Royal River, Yarmouth, Maine
Section 206, Aquatic Ecosystem Restoration

Appendix F: ECB 2018-14 Analysis of Royal River Potential Climate Vulnerability

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US Army Corps of Engineers
New England District

YARMOUTH
MAINE

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EXECUTIVE SUMMARY

This assessment is performed to highlight existing and future challenges facing the study area due to climate change and is conducted in accordance with United States Army Corps of Engineers' (USACE) 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 ECB 2018-14 assessment is an evaluation of potential climate vulnerabilities facing the Royal River, conducted to support an evaluation of partial or complete dam removal and the potential improvement of fish passage, particularly the habitat for salmon, alewife, striped bass, sea-run trout, rainbow smelt, American eel, sea lamprey, and herring in the river system. The project area is located immediately upstream of the mouth of the Royal River, in Yarmouth, Maine. This assessment highlights existing and future climate change driven risks for the study area. Detailed study background information can be found in the main report, and more general background information on climate change driven risk can be found in ECB 2018-14.

Conclusions are summarized here:

1. Recent climate global, regional, and site-specific science literature indicates observed trends of rising mean and extreme temperatures. The literature is equivocal, however, on projected stream runoff trends, but the CHAT does indicate mildly increasing annual mean flows for the Royal River site. Projections indicate less snowmelt with more runoff during the spring migration season, with warmer summers and less runoff during the late summer and fall.

2. The record of Royal River annual mean flows was analyzed. There was a 17-year gap in the record from 2003-2020. There were no statistical signs of nonstationarities in the record. There was a slight trend of reducing flows year over year, but the trend was not statistically significant. For monthly streamflows, there were eight instances of nonstationarities detected in the years 1949 to 2024: two of these may have been associated with months with storms in the Royal River basin; one may have been caused by the drought of the mid-1960s; one may have been a result of a dam removal in the basin.

3. The gage record indicated a mildly decreasing trend for monthly streamflow, but with no statistical significance; the climate model forecasts for the basin indicated mildly increasing forecasts for annual mean streamflow over the 21st century, with increasing certainty for the assumption of the higher RCP 8.5 rate.

4. It is expected that by the middle of the 21st century, late-summer warming would lead to decreases in the minimum streamflows in the late summer and early fall.

5. Sea-level is known to be rising, although there is not yet consensus about the rate of change. The higher relative sea level for this ecosystem restoration project would promote fish passage from the Atlantic to upstream spawning locations. The possibility of non-native species, such as fish, shellfish and aquatic plants, entering the watershed would be aided by the rising water, and possibly also rising temperatures. Removal of dams in the river system could serve to increase flow velocities thereby limiting ingress of these species. Rising sea-levels would limit this dam-removal effect slightly.

6. The watershed is not vulnerable, in the ecosystem-restoration business line, relative to other CONUS watersheds (not in the top 20% list of vulnerable watersheds). The watershed may still be vulnerable to the impacts of climate change in an absolute sense.

7. High flows occasioned by more intense rainfall would lead to greater velocities along the Royal River and its tributaries. Partial or complete removal of dams would accentuate this effect. In general, flows are projected to increase in three seasons, becoming slightly smaller in the summer months. Intense storms are expected to become more frequent during the 21st century. The regional (HUC-specific) data do not indicate a clear climatic change underway for the basin, but there are clearly signs of increasing temperature, projected seasonal changes in precipitation, observed changes in seasonal flows, with a longer growing season and with earlier spring snowmelt and its associated high flows.

8. Extreme heavy precipitation was expected to manifest in a tripling of the frequency of storms previously designated “5-year return period storms”, an effect that was expected to be even more extreme in the New England area; changes in the monthly seasonal precipitation would likely extend the growing season but reduce the severity of spring runoff, indicating changes in seasonality.

9. Mitigation for the inland streamflow effects (warmer, drier summers and falls) is likely to be needed.

10. Although residual risk to the ecosystem restoration objectives of the project due to climate change is classified as moderate (the signs and projections of change are clear), it is likely that design of fish passage structures and shading of any exposed riverbanks can mitigate these concerns.

11. The recreational concern of dam removal generating increased sediment load and additional nuisance shoaling at the downstream boat docks is unlikely to be valid, based on knowledge of a hard rock riverbed with

minimal sediment available, and based also on comparison with dam removals described at the nearby Penobscot River.

Table 1, a brief summary of acronyms, is provided as an aid to the reader.

Table 1: Listing of Acronyms

Acronym	Meaning
°C	Degree Celsius (or degree Centigrade)
°F	Degree Fahrenheit
7Q1	A low-streamflow statistic: the 7-day annual minimum low flow, recurring on an annual basis.
7Q10	A low-streamflow statistic: the 7-day annual minimum low flow, recurring with a frequency of once in 10 years.
AEP	Annual Exceedance Probability. A value of 0.1 indicates an expected probability of once in 10 years.
BCSD	Bias Corrected Spatially Disaggregated
CHAT	Climate Hydrology Assessment Tool
CMIP	Coupled Model Intercomparison Project
CONUS	Contiguous/Conterminous/Continental United States
CoP	Community of Practice
ECB	Engineering Construction Bulletin
FIS	Flood Insurance Study (FEMA-generated report). The studies are prepared by FEMA for communities under the National Flood Insurance Program.
FEMA	Federal Emergency Management Agency, a component of the Department of Homeland Security.
FRM	Flood Risk Management
GCM	Global Climate Model (or General Circulation Model)
HUC; HUN	Hydrological Unit Class (or classification) Hydrologic Unit Name
LOCA	Local Constructed Analogs
NAVD/ NAVD88	North American Vertical Datum of 1988

Acronym	Meaning
NCIA	Northeast Climate Impact Assessment
NCA, NCA4	(Fourth) National Climate Assessment
NCA5	Fifth National Climate Assessment
NFIP	National Flood Insurance Program
NGVD, NGVD27	National Geodetic Vertical Datum of 1927
NOAA	National Oceanic and Atmospheric Administration
NSD	Non-Stationarity Detection
NTDE	National Tidal Datum Epoch
PA	Periodic Assessment
RCC	Reservoir Control Center
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RRRP	Royal River Restoration Project
SCADA	Supervisory Control and Data Acquisitions
SQRA	Semi-Quantitative Risk Assessment
TST	Time Series Tool
UMRB	Upper Mississippi River Basin
USACE	US Army Corps of Engineers
USBR	US Bureau of Reclamation
USGS	US Geological Survey
VA	Vulnerability Assessment
VIC	Variable Infiltration Capacity
WOWA	Weighted-Order, Weighted-Average

1.0 STUDY BACKGROUND

The Royal River has its origins in springs in southern Danville, Maine, flowing south and east in its course through New Gloucester, Gray, Pownal, North Yarmouth and Yarmouth to its mouth at Callen Point. The State of Maine is in Water Resource Region (i.e., HUC-2 watershed) number 01, the New England Region. At its mouth, the Royal River basin drainage basin area is 142 square miles.

The available systematic record of flows is from a gaging station near the Bridge Street Dam. Any changes in the way any upstream dams are operated might cause changes that might appear as discontinuities or nonstationarities in the record. Similarly, construction or maintenance work on dams or bridges, or changes in pumping routines for agriculture or water supply, could appear as nonstationarities. Bridges with high clearance would not cause an obvious change in the record, but changes such as installation or removal of low bridges, or temporary coffer dams, could show as potential nonstationarities. In addition, the start or end of a multi-year drought, or of a series of consecutive rainy years, might appear as a nonstationarity.

In the last 24 miles of the river's course (to the border with Androscoggin County), there are inflows from:

- Natural springs in northern New Gloucester, bordering on Poland ME, partly regulated by Jordan Mill Dam, approximately 24 miles upstream of East Elm Street in Yarmouth;
- Meadow Brook, 19.7 miles upstream of East Elm Street in Yarmouth;
- Stevens Brook, approximately 19 miles upstream of East Elm Street (inflows from Stevens Brook are regulated at one unnamed dam);
- Bear Brook, 16.6 miles upstream of East Elm Street;
- Collyer Brook, 11.9 miles upstream of East Elm Street, partly regulated by the Pownal State School Dam, and by an unnamed dam on the Eddy Brook tributary; and
- Chandler River, 6.0 miles upstream of East Elm Street, partly regulated by Florida Lake on the Collins Brook tributary, and partly regulated by Runaround Pond Dam on the Alder Brook tributary.

In Yarmouth, there are dams immediately downstream of North Elm Street (3 miles upstream of the confluence with Casco Bay) and immediately upstream of Bridge Street (2.2 miles upstream of the confluence with Casco Bay).

There are four sets of rapids along the Royal River in the last mile of its course to Yarmouth Harbor in the sheltered Casco Bay region of the Gulf of Maine, which is a region of the Atlantic Ocean extending along the North American coastline from Cape Cod in Massachusetts to Nova Scotia and New Brunswick in Canada. These rapids are numbered First through Fourth, with the Fourth being the farthest upstream and the First being the closest to the ocean.

At the **First Falls** of the Royal River, at Grist Mill Park, the river falls approximately 10 feet over a distance of 200 feet, and the river power had been used at this location for mills since 1674 and later for hydroelectric power. This dam is no longer in use, and it does not appear in the FIS for the county.

At **Bridge Street**, there is a more significant run-of-river dam in Yarmouth at the **Second Falls** of the Royal River, creating the Royal River Reservoir that extends upstream approximately 1800 feet to the Third Falls. The location has provided power for the material industry since 1847. The reservoir has a maximum depth of 25 feet under normal conditions, with a normal impounded volume of approximately 100 acre-feet. There is a functional hydroelectric facility at the dam, although the facility is reportedly not in use. There is a fish ladder structure at the dam, designed to promote fish passage by allowing for fish passage of 25 feet vertically over a distance of 90 feet.

The **Third Falls** has powered a grist mill, carding mill, nail mill, soda pulp-and-paper mill. Following a fire in 1931, the complex fell into disuse and the remains of the buildings existed until they were removed by the Marine Corps in 1971. The dam does not appear in the FIS for the county.

The **Fourth Falls** of the Royal River is located 900 feet upstream of the Third Falls, at Gooch Island. A dam at this location has been used to supply water and power for local industries.

USACE recognizes a need to review sea-level rise for projects that lie at or below elevation 50 feet NAVD. The 50-ft NAVD limit is reached in a river reach downstream of the dam at the Fourth Falls and but upstream of the impoundment behind the Bridge Street Dam (essentially, the 50-ft limit is at the location of the Third Falls). This is 900 feet downstream of the dam at the Elm Street Bridge, or 2.7 miles upstream of the Royal River’s confluence with Casco Bay.

Upstream of the four waterfalls, the water elevations are above 70 feet NAVD and so are clearly above the likely influence of storm surges and tides in the Atlantic Ocean.

