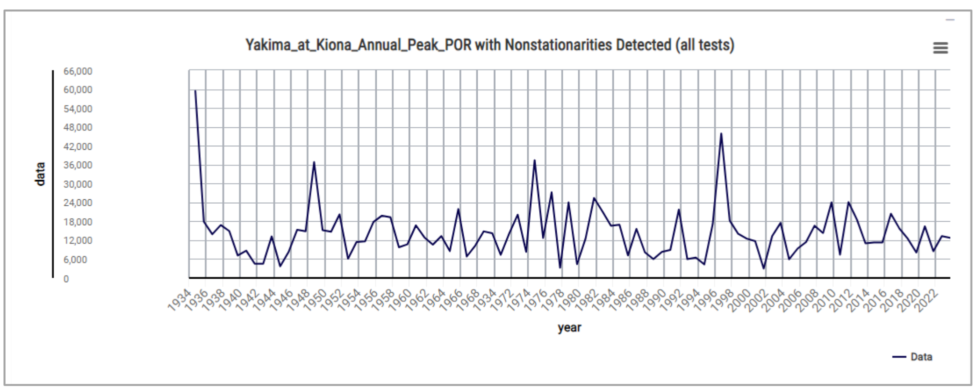


Figure A-1-4 Annual Peak Flow NSD

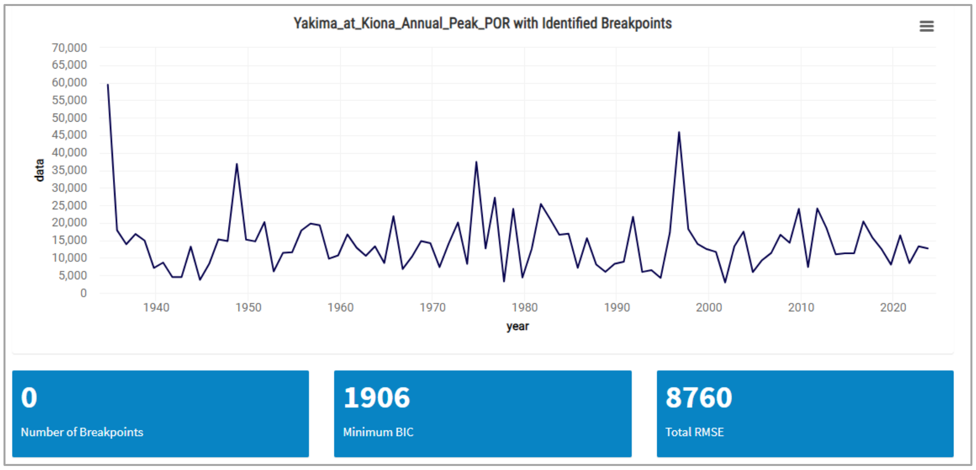
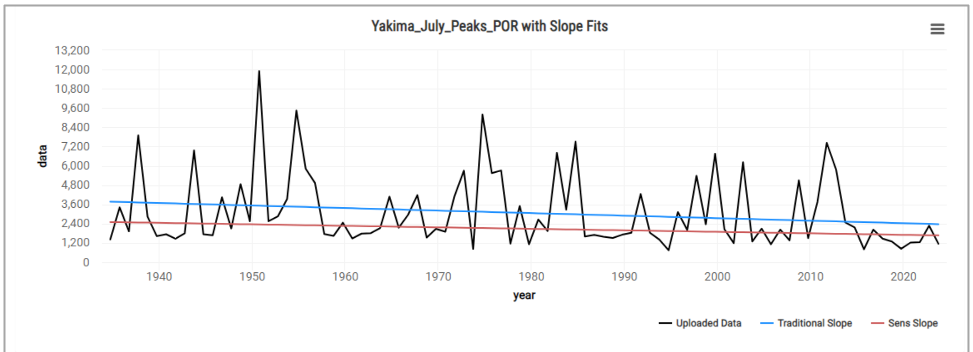


Figure A-1-5 Annual Peak Flow BA



Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-16	34174
Sen's Slope	Negative	-9	20551

Trend Hypothesis Test

Test	P-Value
t-Test	0.084296
Mann-Kendall	0.036508
Spearman Rank-Order	0.023369

Figure A-1-6 Yakima River Annual July Peak Flows

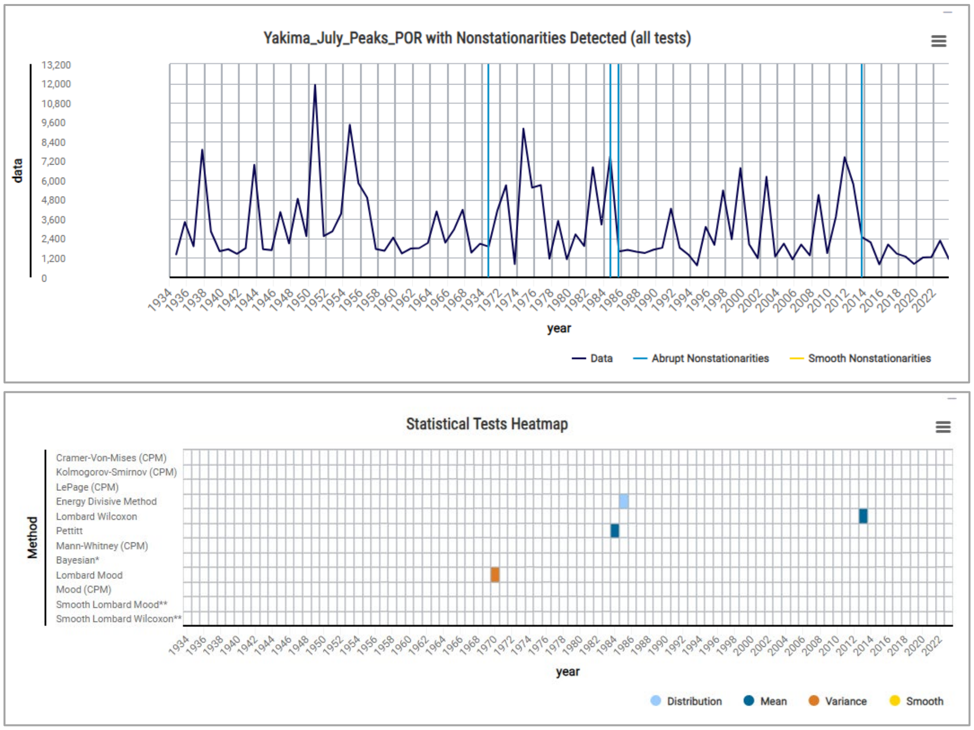


Figure A-1-7 Yakima River Annual Peak July Flows NSD

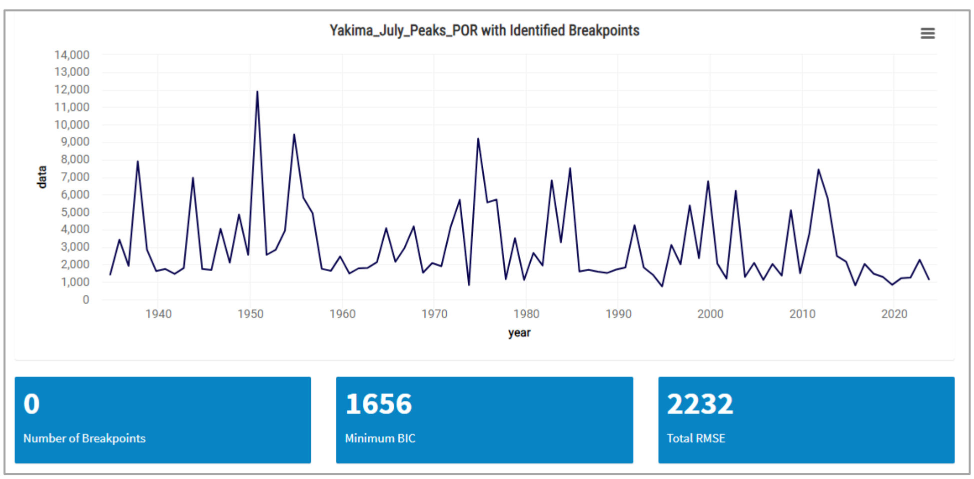
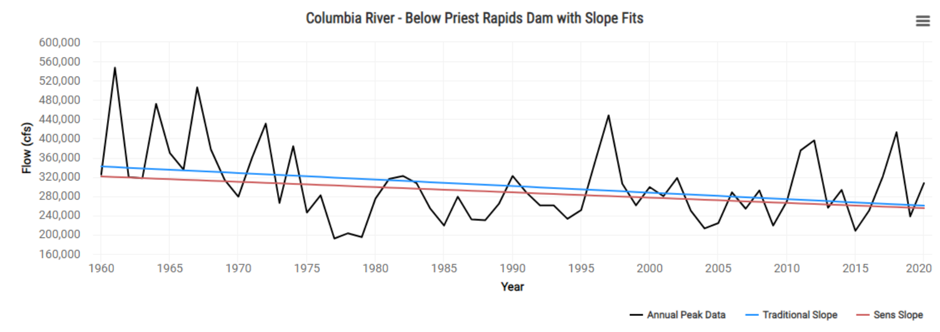


Figure A-1-8 Yakima River Annual Peak July Flows BA

Columbia River Results



Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-1358	3004423
Sen's Slope	Negative	-1098	2472146

Trend Hypothesis Test

Test	P-Value
t-Test	0.01189
Mann-Kendall	0.023859
Spearman Rank-Order	0.020562

- **A statistically significant trend (at the alpha = .05 level) was detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was detected by the Spearman Rank-Order Test.**