Ecosystem restoration is the focus of this analysis because the project seeks to improve and create habitat primarily through improved fish passage from the Atlantic, upstream into the Royal River. Future climate conditions may impact the establishment and design of project features. USACE 2015 reviews Hayhoe et al 2007, noting a range of flow measurements from annual peak flows to 7-day annual minimum flows, with emphasis on departures from “normal” flow.

Reference is made to studies in the Upper Mississippi River Basin (UMRB) and in Quebec, Canada. The UMRB study speaks to the kinds of information that are pertinent to ecosystem restoration studies in general; the Quebec studies extend this line of thinking but are based on basins much nearer to the Royal River site (approximately 200 miles north of Yarmouth ME).

UMRB notes: Rajib et al (2020) noted the importance of the UMRB as a potential source of almost half the average annual nitrogenous pollution to the Gulf of Mexico, exacerbating seasonal hypoxic conditions, largely because the UMRB region includes significant agricultural activity, and drains 15% of the Mississippi River Basin, which covers 40% of the contiguous land area of the United States.

Quebec notes: Both Beaupre et al (2020) and Assani et al (2023) reviewed applications of mean and elevated flows in evaluating the surface storage method for basins in southern Quebec, approximately 200 miles north of Yarmouth ME. Beaupre et al (2020) noted that temperature measurements alone are a powerful predictor of thermal stress of a fish habitat. Assani et al (2023) reviewed annual mean flows, normalized as specific flows (flow per unit drainage-basin area), finding that exceedances, measured in days per year, of the lower-intensity flow of the 2-year event was a useful predictor of stressed environments. More extreme flow rates were estimated, up to the 50-year frequency/ 0.02 Annual Exceedance Probability (AEP) flow, but these proved less useful in the estimates (the more frequent, less extreme, departures from mean values were more useful).

This pattern in Quebec is echoed in the findings of the U.S. Geological Survey (USGS) in their 2022 report, *Ecological Status and Trends of the Upper Mississippi and Illinois Rivers* (Van Appledorn M. (2022), that hydrologic indicator variables most relevant to the ecological health of a watershed are annual discharge (maximum, mean, and minimum), duration of high discharges (exceeding the 20% annual exceedance probability (AEP) discharge), and monthly mean discharge. Thus, to analyze the effects of climate change on ecosystem restoration features for this study, the annual average and mean monthly streamflow records are evaluated since they are representative of flows impacting project features throughout the year.

For the Royal River in Yarmouth ME, the Town of Yarmouth developed a Royal River Restoration Project (RRRP) in conjunction with their contractor Stantec Consulting Services Inc. Although improved fish passage was a stated objective of the RRRP, there was also concern over sedimentation and dredging needs in the Yarmouth ME harbor. Phase II of the RRRP study was released in 2013 (Stantec 2013). The Phase II report noted a need in 2013 to dredge between 40,000 and 70,000 cubic yards (cy) of material (an estimated quantity) since the previous (1995) dredging exercise. The 2013 report noted, based on chemical sampling performed at the time, that sediments that might be released in removal of the dams were unlikely to create risk of adverse effects to aquatic life. GZA (2018) reported an estimated 100,000 cy behind the Elm Street Bridge, but only 6,000 cy behind the Bridge Street dam. Observations by Stantec in 2023, reported in January 2024, and separate observations by a USACE field team in 2023, indicate that these estimates are likely excessive, and the actual quantities of sediment are smaller (qualitative assessment indicated “significantly smaller”).

The RRRP Phase II report documented values for the 7Q10, annual mean flow, annual median flow, noted changes in the hydrology in the river, mean and median monthly flows, flow-duration statistics for two possible migration windows (mid-May-to-mid-June and the two-month period May through June) and reviewed the available peak-flow record 1950 through 2002, noting a marginal increase in annual peaks in the more recent period 1970-2002. The “marginal increase” amounted to 10 to 20 percent for the more frequent return periods (up to the 5-year event), while the 32 years post-1970 showed increases of 20% to 75% over the values estimated from the values 1950-1970. For Stantec’s purposes, the more extreme annual peaks were taken as valid, while the years 1950 to 1970 were ignored in their estimates of peak flow return frequencies, consistent with the findings of Collins, M.J. (2009).

Hodgkins and Dudley (2013) in a study of annual peak streamflows in four coastal river systems in Maine, including the Royal River, took into account potential changes in air temperature (-3.6 °F to +10.8 °F) as well as possible changed (-15% to +30%) precipitation patterns in hydrological estimation procedures, to generate estimates of climate-changed 2-year and 100-year (50% AEP and 1% AEP) flows, as a means to prepare for conditions in the northeastern United States in the middle of the 21st century. Like Stantec, the Hodgkins and Dudley (2013) report referenced Collins, M.J. (2009), since Collins had noted an apparent sudden increase in the observed annual peak flows, noted as a “step change” beginning around 1970. The timing of the change coincides with the ending of the “sixties drought” in New England.

The Royal River watershed is shown in the map in **Figure 1**.

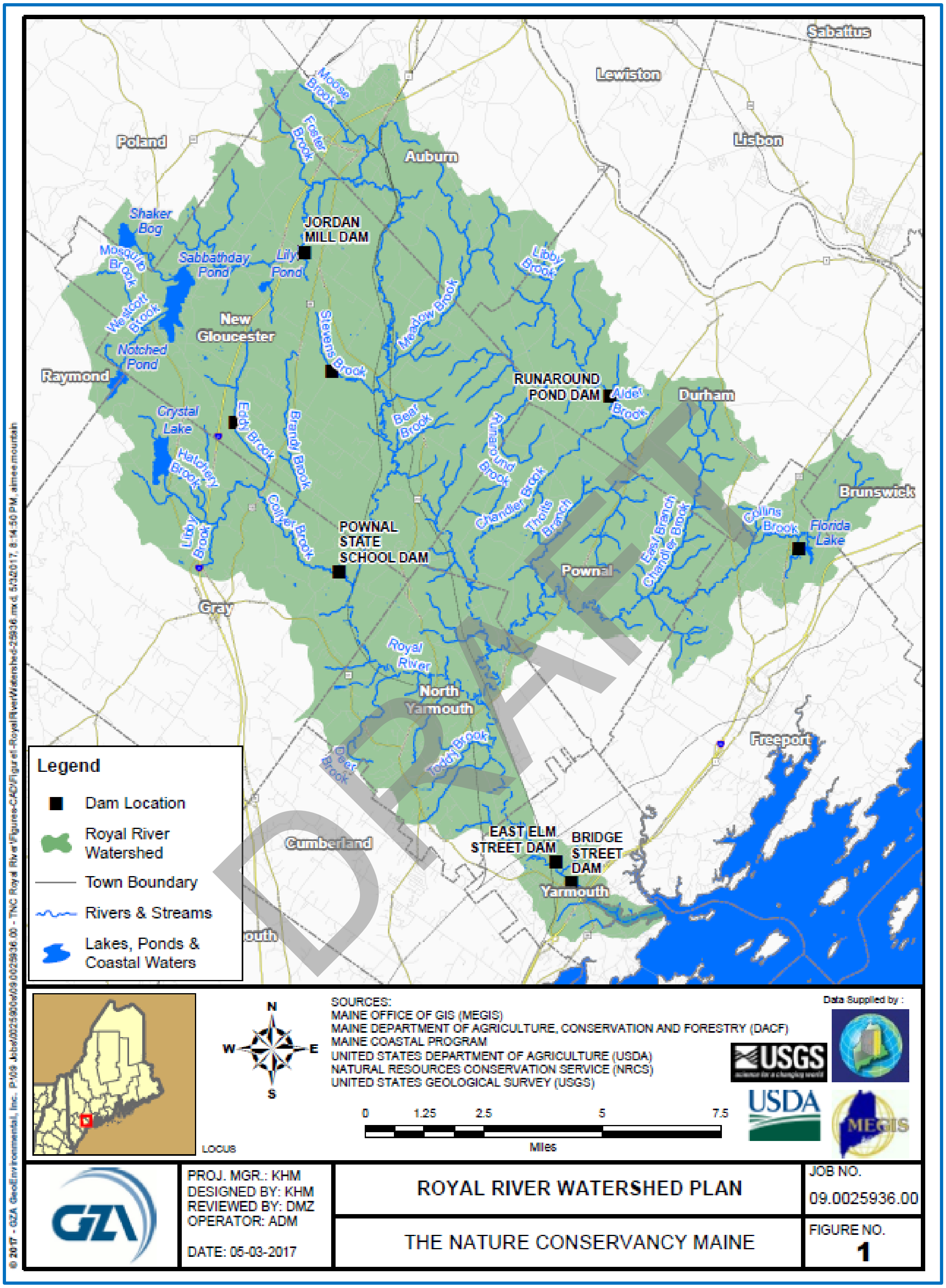


Figure 1: Royal River Watershed (from GZA, 2018)

Downstream of the Royal River mouth is a bay area that includes a boat club with moored boats. This community, primarily the owners of the mooring facilities, has expressed a concern that additional sedimentation might occur in the event of any dam removals. The marinas have indicated that they routinely conduct dredging operations. Stantec (2013) noted that dredging had been performed in 1995 and was required again (almost 20 years later), based on boat handling conditions around the marina.

This assessment was performed to highlight existing and future challenges facing the project due to past and future climatic changes, in accordance with the guidance in Engineering Construction Bulletin (ECB) 2018-14, revised 10 Sep 2020. Background information on the project can be found in the main report; background information on climate-affected risks to projects and assessments thereof can be found in the ECB.

2.0 LITERATURE REVIEW

The Royal River is in the Presumpscot Basin (HUC-8 watershed 01060001) which is in the Saco River Basin (HUC-4 watershed 0106). The reach selected for review by the CHAT tools was not at the mouth of the river, but the next reach upstream of the mouth, at Stream Segment 01000915, which is flagged by the CHAT as potentially influenced by ocean effects (tides, storm surge, relative sea-level change). The Hydrologic Unit is located entirely in Water Resource Region (i.e., HUC-2) watershed number 01, the New England Region. Given the ecological restoration objective of the project, climate variables of greater concern include changes in temperature, precipitation, river flow, and seasonality of flows. Changes in the average and/or median values of streamflow, and any increases in drought frequency probability, and sensitivities to temperature-changes, are of greater concern than changes in the frequencies of extreme high flows.

The fifth National Climate Assessment (NCA5) was released in 2023. It reviewed recent trends in published observed temperatures, precipitation, and the results of projected future climate conditions based on the outputs of Global and Regional Climate/Circulation Models (GCMs and RCMs). The NCA5 included reviews of how forests, urban development, and oceans were being affected, and how ecological and societal systems were adapting, or were projected to need to adapt, to changes in the environment. The NCA5 included regional reports in chapters dedicated to each of ten broad regions of the United States. These included a report on the Northeast, which included the six New England states as well as New York, New Jersey, Philadelphia, Maryland, West Virginia, Delaware, and Washington DC.

A January 2015 literature synthesis conducted by the USACE Institute for Water Resources (USACE 2015b) summarizes the available climate change literature for this region, covering both observed and projected changes. These include temperature, precipitation, and streamflow. Dupigny-Giroux, L.A. et al (2018) reviewed climate changes in progress in the United States in a report widely referred to as simply the fourth National Climate Assessment (NCA) or NCA4. The NCA5, the USACE literature synthesis, and NCA4 are major sources of the information referenced in this literature review. The focus of these references is on summarizing trends identified within historical and observed temperature, precipitation, and streamflow records, as well as providing an indication of future hydrometeorology based on the outputs from Global and Regional Climate/Circulation Models (GCMs and RCMs). In this assessment, background on observed and projected temperature and precipitation is provided as context for the impact they have on observed and projected streamflow.

The NCA4 considers climate change research at both a national and regional scale (USGCRP, 2018). *Civil Works Technical Report CWTS-2015-20* was published as part of a series of regional summary reports covering peer-reviewed climate literature. The 2015 USACE Technical Reports cover 2-digit, United States Geological Survey (USGS), hydrologic unit code (HUC) watersheds in the United States (U.S). Yarmouth ME is located in 2-digit HUC 01 the New England Region (USACE, 2015), and in the NCA4 Northeast climate region.

In many areas, temperature, precipitation, and streamflow have been measured since the late 1800s and provide insight into how the hydrology in the study area has changed over the past century. GCMs are used in combination with different representative concentration pathways (RCPs) reflecting projected radiative forcings up to year 2100 to model future climate. Radiative forcings encompass the change in net radiative flux due to external drivers of climate change, such as, for example changes in carbon dioxide or land use/land cover. 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 (Graham, Andreasson, and Carlsson, 2007). 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).

3.0 TEMPERATURE

3.1 TEMPERATURE OBSERVATIONS

The NCA5 Ch 2 (Marvel K. et al, 2023) reports a trend of fewer days below freezing (6.7 fewer days per year in the Northeast Region) and 2.1 more warm nights (above 70 deg F) per year. There were 1.3 fewer hot days reported for this region, when the period 2002-2021 was compared to the period 1901-1960. **Figure 2** was provided to illustrate the point:

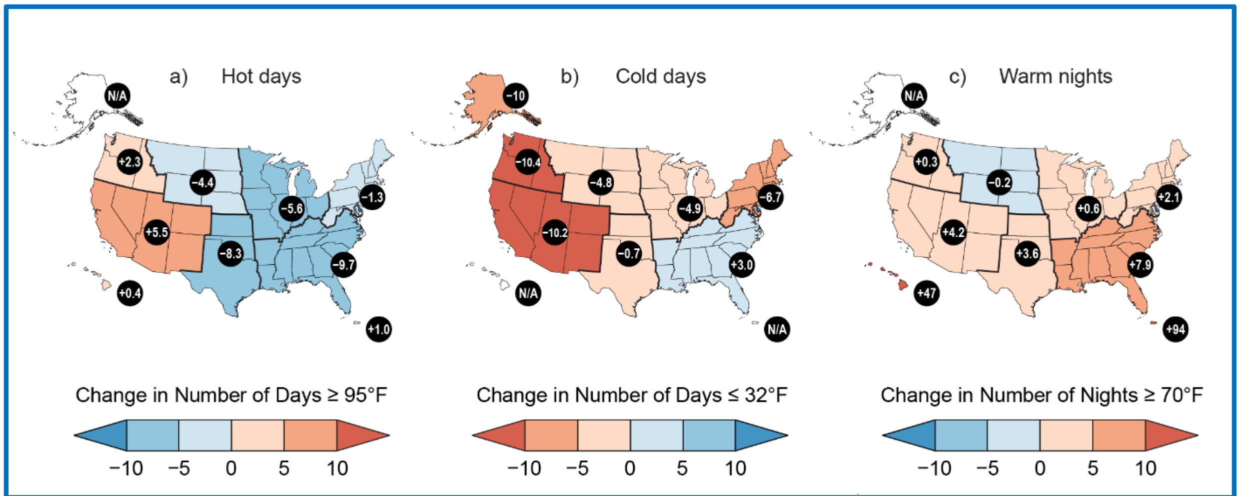


Figure 2: Observed Changes in Hot and Cold Extremes 1901 to 2021

Observed changes in annual average temperature for the Northeast Region have increased by 1.43 °F for the 1986-2016 period relative to the 1901-1960 period. Observed annual average maximum and annual average minimum temperature has increased by 1.16 °F and 1.70 °F in the Northeast region, respectively (NCA4, as Dupigny-Giroux, L.A. et al (2018)). Observed increases in temperature in the Northeast Region (New England, New York State, Pennsylvania, and New Jersey), including statistically significant increasing trends, have been reported in numerous studies (Hayhoe et al (2008); Burakowski et al 2008; the Northeast Climate Impacts Assessment (NCIA) (Frumhoff et al, 2007); Brown et al (2010); Huntington et al (2009)). These included increases in summer temperatures, an average increase of temperature of 1.5 °C during the 20th Century, and a doubling of the number of days per year exceeding 32 °C (90 °F) since 1970.

More specifically, in New England, a general warming trend has been observed, with a rising trend of 0.8 °C to 3.0 °C per century, although two studies also detected a cooling trend for the months of December to February. Spring warming since 2001 appears to be occurring 0 to 4 days earlier than it did during the 1950's, which indicates a potential change in seasonality. In a review of 361 station records over the period 1930 to 1996, only 4 stations had records of decreasing temperatures, and none of these results was statistically significant. These studies are included in Wang et al (2009); Westby et al (2013); Meehl et al (2012); Schwartz et al (2013); DeGaetano et al (2002); Horton et al (2014).

Trombulak and Wolfson (2004) reviewed temperature data at 36 locations in New England and New York State for 1903-2000, reporting an average increase of 3 °C per century for the region, without reporting on significance. For the Royal River location in southern coastal Maine, the interpolated rate of temperature-change appeared to be 1° C to 2° C per century (See **Figure 3**).

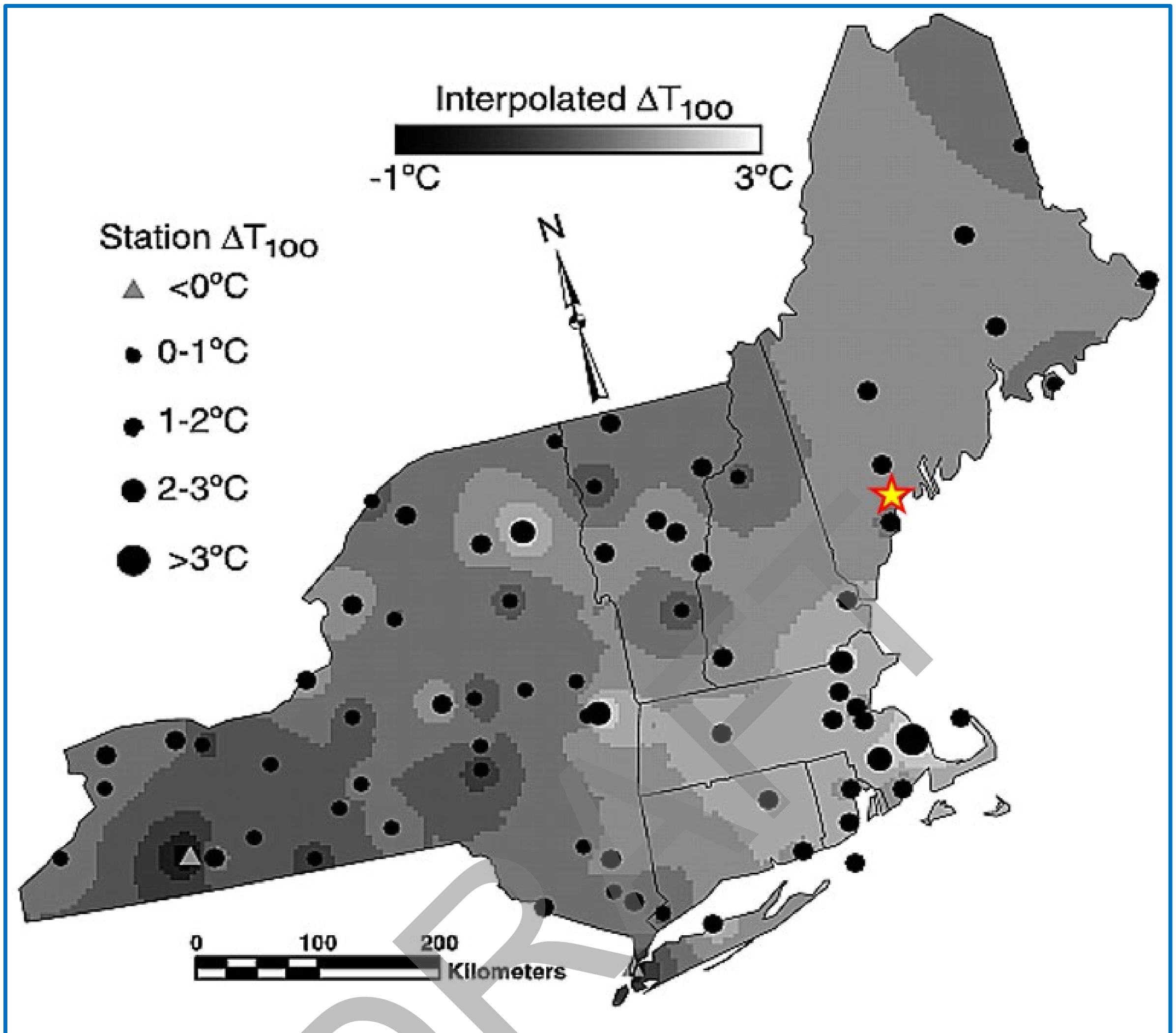


Figure 3: Trombulak and Wolfson 2004 Review of Temperature Changes in the New England - New York Region. The Royal River location is shown with a red star symbol.

3.2 TEMPERATURE PROJECTIONS

The NCA5, in Marvel et al 2023, reported that warming in the US was expected to be greater than the global average during the balance of the 21st century. They reported results of projections based on assumed increases of 1.5, 2.0, 3.0 and 4.0 °C (2.7 to 7.2 °F). For the case of a 2.0 °C (3.6 °F) global rise, they presented the maps shown in **Figure 4**.