Figure A-1-9 Columbia River Annual Peak Flows

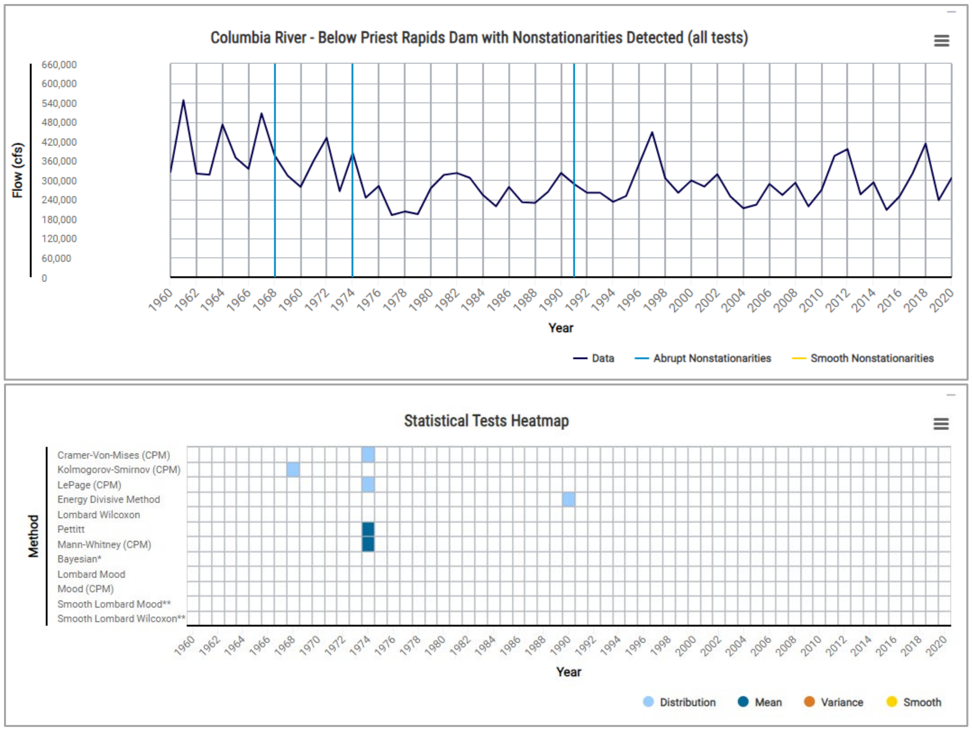
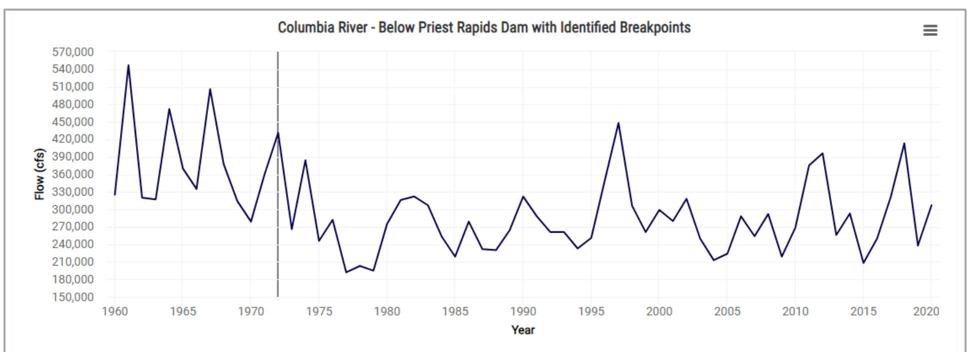


Figure A-1-10 Columbia River Annual Peak NSD

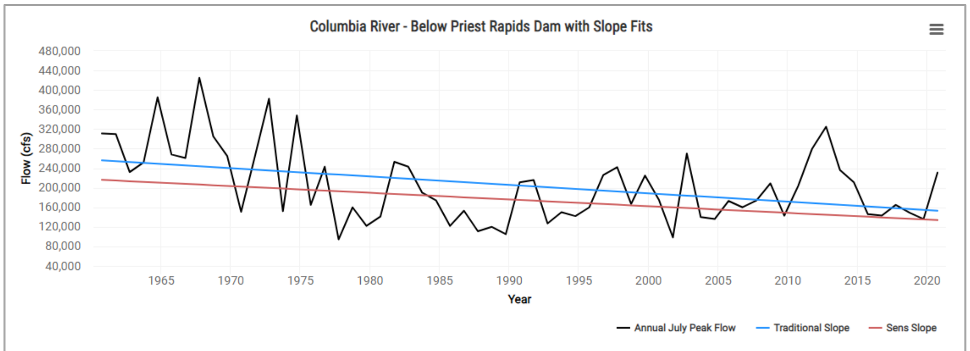


1	1536	62044
Number of Breakpoints	Minimum BIC	Total RMSE

Breakpoint Segment Details

Date Range	Slope	P-Value (Trend)	Intercept	Directionality
1959-10-01 to 1972-01-01	-2890.10989	0.65837	401230.76923	Negative
1972-01-01 to 2020-09-30	296.428571	0.63181	275058.67347	Positive

Figure A-1-11 Columbia River Annual Peak BA



Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-1715	3618408
Sen's Slope	Negative	-1372	2905465

Trend Hypothesis Test

Test	P-Value
t-Test	0.0013934
Mann-Kendall	0.010712
Spearman Rank-Order	0.0050614

- **A statistically significant trend (at the alpha = .05 level) was detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was detected by the Spearman Rank-Order Test.**

Figure A-1-12 Columbia River Annual July Peak Flows

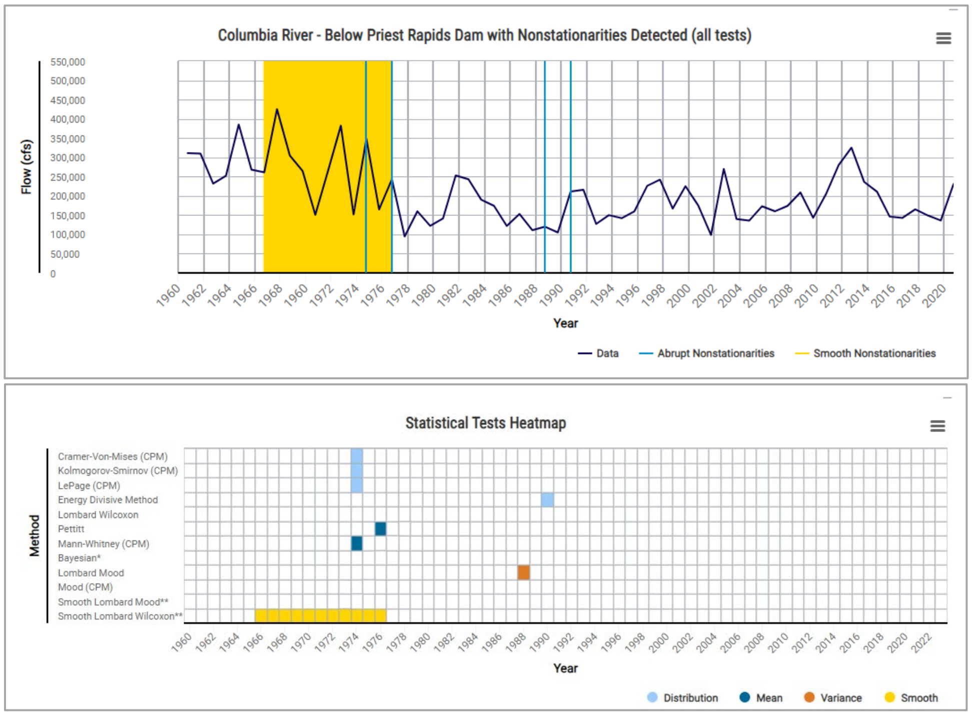
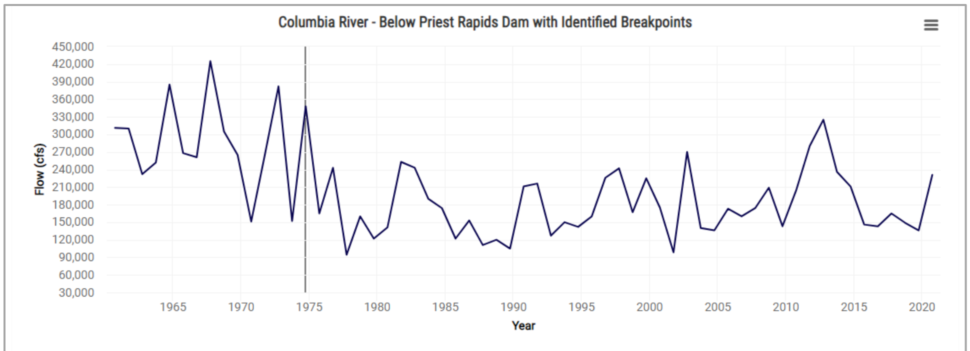


Figure A-1-13 Columbia River Annual July Peak Flows NSD



1
Number of Breakpoints

1529
Minimum BIC

58776
Total RMSE

Breakpoint Segment Details

Date Range	Slope	P-Value (Trend)	Intercept	Directionality
1960-09-30 to 1974-09-30	-1967.857143	0.68997	303209.52381	Negative
1974-09-30 to 2020-09-30	244.449584	0.69834	175303.42276	Positive

Figure A-1-14 Columbia River Annual July Peak Flows BA

A1.1.3 June-August Volumetric Yield Results

Monthly volumetric yield from the Yakima River at Kiona, WA and Columbia River Below Priest Rapids Dam records were evaluated in the TST as an indicator of the available water for the project area during hot summer periods. Monthly volumes for the entire year were determined to have significant variability in magnitude and numerous nonstationarities were flagged. Therefore, the months of June through August were chosen to determine trends in summer volumes. Nonstationarities in between years could be because the Yakima River subbasin is heavily regulated for irrigation use.

As summarized in Table A-4 there were significant trends identified in the record of annual June-August runoff volume for the Yakima River at Kiona, WA gage; there was one breakpoint detected in 1976. A strong nonstationarity was detected around 1977 with two mean tests and one distribution est. This nonstationarity could be attributed to one of the largest peaks in the dataset being followed by one of the smallest values in the dataset. This nonstationarity appears inconsistent with coincident tests and provides limited insight on detected trends. Reducing the record to 1980 – 2022 removed all nonstationarities.

The overall summer volume trend for the Columbia River was negative and did meet the $\alpha = 0.05$ threshold for all hypothesis tests. The Columbia River Below Priest Rapids Dam gage shows a breakpoint at the end of the 1972 water year that correlates to breakpoints found in other datasets. This supports that there was a change in trends of the data during the 1970's however the overall negative trend is still significant for all three hypothesis tests. To further validate this, the TST results for the Columbia River Below Priest Rapids Dam gage were analyzed for the period of 1980-2020, which resulted in zero nonstationarities or breakpoints detected in the data.