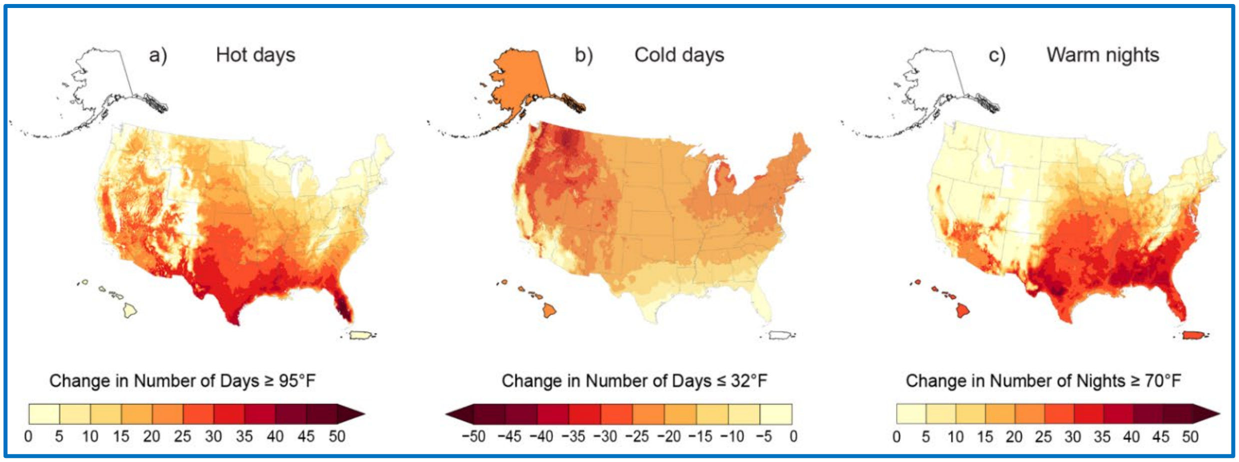


Figure 4: Projected Changes to Hot and Cold Extremes at 2 °C of Global Warming (*relative to the period 1991-2020*)

For southeastern Maine, by the end of the 21st century, under this 2 °C global warming case, there would be up to 5 more days per annum of temperatures above 95 °F; about 20 fewer days of temperatures below freezing; and up to 5 more nights of temperatures above 70 °F.

NCA4 (Dupigny-Giroux, L.A. et al (2018)) reviewed temperature changes and projections of temperature-change for 7 regions of the US. For the Northeast, they reported on average, minimum, and maximum temperatures and how these were expected to differ from "near-present" (1976-2005) conditions as projected by 32 climate models, under two sets of assumed inputs, during the 21st century. Time periods examined were for mid-century (2036-2065) or late-century (2071-2100). The average temperatures were expected to rise 4.0 to 5.1 °F by mid-century and by 5.3 to 9.1 °F by late-century.

For temperature extremes, NCA4 reported results for the mid-century (2036-2065) as these were projected to have shifted from the 1976-2005 conditions. For the Northeast, the change in the warmest day of the year was expected to be 6.5 °F; the change in the coldest day of the year was expected to be 9.5 °F. For 5-day periods, the 1-in-10 year coldest spell was expected to be 15.9 °F warmer; the 1-in-10 year warmest spell was expected to be 12.9 °F warmer.

For projections, global climate models, also known as General Circulation Models or GCMs, are used to simulate future weather conditions. Scherer and Diffenbaugh (2014) used varying assumptions about emissions to model conditions in the United States: their results for New England indicated increased summer and winter temperatures of 5.2 °C (9.4 °F) and 1.7 °C (3.1 °F).

NOAA has published a set of individual state climate summaries containing information on historical climate variations and trends, future climate model projections of climate conditions, and past and future conditions of sea level and coastal flooding. Regarding temperatures in Maine, NOAA reported as follows (Runkle et al 2022):

“Temperatures in Maine have risen almost 3.5 °F since the beginning of the 20th century. Winter temperatures have been increasing about twice as fast as summer temperatures. Under a higher emissions pathway, historically unprecedented warming is projected during this century.”

NOAA reported winter warming, measured as the number of very cold winter nights, which had been reducing since the 1990s. The number of hot days had not increased. Lakes were experiencing earlier ice-out dates: the example given was Damariscotta Lake, in which ice-out happened in mid-to-late April in the mid-20th century, but the typical current (2020, 2021) ice-out date was in early April, while the growing season had lengthened.

Figure 5 provides a summary of the expected changes. Historically unprecedented warming is projected to continue (higher emission) through the 21st century. Less warming is expected under a lower emissions future (the coldest years being about 2 °F warmer than the historical average; green shading) and more warming under a higher emissions future (the hottest years being about 12 °F warmer than the hottest year in the historical record; red shading).

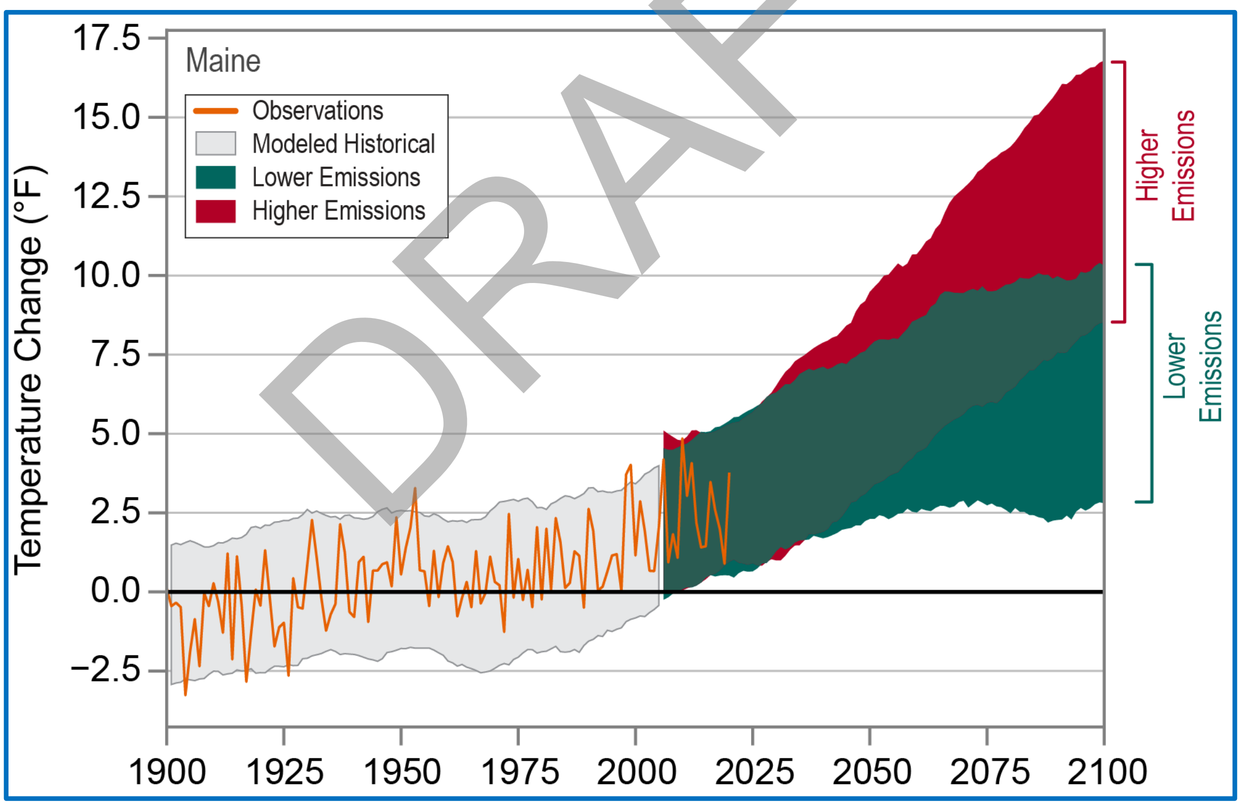


Figure 5: Observed and Projected Temperature Change in Maine
(*Source: NOAA State Climate Summary 150-ME*)

3.3 TEMPERATURE: OCEAN OBSERVATIONS AND PROJECTIONS

In a review of how climate change is affecting the Gulf of Maine, Skerry (2024) cited researchers at universities and research facilities in the New England region (*Gulf of Maine Research Institute, University of New England, Bigelow Laboratory for Ocean Sciences, University of New Hampshire, Shoals Marine Laboratory, New Hampshire Fish and Game Department, Brown University*) to document how the rising temperatures are causing changes in currents and leading to more acidic conditions. The lead author of one of the referenced papers (Pershing et al, 2015) had been at the *Gulf of Maine Research Institute* at the time of acceptance by the journal *Science*, but Pershing had moved to the *Woods Hole Oceanographic Institution* in Massachusetts by the time of the publication. The temperature changes are causing fish (example, butterfish) from farther south to move north, where terns were mistaking butterfish for hake and herrings and trying with extremely limited success (less than 20%) to feed them to hatchling terns.

Removal of dams on the Presumpscot and the Penobscot had led to the resurgence of alewife population in the Gulf of Maine, as evidenced by Skerry at Mill Brook Preserve in the Presumpscot river basin.

The lobster industry had suffered of the coasts of New York, Connecticut, and Rhode Island; this effect seemed to be moving north, in that 2023 was the worst lobster haul in 15 years. Female lobsters are staying off-shore when the temperature rises above 73 °F so that younger lobsters can feed on the Calanus zooplankton: the effect is to separate the adults by sex, reducing opportunities for mating. At the same time, the increasing acidity is leading to weaker exoskeletons in lobsters and mussels, and the lobsters are hampered in their ability to smell in general, such that finding food or finding a mate is becoming more difficult for them.

The population of green crabs, a non-native species that entered the region accidentally through ships' ballast water in the 1800's, is increasing with the recent milder temperatures, and they are coming to be viewed as an addition to restaurant offerings.

3.3.1 Temperature: Ocean Observations and Projections NCA5

The NCA5 in Mills et al (2023) reported that the mix of fishing and tourism along the Maine coast ranges from primarily fishing near the border with Canada to primarily tourism near the border with New Hampshire. The Royal River site falls nearer to the "tourism" extreme of the mix. Mills et al (2023) noted sensitivities of water to harmful algal blooms (HABs), increases in pathogens, loss of sea ice limiting access to resources, and HABs that make food sources such as razor clams, Pacific walruses and bowhead whales unsafe for human consumption. Sensitivities to ocean warming were noted in "blue carbon" ecosystems, such as coral reefs, seagrass and seaweed beds, mangrove forests, and tidal marshes, any of which would be exacerbated by background risks such as habitat degradation or resource overexploitation. The authors noted that on the East Coast, the northern shrimp fishery collapsed and a fishing moratorium was imposed following a marine heatwave in 2012, and the highest-valued single-species fishery in the US, American lobster, had seen the southern portion of its population decline to very low levels with warming waters.

Climate change was expected to reduce catch in all US regions, including American lobster and Atlantic sea scallops. The losses of “billions of dollars” per annum through 2100 were expected to be twice as high under the RCP8.5 scenario as under the intermediate RCP4.5 scenario.

3.3.2 Temperature: Ocean Observations and Projections NCA4

The NCA4 (2018) reported that ocean and coastal temperatures along the Northeast Continental Shelf had warmed by 0.06 °F per year (0.033 °C/yr) over the period 1982-2016, or three times faster than the global average of 0.018 °F/yr (0.01 °C/yr), while the rate appeared to have increased more recently (2007-2016) to 0.25 °F/yr (0.14 °C/yr) or four times the global rate. In parts of the Gulf of Maine, the duration of summer-like sea surface temperatures had increased by 2 days per year since 1982.