Table A-4 June – August accumulated volume summary

Gage - Variable	Trends	Breakpoints	Strong Nonstationarities
Yakima River at Kiona, WA (#12510500) – Annual June-August Accumulated Volume	Traditional Slope = -2520 Sen's Slope = -2159 <u>Significance</u> **t-test = 0.014936** **Mann-Kendall = 0.020275** **Spearman Rank-Order = 0.017504**	1 Breakpoint Detected <u>1976-09-30</u>	**One strong nonstationarity around 1976 (2 mean tests, 1 distribution test)**
Columbia River Below Priest Rapids Dam (#12472800) – Annual June-August Accumulated Volume	Traditional Slope = -180542 Sen's Slope = -170975 <u>Significance</u> **t-test = 0.0034933** **Mann-Kendall = 0.032261** **Spearman Rank-Order = 0.018416**	1 Breakpoint Detected <u>1972-09-30</u>	**One strong nonstationarity around 1972 (2 mean tests, 2 distribution tests, 5 smoothing tests)**

<u>Yakima River Results</u>

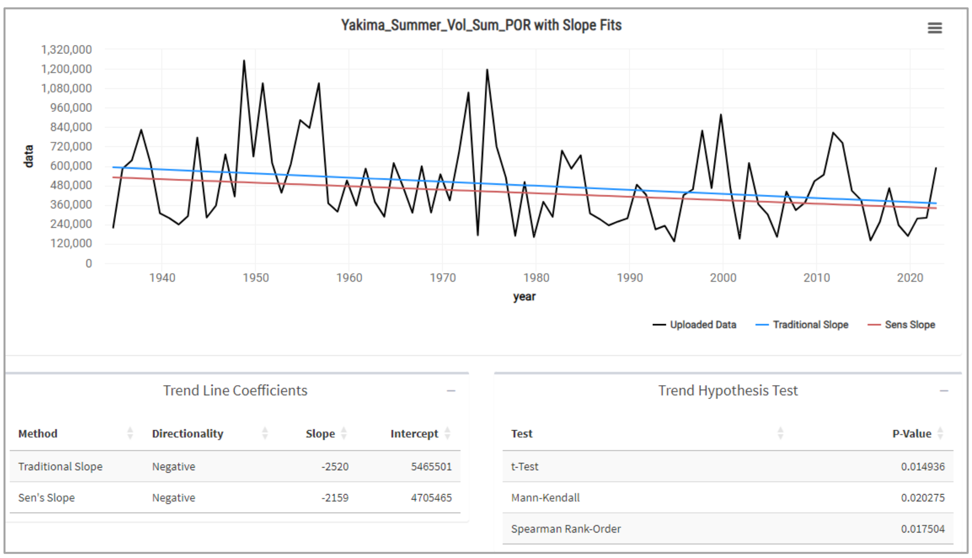


Figure A-1-15 Yakima River Annual Monthly Volume Trend

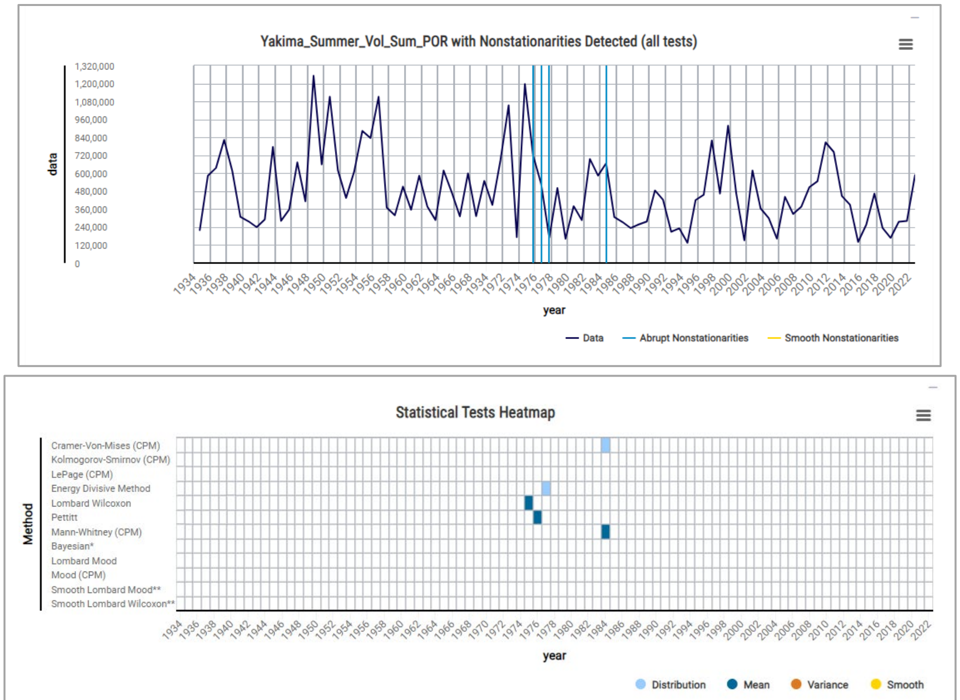


Figure A-1-16 Yakima River Annual Monthly Volume

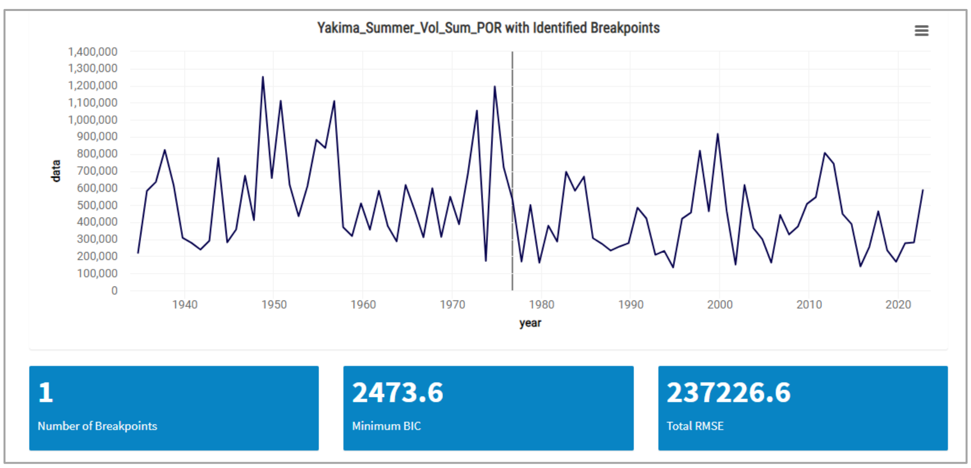
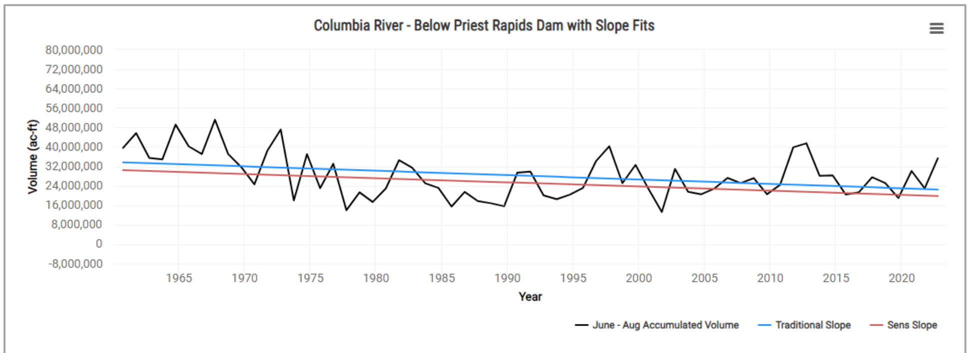


Figure A-1-17 Yakima River Annual Monthly Volume BA

Columbia River Results



Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-180542	387553470
Sen's Slope	Negative	-170975	365545649

Trend Hypothesis Test

Test	P-Value
t-Test	0.0034933
Mann-Kendall	0.032261
Spearman Rank-Order	0.018416

- **A statistically significant trend (at the alpha = .05 level) was detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was detected by the Spearman Rank-Order Test.**

Figure A-1-18 Columbia River Summer Volume Accumulation

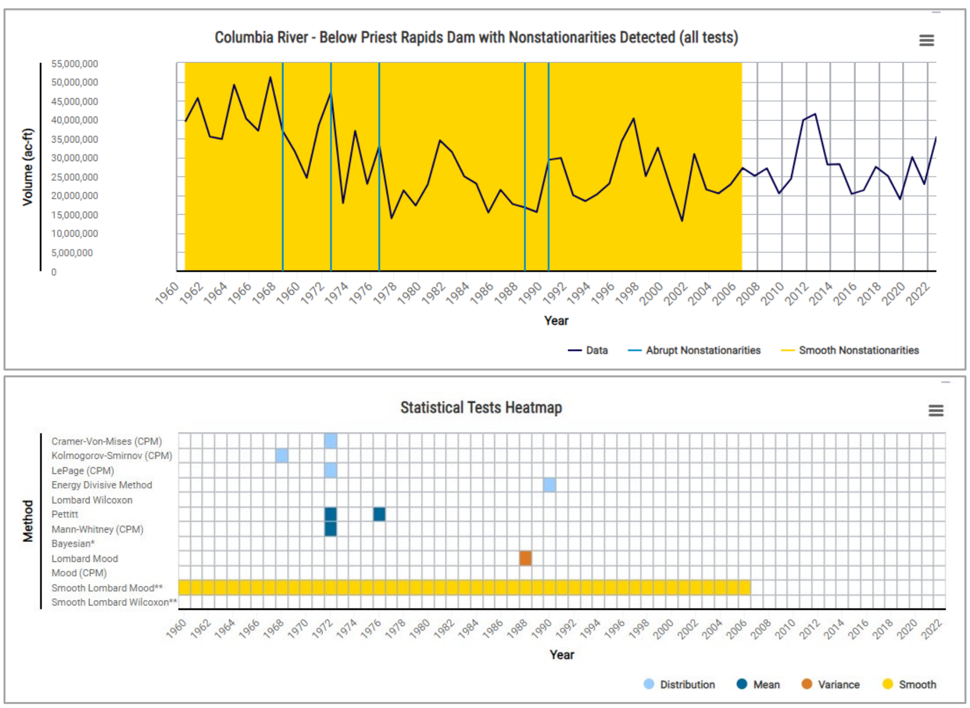
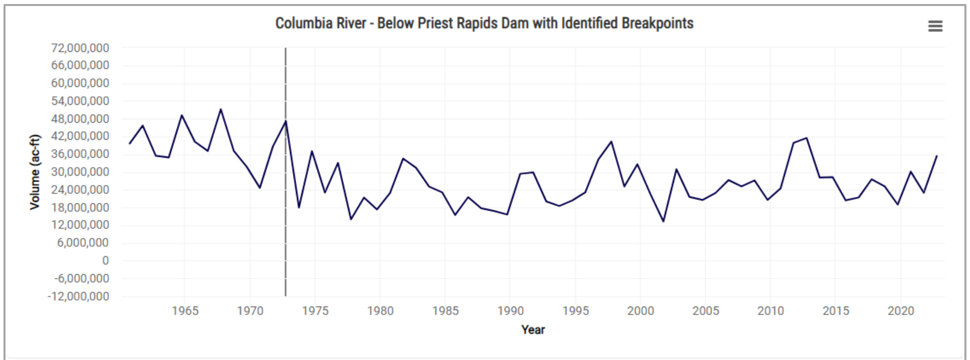