The NCA4 anticipated changes in tourism activities such as fishing and whale watching, if observed changes in fish and invertebrate species were to continue. Northern species such as northern shrimp, surf clams, and Atlantic cod were declining as waters warmed, while species such as black sea bass were experiencing increased productivity. The balance between species had been changing; increasing shell disease in lobsters and pathogens in oysters were known to occur in warmer water, and some shellfish pathogens were expected to pose risks to human health. The NCA4 noted that in addition to Atlantic cod and Atlantic American lobster, there were also already-threatened species like Atlantic sturgeon, Atlantic salmon, and right whales, that were expected to be further threatened by climate change.

Figure 6 presents a summary of these temperature-related changes with respect to Atlantic cod, American Lobster, Gulf of Maine - Georges Bank Lobster, Southern New England Lobster, Gulf of Maine Cod, and Black Sea Bass.

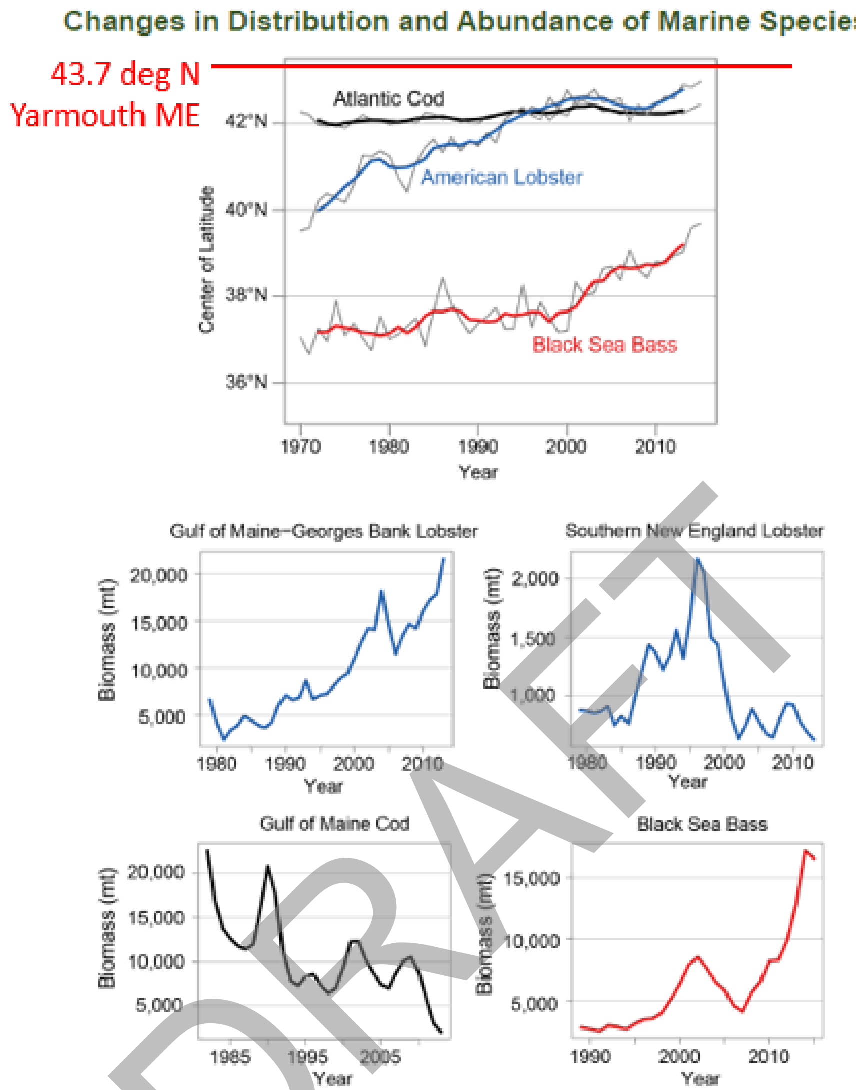


Figure 18.6: The figure shows changes over time in geographic distribution (top panel) and biomass (four bottom panels) for various marine species along the Northeast Shelf. As waters in the region have warmed, the spatial distributions of many fish species have been shifting northward, while population trends of several marine species show more variability over time. The top panel shows shifts in spatial distribution over time for select fish species, based on their latitudinal centers of biomass. The four panels on the bottom show biomass estimates for the same marine resource stocks. Gulf of Maine cod, a coldwater species, has not shifted in location but has declined in biomass, while black sea bass (a warmwater species) has moved northward and increased in biomass as waters have warmed. The lobster distribution shift reflects declines in productivity of the southern stock and increasing biomass of the northern stock. Sources: (black sea bass) adapted from Northeast Fisheries Science Center 2017;[204] (all others) Gulf of Maine Research Institute.

Figure 6: NCA4 Summary Charts: Changes in Distribution and Abundance of Marine Species - Northeast USA. Latitude of Yarmouth ME is Shown with a Red Line in the First Chart

4.0 PRECIPITATION

4.1 PRECIPITATION OBSERVATIONS

The NCA5 reported in Whitehead et al 2023 that both total precipitation and precipitation intensity extremes appeared to be rising throughout the Northeast United States. This is illustrated in the four charts shown in **Figure 7**.

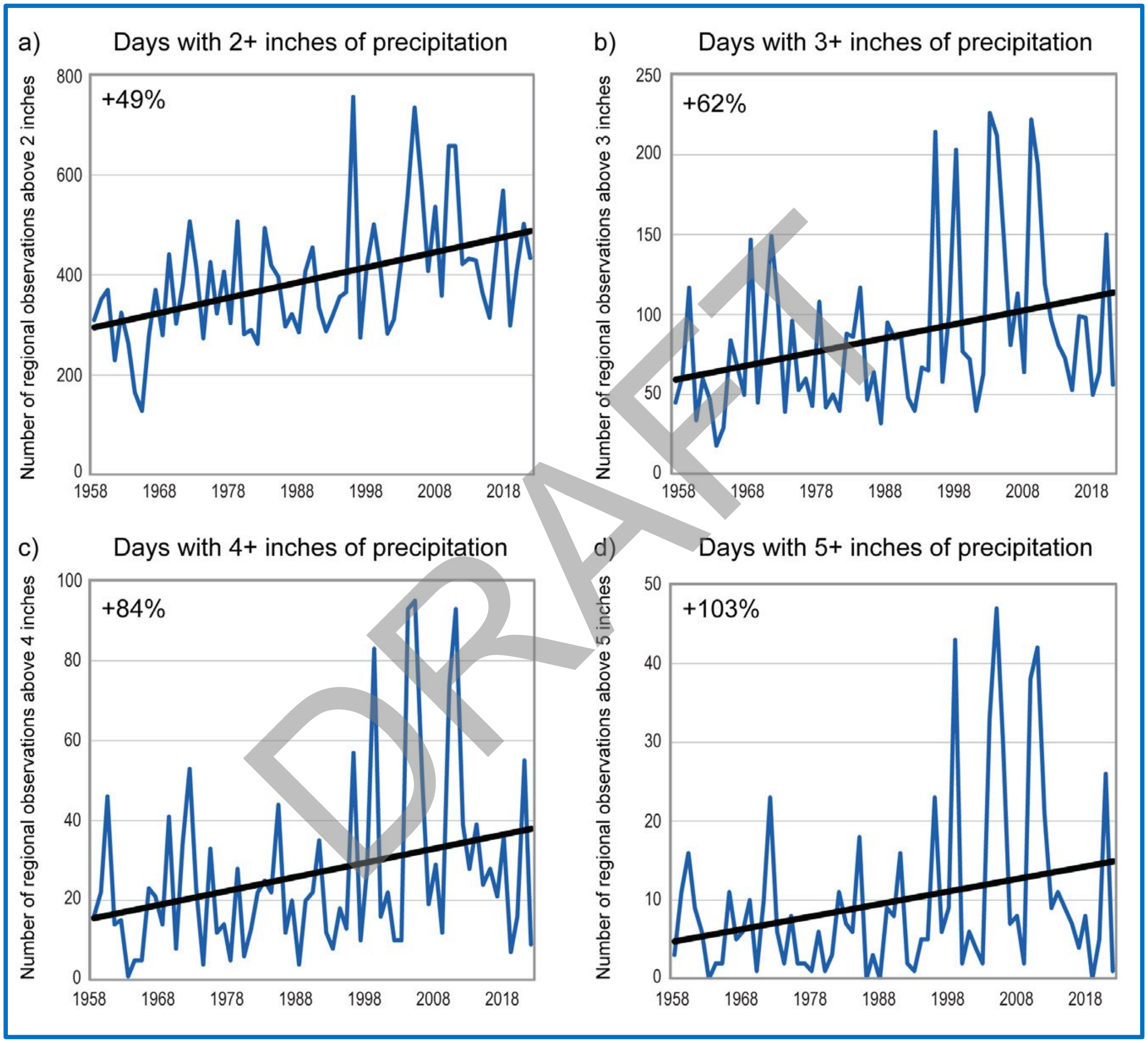


Figure 7: Trends in Extreme Precipitation in the Northeast

The NCA5 noted that the percent increases noted in the top left corner of each chart were measured relative to the average result for the period 1958 to 2022. For the number of 2-inch-precipitation days, the 49% total corresponds to an increase in 1958 to 2022 of 98% (essentially, a doubling of the frequency of these events). For 3-inch, 4-inch, and 5-inch-precipitation days, the frequencies were even higher.

The NCA5 noted also that the frequency of droughts had decreased in the Northeast over the years 1901 to 2015. They reported also that heatwaves had been lasting longer, were more severe, and were increasing heat stress, especially in densely populated areas.

NCA4 (Dupigny-Giroux et al, (2018)) summarized changes that were observed over a period of 115 years from 1901 to 2016, for a grid of latitudes and longitudes that covered the contiguous United States. Maximum daily precipitation was reviewed for this grid, and it was noted that the 20-year-return-level precipitation had increased in each of the four seasons for the Northeast Region. The total increase in inches for winter was 0.08 inches; for spring 0.25 inches; for summer 0.16 inches; for fall 0.23 inches.

The same database was reviewed to demonstrate that the size of a 5-day maximum daily precipitation had increased over 1901 to 2016 by 27% in the Northeast, and noted that the frequency of exceedances of the 5-year 2-day precipitation (as it had been at the start of the observation period) had increased by 74%, in the Northeast during this period; when the shorter, more recent period 1958 to 2016, was reviewed, the percentage increased from 74% to 92%. The 99th percentile annual 1-day precipitation had increased by 55% for the Northeast for the period 1958 to 2016.

Observations of summertime weather indicated that although extratropical cyclones seemed to be becoming less frequent since 1979 (by 35%), the associated intensity appeared to be increasing.

In its Volume II, the NCA4 noted recent increases in rainfall intensity throughout the Northeast, with expected increases in monthly precipitation of about 1 inch during the months December through April by 2100. Although annual minimum streamflows had increased over the previous century, it was expected that late-summer warming might lead to decreases in the minimum streamflows in the late summer and early fall by the middle of the 21st century.