Figure A-1-19 Columbia River Annual Monthly Volume NSD



1	2181	6966184
Number of Breakpoints	Minimum BIC	Total RMSE

Breakpoint Segment Details

Date Range	Slope	P-Value (Trend)	Intercept	Directionality
1960-09-30 to 1972-09-30	-309097.78022	0.59661	41598751.23077	Negative
1972-09-30 to 2022-09-30	35152.871855	0.63069	24663044.1749	Positive

Figure A-1-20 Columbia River Annual Monthly Volume BA

A.1.4 Mean Flow Results

The TST tools were also used to evaluate annual mean flows for Yakima River at Kiona, WA and Columbia River Below Priest Rapids Dam gages. Monthly and annual aggregates of mean daily flow for both gages were used. To determine summer trends monthly data for June, July and August were analyzed. July was determined to be the best dataset to use for analysis of seasonal trends for both gages. Results for the mean flow are summarized in Table A-5 below.

No significant trends were found in the Yakima River or Columbia River annual datasets; however, both gages found significant trends in the July mean flows. The Yakima River and the Columbia River gage found significance in all three tests.

No breakpoints were found in the Yakima River datasets for annual or July mean flows. One breakpoint was found in 1972 for the July mean flow at the Columbia River dataset, which is consistent with other datasets analyzed. The Columbia River gage resulted in an energy-divisive method nonstationarity in the July mean flow data in the early 1990's, which can be attributed to small changes in magnitude of the dataset before that time. Analyzing the July mean flow data between 1980 – 2020 removed all nonstationarities.

During analysis of the Yakima annual average flows, there was one smoothing nonstationarity detected around 2001. In 2001 the small change in magnitude between peaks could have flagged this nonstationarity.

Table A-5 Annual and July mean flows summary

Gage - Variable	Trends	Breakpoints	Strong Nonstationarities
Yakima River at Kiona, WA (#12510500) – Annual Mean Flow	Traditional Slope = -0.74843469 Sen's Slope = -1 <u>Significance</u> t-test = 0. 61363 Mann-Kendall = 0. 74708 Spearman Rank-Order = 0.81297	None Detected	None Detected
Yakima River at Kiona, WA (#12510500) – July Mean Flow	Traditional Slope = -9 Sen's Slope = -8 <u>Significance</u> **t-test = 0.028023** **Mann-Kendall = 0.0027166** **Spearman Rank-Order = 0.0022837**	None Detected	**One strong nonstationarity around 2014 (2 mean tests, 2 distribution tests)**
Columbia River Below Priest Rapids Dam (#12472800) – Annual Mean Flow	Traditional Slope = -101 Sen's Slope = -101 <u>Significance</u> t-test = 0. 49067 Mann-Kendall = 0.56277 Spearman Rank-Order = 0.49853	None Detected	None Detected
Columbia River Below Priest Rapids Dam (#12472800) – July Mean Flow	Traditional Slope = -1230 Sen's Slope = -1206 <u>Significance</u> **t-test = 0. 0017302** **Mann-Kendall = 0.0078796** **Spearman Rank-Order = 0.0056327**	1 Breakpoint detected <u>1972-09-30</u>	**One strong nonstationarity around 2014 (1 mean test, 2 distribution tests)**

<u>Yakima River Results</u>

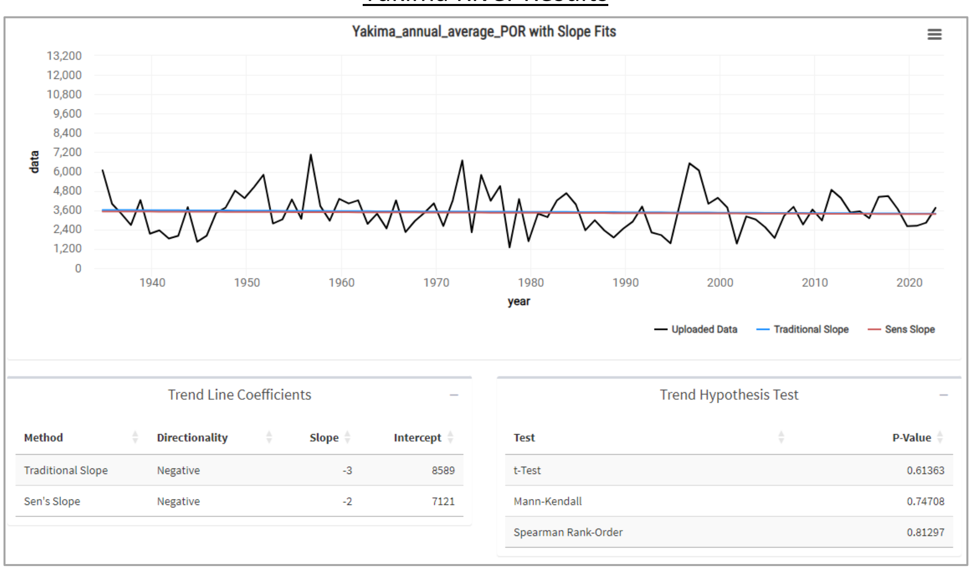


Figure A-1-21 Yakima River Average Annual Flows

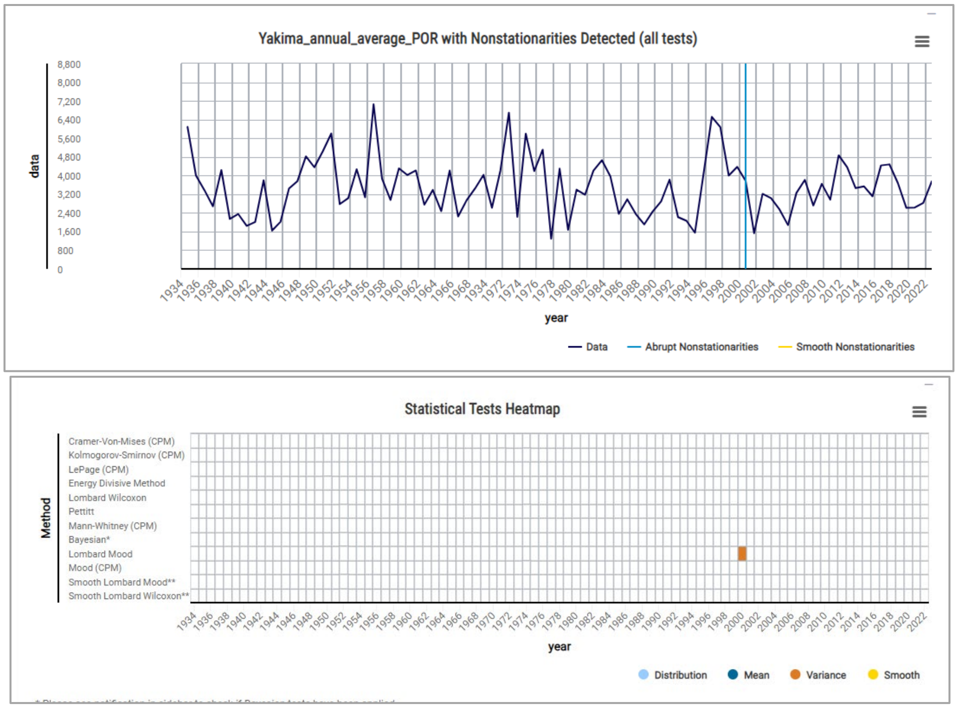


Figure A-1-22 Yakima River Average Annual Flow NSD

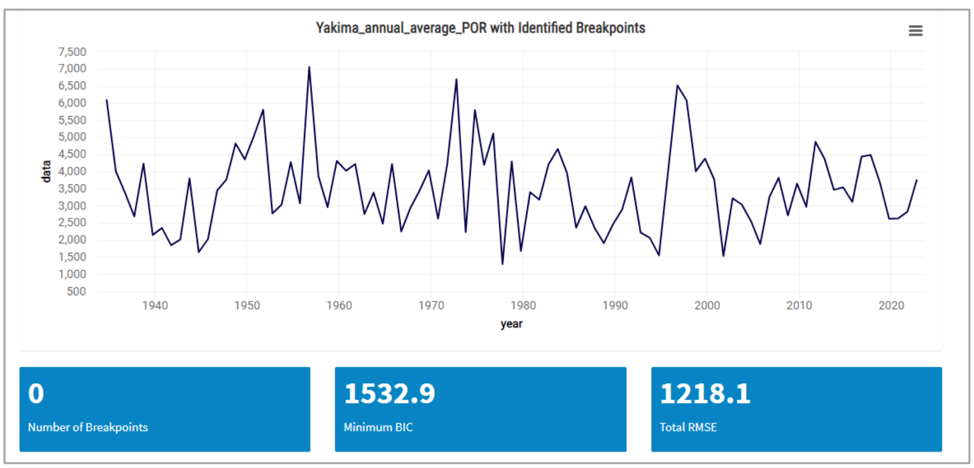
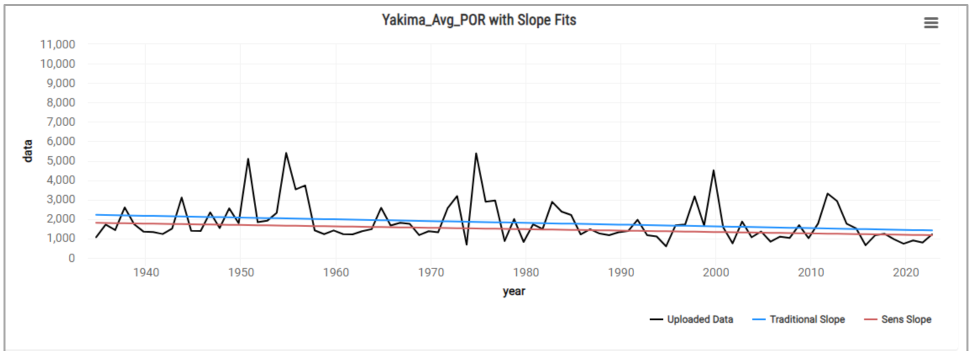