NCA4 also noted that larger cities in the Northeast are deliberately planning to mitigate impacts of more frequent flooding and named Portland ME (10 miles southwest of Yarmouth) among these cities.

Hayhoe et al (2008) reviewed data in the 20th century, developing an estimate for New England of a 5-mm (0.2 inch) per day increase in precipitation, with more intense storms (10 to 15%) occurring more often (12 to 13% more per year), and the wettest annual 5-day period expected to contain 20% more volume by the end of the 21st century.

NOAA has published a set of individual state climate summaries containing information on historical climate variations and trends, future climate model projections of climate conditions, and past and future conditions of sea level and coastal flooding. With respect to precipitation in Maine, NOAA reported as follows (Runkle et al 2022):

"Precipitation since 2005 has averaged 6.6 inches more than during 1895-2004. The number of extreme precipitation events has been near to well above average since 2005 and is projected to increase during this century."

4.2 PRECIPITATION PROJECTIONS

NCA4 (Dupigny-Giroux et al, (2018)) reviewed modeling results that indicated increases in precipitation in the New England region of about 10% in all four seasons. They reference Janssen et al. 2016, in a review of modeling results, and summarized the following: extreme heavy precipitation was expected to manifest in a tripling of the frequency of storms previously designated "5-year return period storms" throughout the US, with the greatest increases being in the Northeast. The projected size of a "20-year" storm was projected to increase by 10 to 13% by mid-21st-century, and by 14 to 22% by late-21st century, for the New England region. Trends associated with hurricanes were less clear from the modeling.

Thibeault and Seth (2014) assumed a high greenhouse gas emissions scenario to develop projections for the Northeast Region, some of which had statistically significant increases of 1.5 mm/day. Rawlins et al (2012) reviewed data since 1971 to develop projections of increases in precipitation through 2070 in New England of 12% in winter, 10% in spring; -2% (less rainy) in summer; and 3% in autumn. For southern coastal Maine, the ranges were 12 to 14% in winter, 6 to 8% in spring; 0 to -2% (less rainy) in summer; and 2 to 4% in autumn. These results can be inferred from review of **Figure 8**. The scope of the Rawlins study extended to New York, New Jersey, and Philadelphia.

The changes in projected precipitation noted in the previous paragraph suggest a potential shift in flood seasonality.

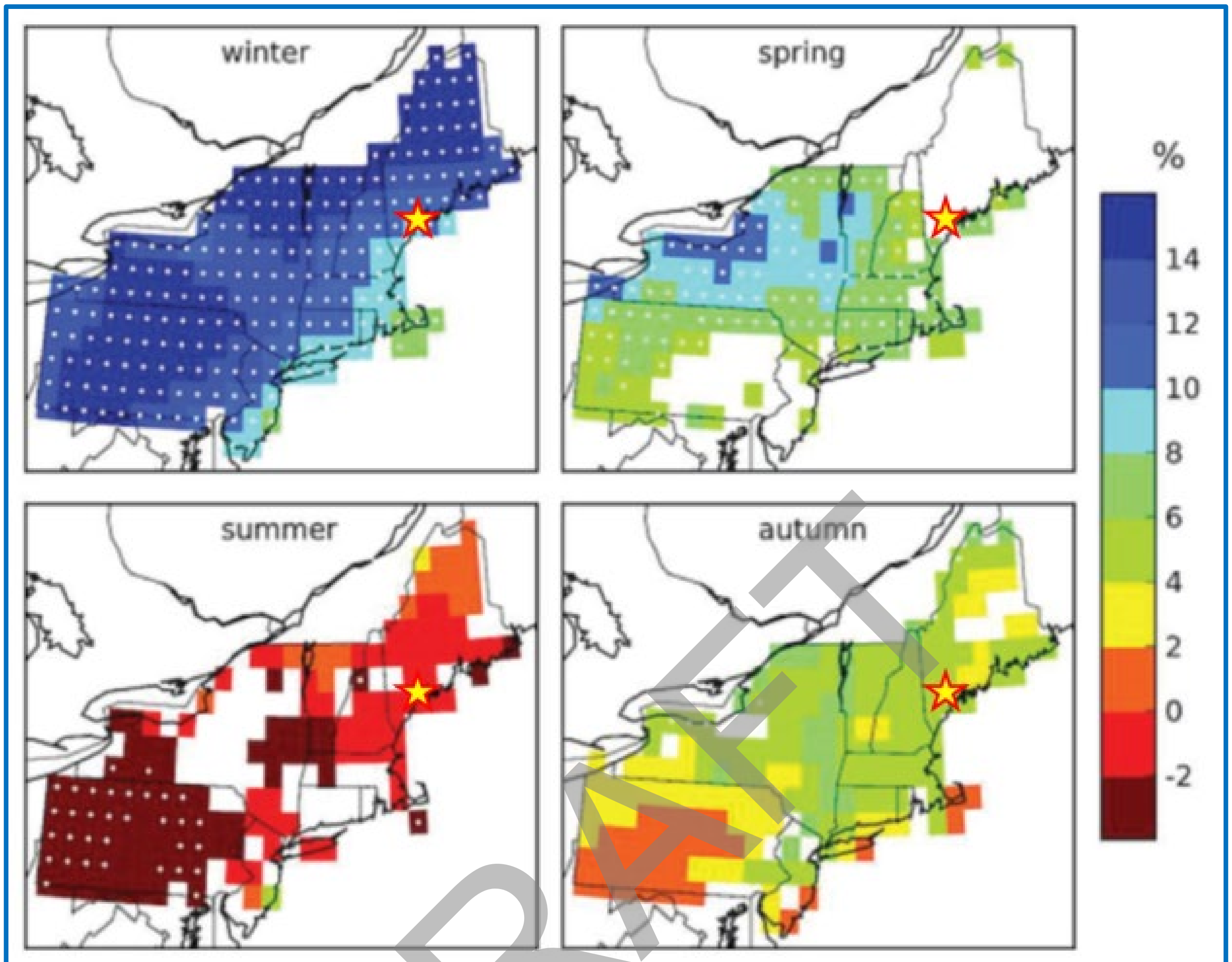


Figure 8: Projected Changes in Seasonal Precipitation Volumes, 1971-2000 Compared with 2041-2070, as a Percent of 1971-2000 Precipitation Volumes (Rawlins et al. 2012). The Royal River location is indicated with a red star symbol.

Thibeault and Seth (2014) having reported seasonal findings and projections, Hayhoe et al (2007) and Hayhoe et al (2008) validated these seasonal findings and projections for the New England area, as they reported their own projections through 2099.

Ahmed et al (2013) created two climate model ensembles, using data from 1976-1995 and projecting to 2065: The average number of rain-days exceeding 10 mm (0.4 inch) increased by 0 to 4 days per year by 2065 under both scenarios, although the frequency and intensity of big storms were less clear (depended on the location). Huntington et al (2009) noted that an increase of up to 10% in annual precipitation was expected by the end of the 21st century, although there was limited agreement between models; the projected increase in winter precipitation, however, was a common theme, as summarized in the fourth National Climate Assessment (Volume II) from NOAA (Dupigny-Giroux et al, 2018), who noted recent increases in rainfall intensity throughout the Northeast, with expected increases in monthly precipitation of about 1 inch during the months December through April by 2100.

NOAA has published a set of individual state climate summaries containing information on historical climate variations and trends, future climate model projections of climate conditions, and past and future conditions of sea level and coastal flooding. With respect to precipitation in Maine, NOAA reported as follows (Runkle et al 2022):

> *"Precipitation since 2005 has averaged 6.6 inches more than during 1895-2004. The number of extreme precipitation events has been near to well above average since 2005 and is projected to increase during this century."*

NOAA reported an expected increase in winter and spring precipitation, and an increased frequency of extreme precipitation, potentially causing more flooding risks and degradation of surface water quality as greater runoff from more intense storms carries pollutants into freshwater resources. The report included **Figure 9**, in which the projected changes in winter precipitation was projected to increase by 10 to 15% by the mid-21st century compared to the late 20th century under a higher emissions pathway, in the southern coastline of Maine.

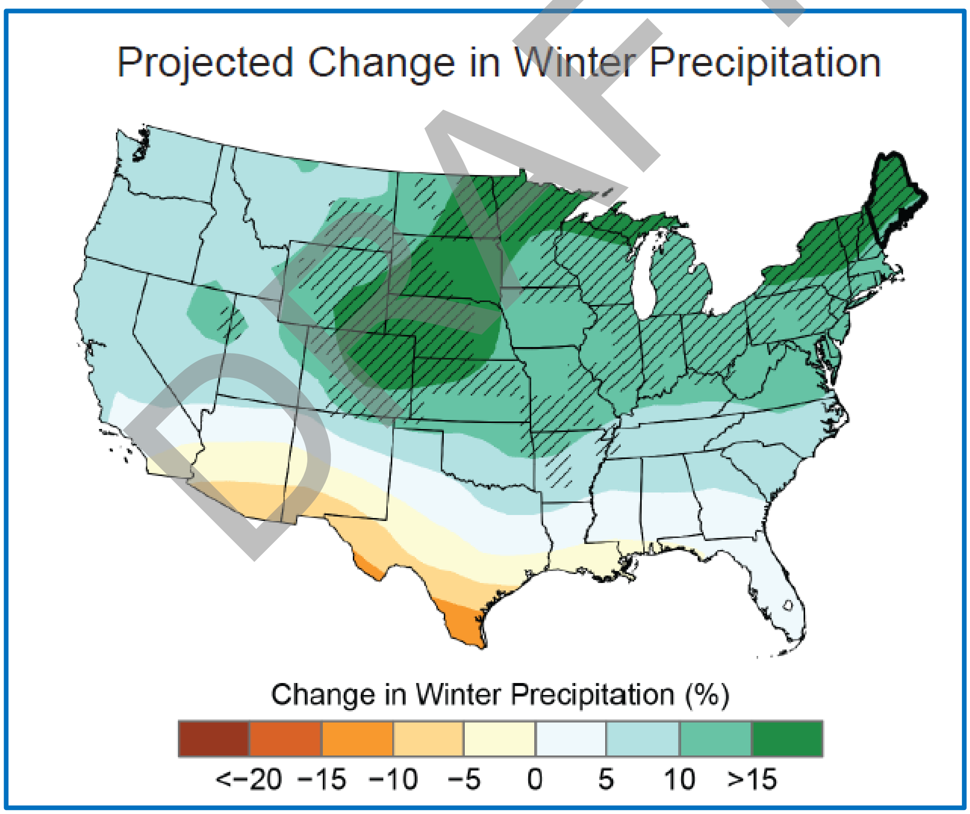


Figure 9: NOAA Maine 2022 Report - Projected Change in Winter Precipitation

5.0 STREAMFLOW

The NCA5 in Whitehead et al (2023) noted that specific hurricanes (Irene, Sandy, the 2019 combination of Henri and Ida, Isaias) had caused flood damage, which had tended to be in areas with less capacity to absorb the losses, but there remained a lack of consolidated information about flooding related to smaller periods of intense rainfall (such as convective thunderstorms), or whether these briefer storms were reliably correlated with flooding issues.