Figure A-1-23 Yakima River Average Annual Flow BA



Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-9	19764
Sen's Slope	Negative	-7	15765

Trend Hypothesis Test

Test	P-Value
t-Test	0.028023
Mann-Kendall	0.0027166
Spearman Rank-Order	0.0022837

Figure A-1-24 Yakima River July Average Flows

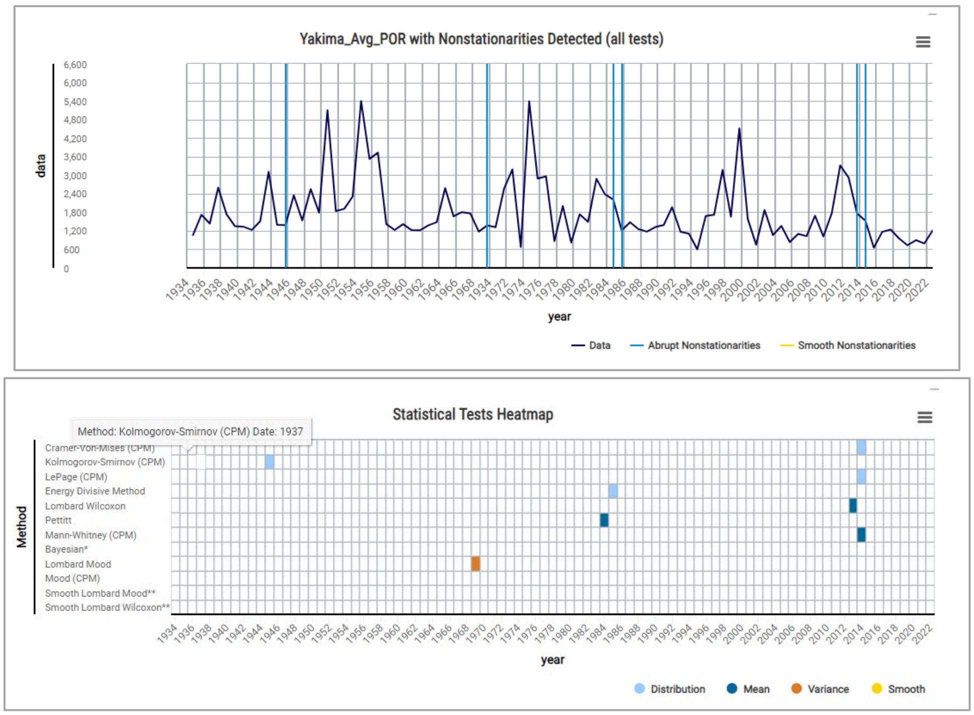


Figure A-1-25 Yakima River Average July Flows NSD

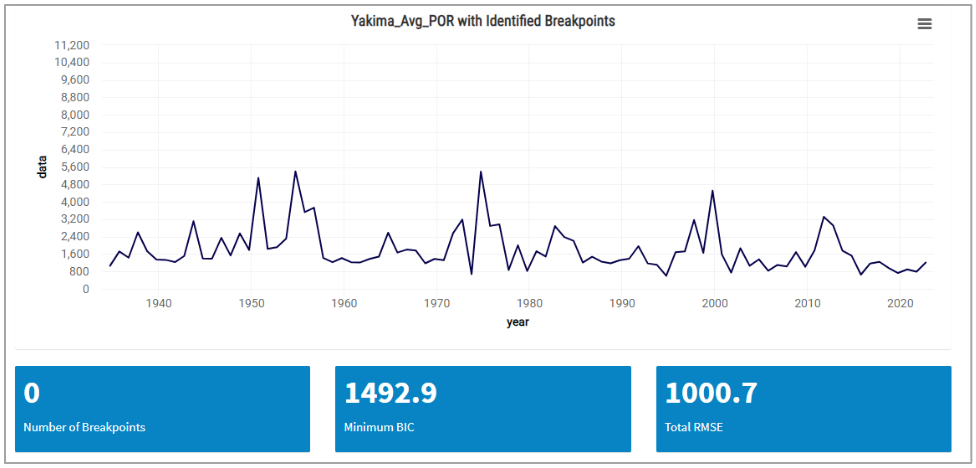
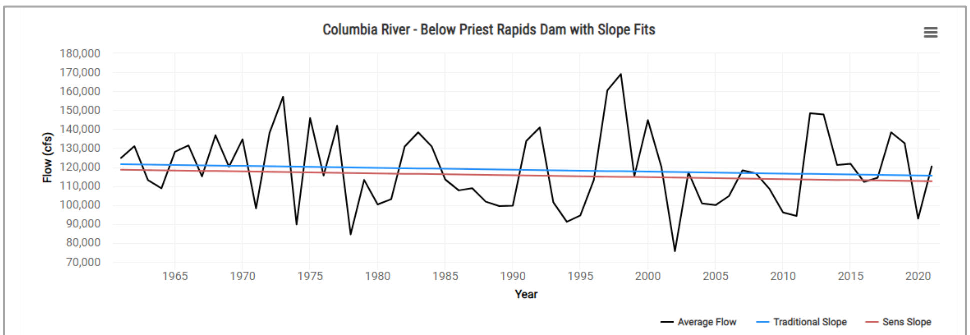


Figure A-1-26 Yakima River Average July Flows BA

Columbia River Results



Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-101	318511
Sen's Slope	Negative	-101	317324

Trend Hypothesis Test

Test	P-Value
t-Test	0.49067
Mann-Kendall	0.56277
Spearman Rank-Order	0.49853

- A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.
- A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.
- A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.

Figure A-1-27 Columbia River Average Annual Average Flow

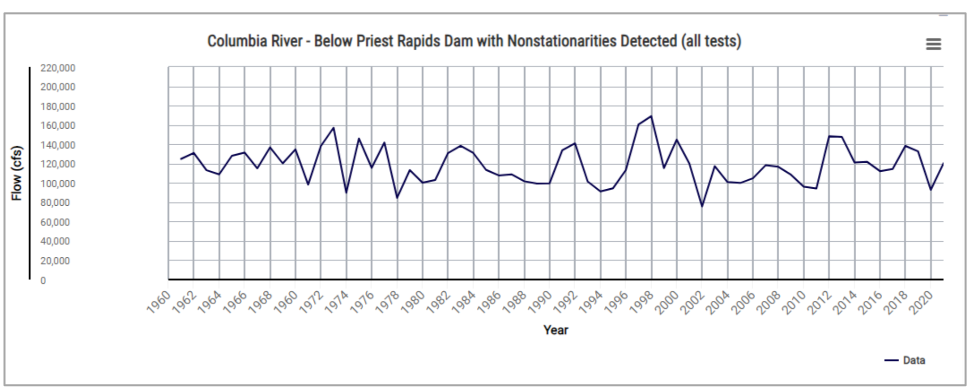


Figure A-1-28 Columbia River Average Annual Flow NSD

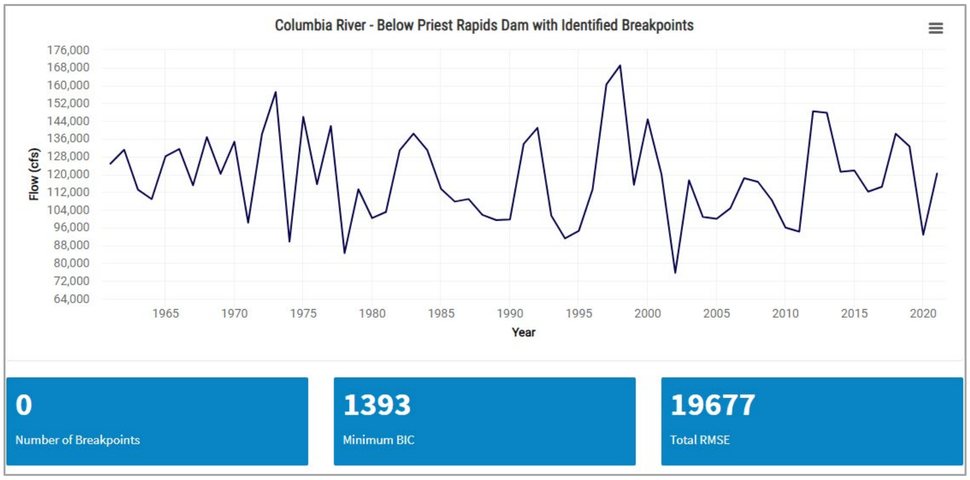
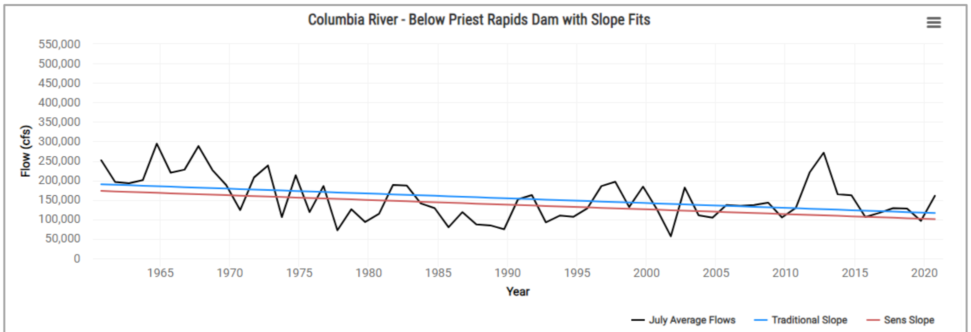


Figure A-1-29 Columbia River Average Annual Flow BA



Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-1230	2599939
Sen's Slope	Negative	-1206	2537284

Trend Hypothesis Test

Test	P-Value
t-Test	0.0017302
Mann-Kendall	0.0078796
Spearman Rank-Order	0.0056327

- **A statistically significant trend (at the alpha = .05 level) was detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was detected by the Spearman Rank-Order Test.**

Figure A-1-30 Columbia River July Average Flows

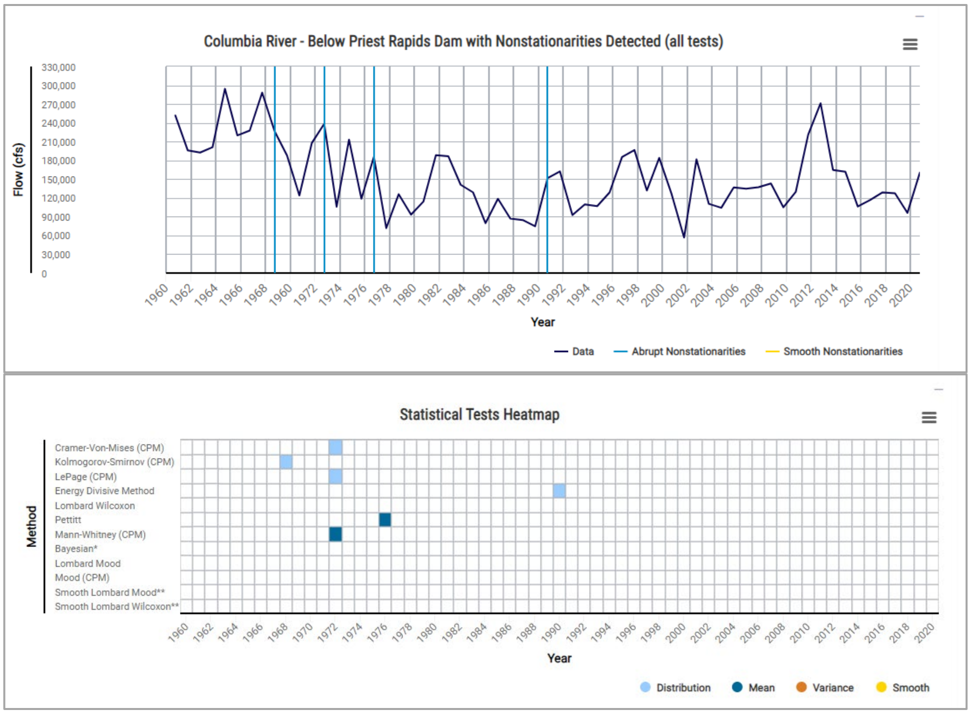
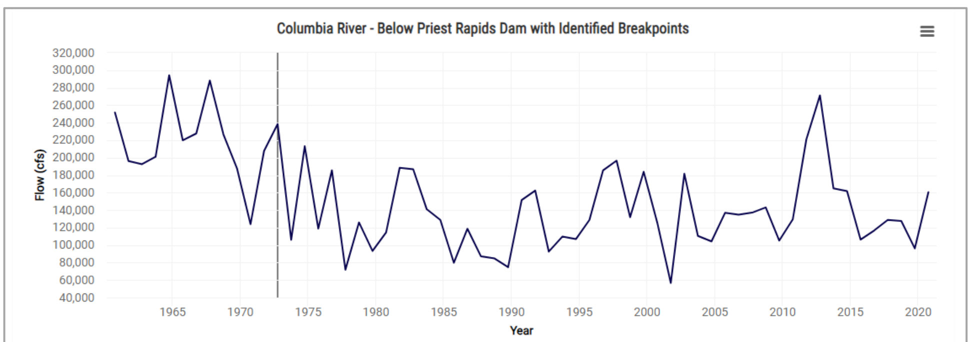


Figure A-1-31 Columbia River July Average Flows NSD



1
Number of Breakpoints

1491
Minimum BIC

42856
Total RMSE

Breakpoint Segment Details

Date Range	Slope	P-Value (Trend)	Intercept	Directionality
1959-10-01 to 1972-09-30	-2219.472527	0.52457	235207.46154	Negative
1972-09-30 to 2020-09-30	106.418878	0.81911	134608.3648	Positive

Figure A-1-32 Columbia River July Average Flows BA

A.1.5 Minimum Flows Results

For both gages the mean daily flow data from USGS was aggregated into annual and monthly minimums to explore low flow trends that may influence performance of the TSP. The months of June, July and August were selected to help identify summer trends in flows every year. July provided the most significant trend with the fewest nonstationarities.

Minimum July flows produced more significant trends than annual flows for both the Yakima and Columbia River gages analyzed. The annual minimum and July minimum flows for the Yakima River data had all three hypothesis tests detect a trend below the $\alpha = 0.05$ threshold. Columbia River flows did not show significant trends for either the annual minimum or July minimum flows. Results from the analysis are summarized in Table A-6 below.

Table A-6 Annual and July minimum flows summary

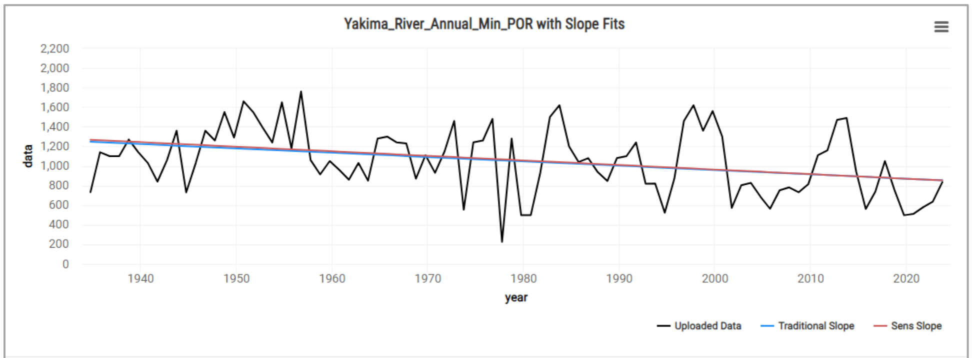
Gage - Variable	Trends	Breakpoints	Strong Nonstationarities
Yakima River at Kiona, WA (#12510500) – Annual Minimum Flow	Traditional Slope = -4 Sen's Slope = -5 Significance **t-test = 0.00075802** **Mann-Kendall = 0.00092731** **Spearman Rank-Order = 0.00054508**	1 Breakpoint detected 2000-09-30	**Three strong nonstationarities detected around 1945 (2 distribution tests, 1 mean), 1956 (2 distribution tests, 2 mean tests), and 2000 (3 distribution, 5 mean tests)**
Yakima River at Kiona, WA (#12510500) – July Minimum Flow	Traditional Slope = -6 Sen's Slope = -6 Significance t-test = 0. 0004385 Mann-Kendall = 0.000090544 Spearman Rank-Order = 0.000034043	1 Breakpoint detected 2000-09-30	**Three strong nonstationarities detected around 1945 (3 distribution tests, 1 mean), 1956 (3 distribution tests, 1 mean tests), and 2000 (2 distribution, 3 mean tests)**
Columbia River Below Priest Rapids Dam (#12472800) – Annual Minimum Flow	Traditional Slope = 22 Sen's Slope = 25 Significance t-test = 0. 61794 Mann-Kendall = 0.37864 Spearman Rank-Order = 0.32791	2 Breakpoints detected 1978-09-30 2000-09-30	**Two strong nonstationarities detected around 1978 (3 distribution tests, 2 mean tests), and 2000 (1 distribution test, 1 mean test, 1 smoothing test)**
Columbia River Below Priest Rapids Dam (#12472800) – July Minimum Flow	Traditional Slope = -524 Sen's Slope = -540 Significance t-test = 0. 071901 Mann-Kendall = 0.13203 Spearman Rank-Order = 0.096768	1 Breakpoint detected 1972-09-30	**One strong nonstationarity detected around 1972 (3 distribution tests, 2 mean tests)**

Nonstationarity analysis found several nonstationarities around three different time periods for the Yakima River gage. For the Yakima gage, the annual minimum flows show fluctuations in the 1940's, the 1950's and again in the 1990's. The Yakima River July minimums show nonstationarities during the same time periods.. The primary nonstationarities detected are through mean tests; this is due to a large change in annual values after several years of high or low annual flows. There was one breakpoint detected in both the annual and July minimum flows for the Yakima at Kiona, WA gage.

The Columbia River Below Priest Rapids Dam gage found nonstationarities during similar time periods, though far less in number. There was only one breakpoint found in the July minimum flows during 1972 that is consistent with other findings. There were two breakpoints found in the annual minimum flow data, one in the 1970's that coincides with previous breakpoint analysis done for other time series on the

Columbia River gage. The other breakpoint was found in the 1990’s which is centered around the nonstationarities found during the analysis. This is not unusual given the flows in the 1990s were historically higher than normal for this period in the study area. Minimum flows vary rapidly from year to year which can be seen by the opposing slopes in the Columbia River gage between annual minimum flows and July minimum flows. Annual minimum flows trend slightly positive due to higher minimum flows outside of the summer months while July minimum flows trend slightly negative due to lower flow summers.