5.1 STREAMFLOW OBSERVATIONS

The NCA4 ((Wehner et al, 2017 in Wuebbles et al, 2018) indicated a possibility of increased frequency of large storms. The response in runoff to precipitation was less readily apparent:

- The winter snow-deposition season appeared to be shrinking over time, so there would be less snow to melt, generating runoff, in the spring.
- The mix of rain to snow was changing (more rain, less snow, so the sudden rain-on-snow snowmelt runoff events would occur with less total runoff being generated, and more opportunities for water to seep into the soil as opposed to increasing the measured runoff.
- For hurricanes and tropical storms, which are an important driver of flooding events in the eastern United States, the expected drier conditions in the summer months would serve to promote hydrologic losses such that intense thunderstorms might produce substantial precipitation, but more of this would be lost to infiltration.

The NCA4 noted that possible deforestation, urbanization, dams, floodwater management activities, or changes in agricultural practices were important factors in statistics connecting runoff and precipitation. The report noted “Projection of future changes is thus a complex multivariate problem.”

Kalra et al (2008) reviewed historical streamflow data for 1951-2001 and found no statistically significant trend in the New England Region for either annual or seasonal streamflow. Small et al (2006) studied flow records in 1948-1997, essentially confirming this “no-trend” finding, but noting also that two stations had a statistically significant decrease in low flows. Armstrong et al (2012) reviewed 23 gage records at “undisturbed” sites and noted that for 22 of the sites, low-magnitude floods were increasing in frequency and magnitude, and that the result was significant at $p<0.1$ for 10 of the stations. Hayhoe et al (2007) reviewed peak spring runoff data since 1950, noting that the peak was occurring earlier by approximately 0.3 days per decade over 1950 to 2000, but with no significance stated; runoff volumes and 7-day annual minimum (7Q1) values presented less clear results with respect to trends over time, although the 7Q1 did appear to be diminishing.

Hodgkins et al (2003) used a more robust measure of peak flow timing at 27 New England stations (center-of-volume date for the January-through-May winter-spring period and the center-of-volume date for the June-through-December summer-fall period) in the 20th century. Half of these stations (14 of 27) exhibited a $p<0.1$ significant trend of earlier dates for winter/spring; four of the stations also had earlier summer/fall dates. The NCIA (Frumhoff et al, 2007) noted that in the Northeast Region over the 20th century, the date of spring thawing of lake ice had shifted by 9 days in the northern part of the region and to 16 days over the southern region.

The USGS has prepared reports specific to Maine, with regressions for monthly, annual, and low flows (Dudley, 2004), updated in Dudley 2015, and for high flows (2-year flows up to 500-year flows) (Lombard and Hodgkins, 2020). The 2015 study on lower flows included ranges of flow for each month, based on basin-specific characteristics, so that a current estimate of flow for a given month could be applied. It did not include a review of nonstationarity. The 2020 study of higher flood flows did mention its underlying assumption of stationarity, reasoning that a formal "break" in the record to review more recent years with the purpose of evaluating whether the most recent 30 years showed any statistically significant break from prior years would discard more than half of the record-peak flows in the respective gage records. For all of the USGS-derived equations, whether for high flows or low flows, an important factor is the drainage basin area.

NOAA has published a set of individual state climate summaries containing information on historical climate variations and trends, future climate model projections of climate conditions, and past and future conditions of sea level and coastal flooding. NOAA noted that the annual number of 2-inch extreme precipitation events seemed to vary over the available record, but that there was a greater number over the years 2005-2014 (not yet enough years for a thorough statistical analysis). There appeared to be more short-term dry periods, with extreme drought in 2002, 2016, and 2020, and that there had been more than 900 wildfires in 2020, which was a 10-year high (Runkle et al 2020).

Lombard et al (2021), in a paper on summer-time flows and suitability for Atlantic Salmon habitat, reported that relatively high baseflow conditions would likely offset the high temperatures of a typical summer (August low flows) because "baseflows are known to moderate stream temperatures in summer low-flow periods." The paper reviewed 31 USGS gaged locations, both near the coast and farther inland, with locations both north and south of the Royal River but did not include the Royal River itself (the nearest locations in the Lombard et al 2021 study were at Kennebunk to the south or North Whitefield to the north).

With respect to flooding in Maine, NOAA reported as follows (Runkle et al 2022):

> *"The frequency of extreme precipitation events is also projected to increase, potentially resulting in increased flooding risks and the degradation of surface water quality as greater runoff from more intense storms carries pollutants into freshwater resources."*

5.2 STREAMFLOW PROJECTIONS

The NCA4 report (Wehner et al (2017) in Wuebbles et al (2018)) referred to a report by Tebaldi et al (2006), prepared for the Federal Insurance and Mitigation Administration of FEMA. Tebaldi et al (2006) had developed a regression-based approach of scaling river gauge data based on seven commonly used climate change indices from the Coupled Model Intercomparison Project (CMIP) database and found that at the end of the 21st century the 1% annual change exceedance floodplain area would increase in area by about 30%. The NCA4 noted also that AECOM (2013) had indicated that there would be larger changes in the Northeast and Great Lakes regions and smaller changes in the central parts of the country and the Gulf Coast.

Thomson et al (2005) used two GCMs with various input assumptions to model flows across the United States. The results were inconclusive with respect to streamflows in the neighboring Mid-Atlantic Region (west of the New England region). For the New England region, the results indicated little to no change over time, and the small change that was indicated, forecast as water yield, was positive in one case and negative in the other, but appeared to register differences smaller than 15 mm in either case.

Hagemann et al (2013) reviewed runoff trends based on a set of General Circulation Model (or Global Climate Model) (GCM) simulations. The models indicated runoff increases of up to 3.1 inches per year, with larger increases in the winter and smaller increase in the spring. For the New England region, however, the modeled projections demonstrated appreciable uncertainty, based on setting the starting boundary conditions (seeding), as well as with the models' GCM assumptions.

Frumhoff et al (2007) noted changes in seasonal timing of runoff (10 days shift for the spring peak flow by 2100), and that the probability of high-flow events increasing by up to 80%, especially in Maine, New Hampshire, and Vermont. Drought frequency was expected to increase due to reductions in summer runoff and soil moisture, with a reduction of 10% for the annual low flow 7Q1 (the annual minimum 7-day low-flow).

USACE (2015) summarized a two-model GCM study with estimates of 60 to 200 mm increase (approximately 2.5 to 8 inches) in annual runoff expected for the USACE planning horizon 2071-2100, compared to the period 1971-2000.

The runoff response to extreme storms (for example, 100-year or larger) was less clear, and USACE 2015 includes the statement "There is little consensus in the literature regarding future projections of annual streamflow volumes, but in general spring streamflow peaks are expected to arrive earlier in the year and may increase in volume."

Both USACE (2015) and CDM Smith (2012) cautioned that hydrologic parameters were a significant source of uncertainty.

6.0 SEDIMENTATION

Downstream of the Royal River mouth is a bay area that includes a boat club with moored boats. This community, primarily the owners of the mooring facilities, have expressed a concern with the sedimentation that might occur in the event of any dam removals.

Review of the experience at Bangor Maine, where two dams (Great Works Dam and Veazie Dam) were removed from the Presumpscot River in 2012-2013, indicated that the concern over small gravel and sand (particle sizes up to 20 mm) is likely overblown: Collins et al 2020 found that "…large-scale physical changes are likely to be minimal when impoundments storing relatively little sediment are removed from erosion-resistant streambeds.” Field data indicates that the sediments shoaling in Yarmouth are largely (50 to 90%) fines, <74 microns.

GZA (2018) reported estimates of up to 100,000 cubic yards of sediment potentially available for release in the event of the Elm Street Dam being removed, and up to 6,000 CY at the Bridge Street Dam. Exploratory boring in 2023 indicated that the quantity was smaller, and possibly significantly smaller.

7.0 SEASONALITY

The estuary supports a broad range of fish species, including shellfish, anadromous and catadromous fish species such as blueback herring (*Alosa aestivalis*), alewife (*A. pseudoharengus*), American shad (*A. sapidissima*), and American eel (*Anguilla rostrata*), and a strong recreational fishery including bluefish (*Pomatomus saltatrix*) and striped bass (*Morone saxatilis*).

For species of concern, mid-May to mid-June is the accepted temporal migration period, but as climate signals change on seasonal water temperature, the species are expected to migrate and lay in the spring earlier (when the water is between 41 °F and 50 °F).

Of concern are the water temperature and the water flow against which the fish would need to swim in a typical migration season.

Younger fish attracted too early might not yet be capable of the swim against rapids; they might be attracted by high flows when temperatures are still too cold for egg-laying, or by ideal temperatures when the flows are low (but velocities too high for the upstream migration). Competition with new (non-native) species for ideal laying spots might limit the success of the project with respect to target species.

Fish attracted too late in the season might find themselves out-competed by non-native species for food, as well as spawning and laying spots.

The NCA5 (Ch 21 Northeast) noted:

> *The timing of important life-history events, such as fish feeding and spawning migrations, is shifting in the Northeast. Spring and autumn phytoplankton blooms occurred later in recent decades. Larval fish occurrence and fish migration are both happening earlier. Warmwater fish remain longer in Rhode Island’s Narragansett Bay, while coldwater species stay for shorter periods, changing when species can be fished. Warming seas are linked to increased cold-stunning events for Kemp’s ridley sea turtles in the northwest Atlantic, in which turtles acclimated to warm water become motionless when subjected to sudden cold water.*
>
> *Increased temperatures make some diseases more prevalent in aquatic organisms, affecting the availability of seafood and increasing seafood-borne*

diseases. Shell disease in American lobster is associated with changing molting patterns due to spring warming and increased exposure to summer heat. Climate change is expected to cause higher mortality of blue crabs due to infection by Hematodinium and Callinectes sapidus reovirus 1. Harmful algal blooms occur more often in the Northeast. Evidence links climate change to an increase in the potential growth rates and bloom-season duration of Margalefidinium polykrikoides, which kills finfish and bivalve mollusks, and in the number of blooms of Prorocentrum minimum. Increasing temperature is linked to increases in the occurrence of pathogens (e.g., Vibrio species), which are among the most important causes of seafood-borne diseases.

7.1 SEASONALITY IN TEMPERATURE – OBSERVATIONS AND PROJECTIONS

Several studies noted that spring warming since 2001 appears to be occurring 0 to 4 days earlier than it did during the 1950's which indicates a potential change in seasonality. These studies are included in Wang et al (2009); Westby et al (2013); Meehl et al (2012); Schwartz et al (2013); DeGaetano et al (2002); Horton et al (2014).