Yakima River Results



Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-4	9794
Sen's Slope	Negative	-5	10293

Trend Hypothesis Test

Test	P-Value
t-Test	0.00075802
Mann-Kendall	0.00092731
Spearman Rank-Order	0.00054508

Figure A-1-33 Yakima River Annual Minimum Trend

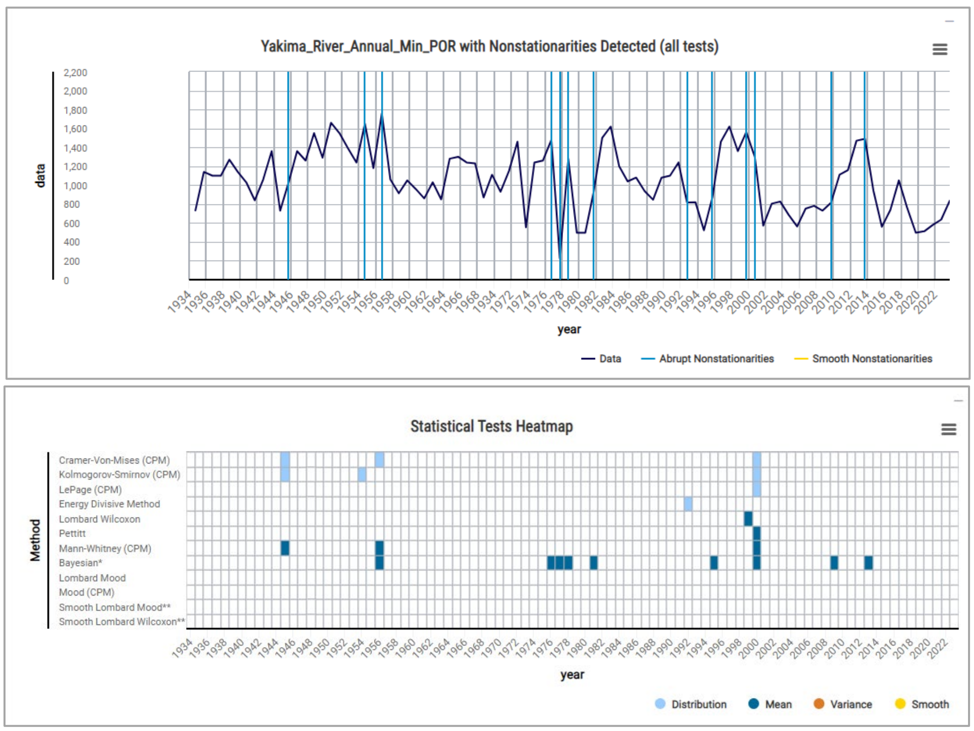


Figure A-1-34 Yakima River Annual Minimum Flow NSD

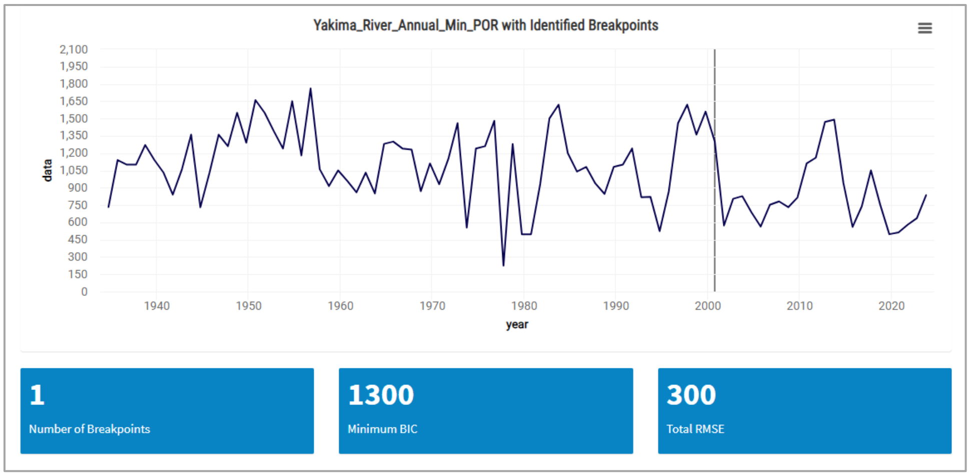


Figure A-1-35 Yakima River - Annual Minimum Flow BA

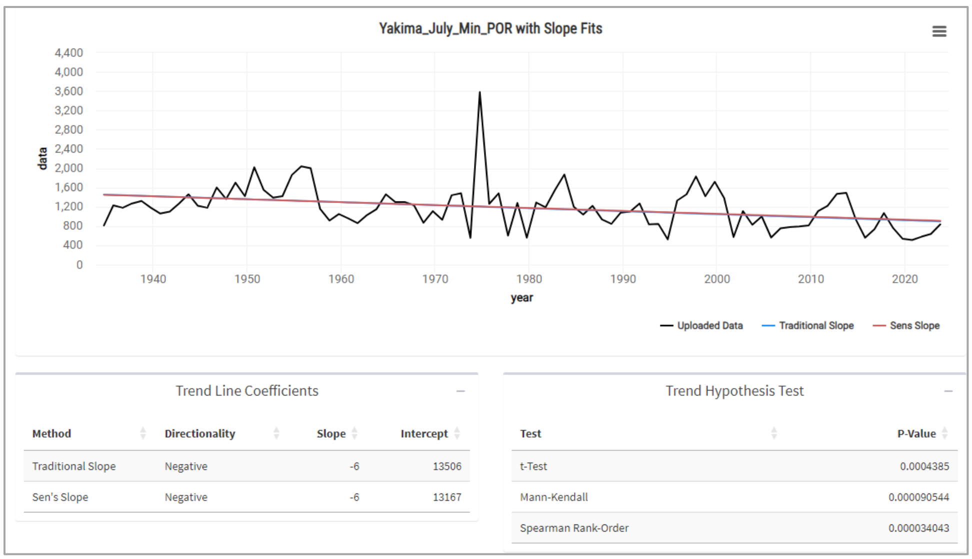


Figure A-1-36 Yakima River Minimum July Flows

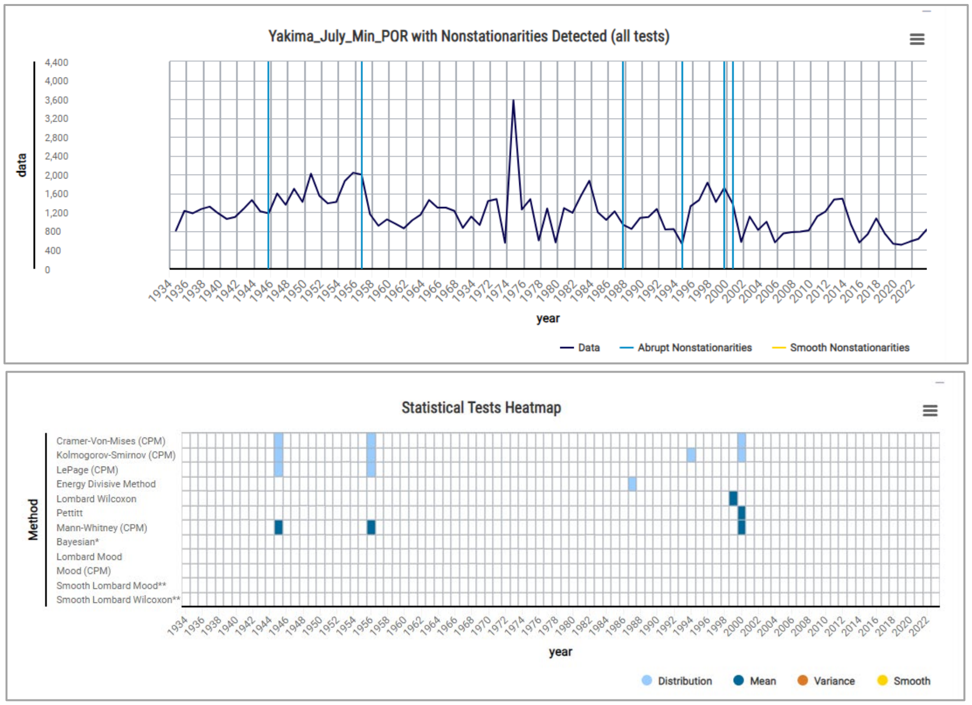


Figure A-1-37 Yakima River Minimum July Flows

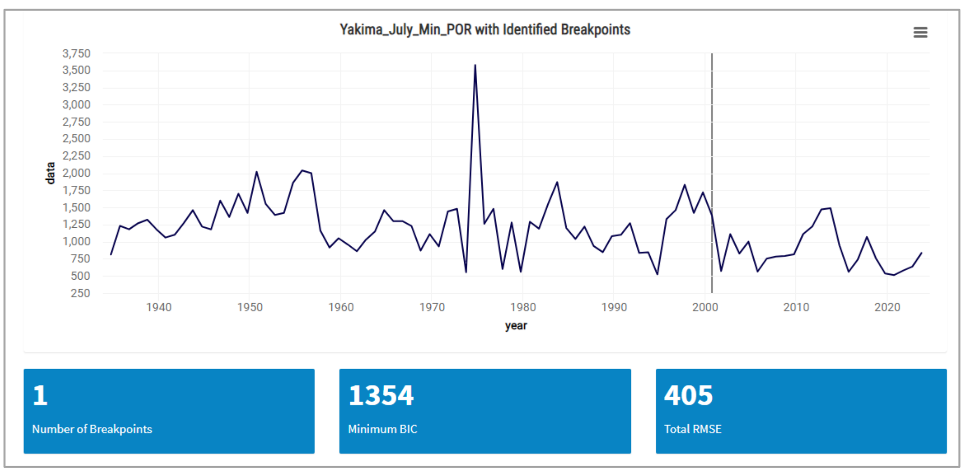
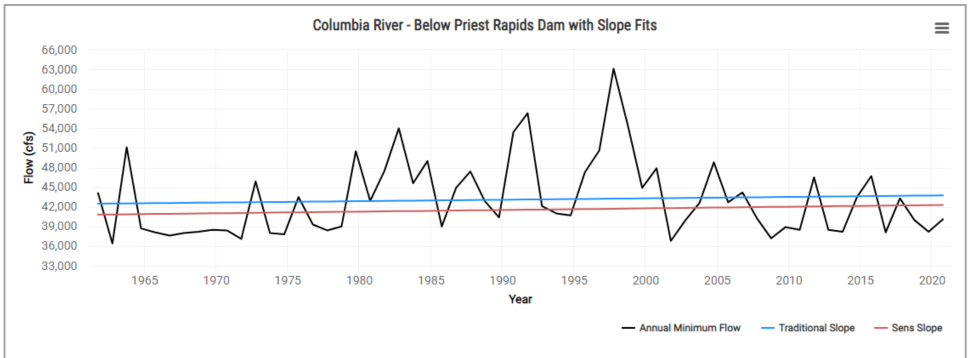


Figure A-1-38 Yakima River Minimum July Flows BA

<u>Columbia River Results</u>



Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Positive	22	269
Sen's Slope	Positive	25	-8212

Trend Hypothesis Test

Test	P-Value
t-Test	0.61794
Mann-Kendall	0.37864
Spearman Rank-Order	0.32791

- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Figure A-1-39 Columbia River Annual Minimum Flow

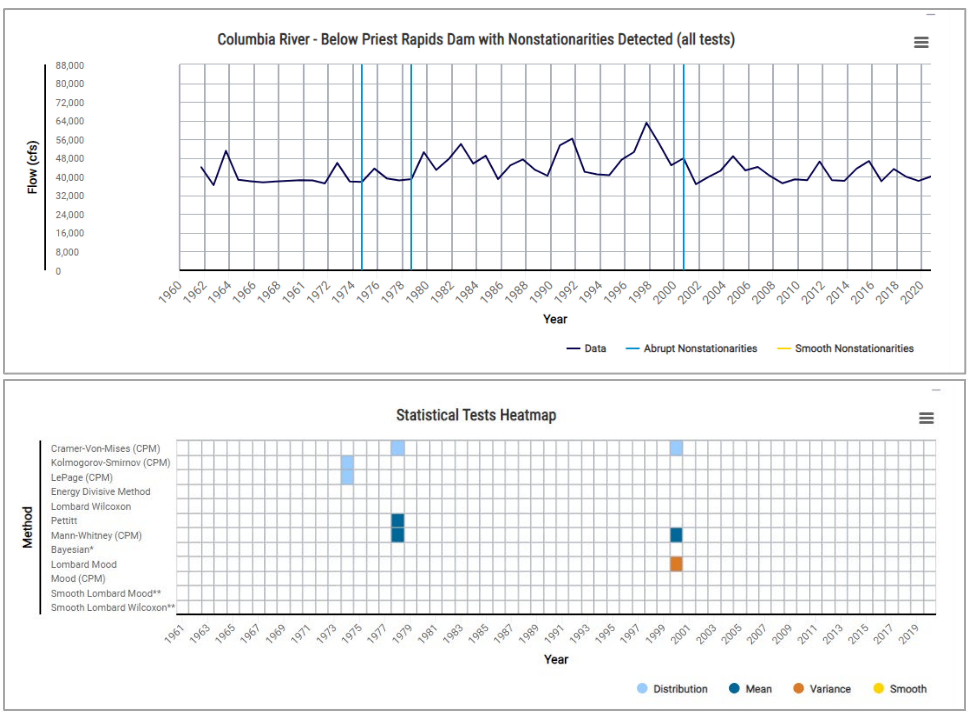
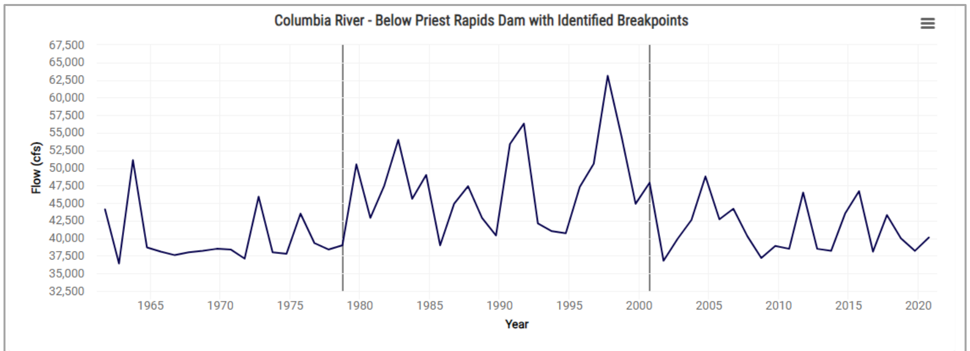


Figure A-1-40 Columbia River Annual Minimum NSD



2
Number of Breakpoints

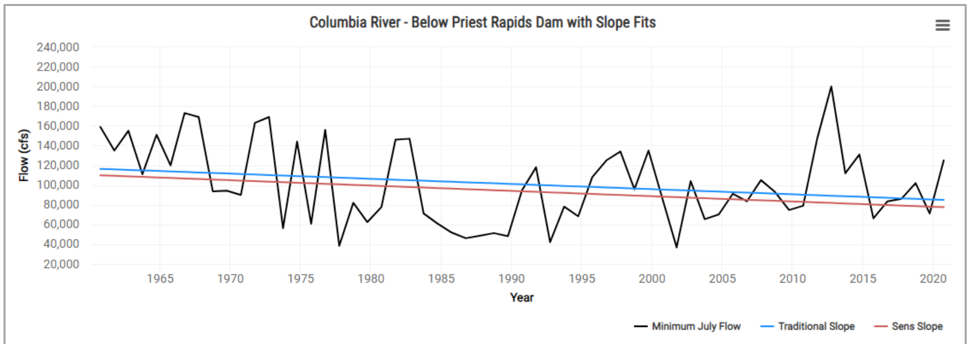
1205
Minimum BIC

4541
Total RMSE

Breakpoint Segment Details

Date Range	Slope	P-Value (Trend)	Intercept	Directionality
1960-10-01 to 1978-09-30	-124.9742	0.48478	41081.69935	Negative
1978-09-30 to 2000-09-30	240.118577	0.22317	44283.79447	Positive
2000-09-30 to 2020-09-30	-133.506494	0.3261	42940	Negative

Figure A-1-41 Columbia River Annual Minimum Flow BA



Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-524	1143729
Sen's Slope	Negative	-540	1167307

Trend Hypothesis Test

Test	P-Value
t-Test	0.071901
Mann-Kendall	0.13203
Spearman Rank-Order	0.096768

- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Figure A-1-42 Columbia River July Minimum Flows

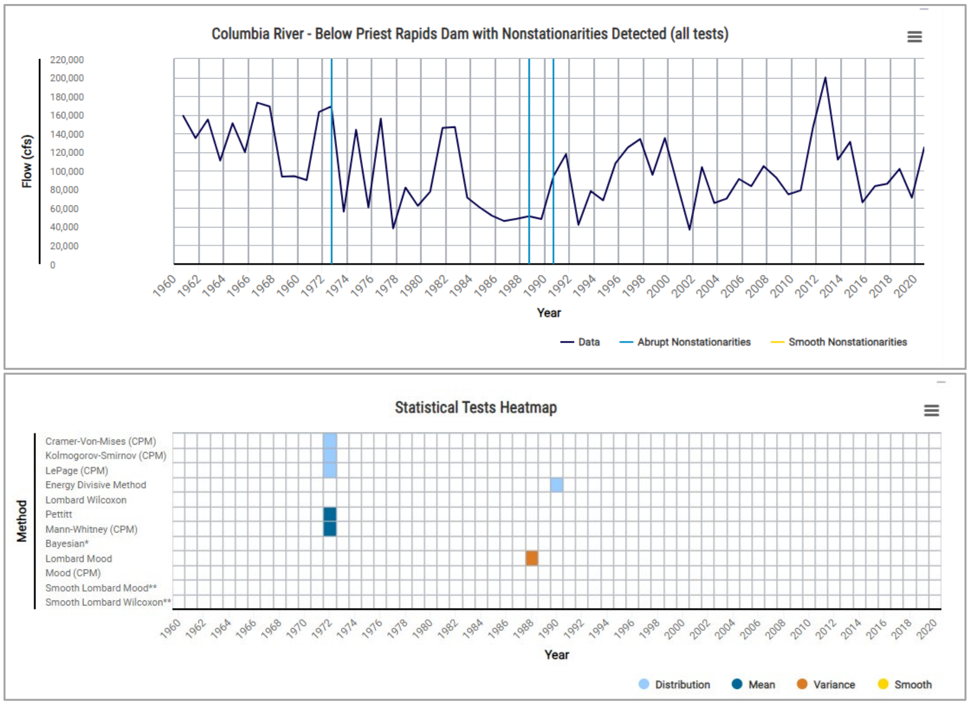
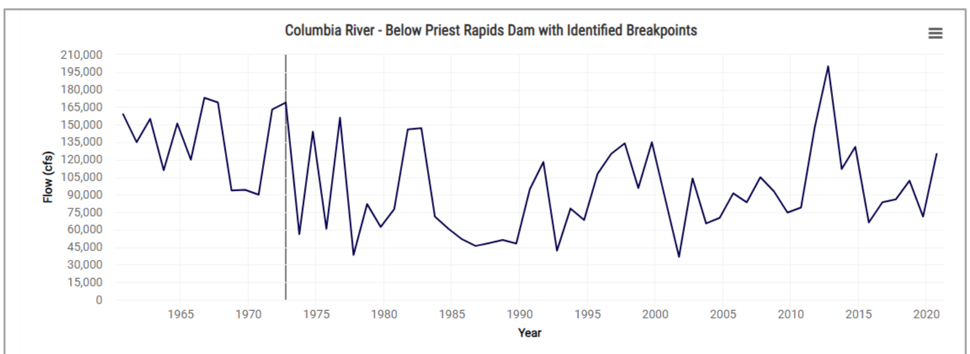


Figure A-1-43 Columbia River July Minimum Flows NSD



1 Number of Breakpoints

1466 Minimum BIC

34949 Total RMSE

Breakpoint Segment Details

Date Range	Slope	P-Value (Trend)	Intercept	Directionality
1959-10-01 to 1972-09-30	-967.032967	0.69727	143915.38462	Negative
1972-09-30 to 2020-09-30	289.734694	0.45379	85181.12245	Positive

Figure A-1-44 Columbia River July Minimum Flows BA