NOAA (Runkle et al 2022) reported winter warming, measured as the number of very cold winter nights, which had been reducing since the 1990s. Lakes were experiencing earlier ice-out dates: the example given was Damariscotta Lake, in which ice-out happened in mid-to-late April in the mid-20th century, but the typical current (2020, 2021) ice-out date was in early April, while the growing season had lengthened. Damariscotta Lake is approximately 44 miles northeast of Yarmouth and about 14 miles inland. For the Royal River location, the difference in the shift to "early April" from the previous "mid-to-late April" can be taken as 15 days.

7.2 SEASONALITY IN PRECIPITATION – OBSERVATIONS AND PROJECTIONS

In its Volume II, the NCA4 noted recent increases in rainfall intensity throughout the Northeast, with expected increases in monthly precipitation of about 1 inch during the months December through April by 2100. Although annual minimum streamflows had increased over the previous century, it was expected that late-summer warming might lead to decreases in the minimum streamflows in the late summer and early fall by the middle of the 21st century.

Rawlins et al (2012) reviewed data since 1971 to develop projections of increases in precipitation through 2070 in New England of 12% in winter, 10% in spring; -2% (less rainy) in summer; and 3% in autumn. For southern coastal Maine, the ranges were 12 to 14% in winter, 6 to 8% in spring; 0 to -2% (less rainy) in summer; and 2 to 4% in autumn. These results were inferred from review of **Figure 9.**

Ahmed et al (2013) created two climate model ensembles, using data from 1976-1995 and projecting to 2065: the average number of rain-days exceeding 10 mm (0.4 inch) increased by 0 to 4 days per year by 2065 under both scenarios, although the frequency and intensity of big storms were less clear (depended on the location). Huntington et al (2009) noted that an increase of up to 10% in annual precipitation was expected by the end of the 21st century, although there was limited agreement between models; the projected increase in winter precipitation, however, was a common theme, as summarized in the fourth National Climate Assessment (Volume II) from NOAA (Dupigny-Giroux et al, 2018), who noted recent increases in rainfall intensity throughout the Northeast, with expected increases in monthly precipitation of about 1 inch during the months December through April by 2100.

7.3 SEASONALITY IN STREAMFLOW – OBSERVATIONS AND PROJECTIONS

Frumhoff et al (2007) noted changes in seasonal timing of runoff (10 days shift for the spring peak flow by 2100) and noted the probability of high-flow events increasing by up to 80%, especially in Maine, New Hampshire and Vermont.

Dudley and Nielsen (2010) noted a pattern of flows peaking in April with a median monthly flow of 3.6 cfs/square mile and reducing during the summer to a minimum value of approximately 0.3 cfs per square mile in August and September, based on data gathered 1949-2004. This pattern is summarized in **Figure 35**.

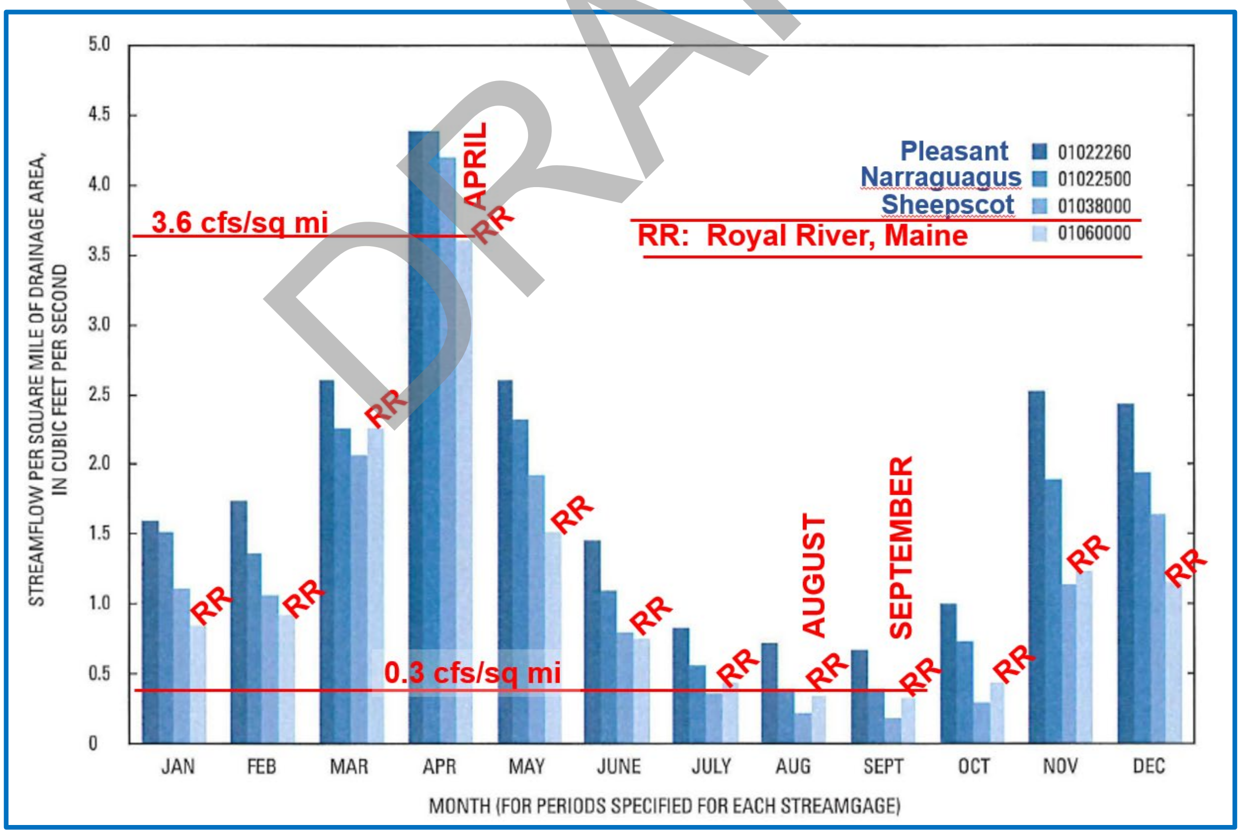
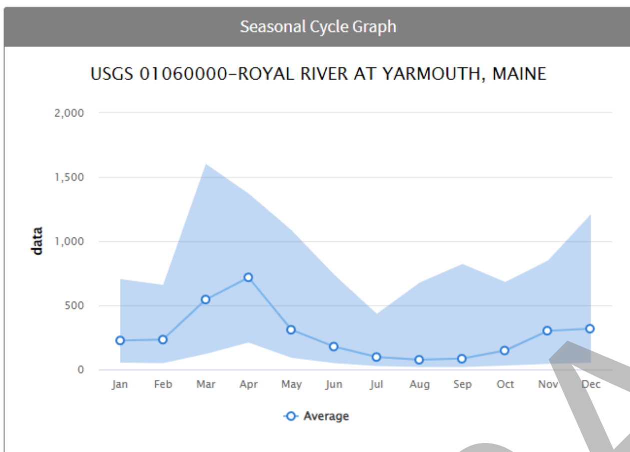


Figure 16: Median Monthly Streamflows per Square Mile for Four Rivers in Maine, including Royal River (from Dudley and Nielsen 2010): Max in April, Min in Aug-Sept.

The runoff response to extreme storms (for example, 100-year or larger) was less clear, and USACE 2015 includes the statement “There is little consensus in the literature regarding future projections of annual streamflow volumes, but in general spring streamflow peaks are expected to arrive earlier in the year and may increase in volume.”

More recently (2023), the CHAT generated the chart shown in **Figure 11**, showing how streamflow in the Royal River varied by month over the recorded period 1950 to 2022. The CHAT chart included ranges for each month but summarized mean values (not median).



The seasonal cycle graph shows aggregated monthly data throughout all of the years. This data includes monthly minimum, maximum, and average values. These values represent variance throughout the years for a particular month.

Seasonal Cycle Data

month	ymin	ymax	avg
Jan	52.5	704	225.5
Feb	48.6	658.2	232.5
Mar	121.3	1603	544.9
Apr	209.7	1372	717.3
May	91.7	1085	309.2
Jun	48.4	738.5	178.1
Jul	26.1	434.5	96.5
Aug	19.7	678.8	75.2
Sep	18.7	822.3	85.2
Oct	30.5	682.2	147.5
Nov	42.8	851	301.9
Dec	52.1	1210	317.9

Figure 11: Royal River - Observed Flow Seasonality

7.4 ROYAL RIVER - OBSERVED FLOW SEASONALITY

Given the wide range of flows for any given month, and the constantly changing flow due to individual storms and tides, it is likely that there would be acceptable flows at some time during most days of the migrating season, which in the record begins about a month after the maximum spring flows, and lasts about one month.

The NCIA (Frumhoff et al, 2007) noted that in the Northeast Region over the 20th century, the date of spring thawing of lake ice had shifted by 9 days in the northern part of the region and to 16 days over the southern region. For the State of Maine, in northern New England, a range of 10 to 12 days is inferred.

An increase in precipitation during the winter (taken as December to February) of 12% is expected through 2065, with a smaller increase in the spring and small reductions over current conditions in the summer. Similar changes in flow can be inferred, although the exact relationship of rainfall to runoff is not linear.

The water temperature is not likely to change during the ice-melt and snowmelt-driven peak spring runoff season, but on average the volume will likely increase fractionally. The range 41 to 50 °F (9 to 18 °F above freezing) is likely to be maintained, although the earlier high-flow season may mean that the beginning of the migration season becomes less well defined and the weaker-swimming species will be forced to wait longer for favorable phases of the daily tide cycles, or, during storm events, for the storm peak flows to subside.

8.0 ECOSYSTEM HEALTH

As mentioned in **Section 7.0 Seasonality**, the estuary supports a broad range of fish species, including shellfish, anadromous and catadromous fish species such as blueback herring (*Alosa aestivalis*), alewife (*A. pseudoharengus*), American shad (*A. sapidissima*), and American eel (*Anguilla rostrata*), and a strong recreational fishery including bluefish (*Pomatomus saltatrix*) and striped bass (*Morone saxatilis*).

For species of concern, mid-May to mid-June is the accepted temporal migration period, but as climate signals change on seasonal water temperature, the species are expected to migrate and lay in the spring when the water is between 41 and 50 °F.

Stantec (2013) reviewed daily data 1949 to 2002 and computed a low flow (7Q10) of 23 cfs for the site; an annual median flow of 120 cfs; and an annual mean flow of 270 cfs.

Monthly mean flows ranged from a 90th percentile flow of 76 cfs in August to a 10th percentile flow of 550 cfs in March. Monthly median flows varied from a 90th percentile flow of 54 cfs in September to a 10th percentile flow of 734 cfs in April.

Flows in the May 15 to June 15 migration window ranged from 76 to 461 cfs with a median value of 149 cfs. In the wider window May 1 to June 30, flows were 65 to 489 cfs with a median value of 154 cfs.

The Stantec (2013) May-June flow patterns are presented in **Figure 12**.

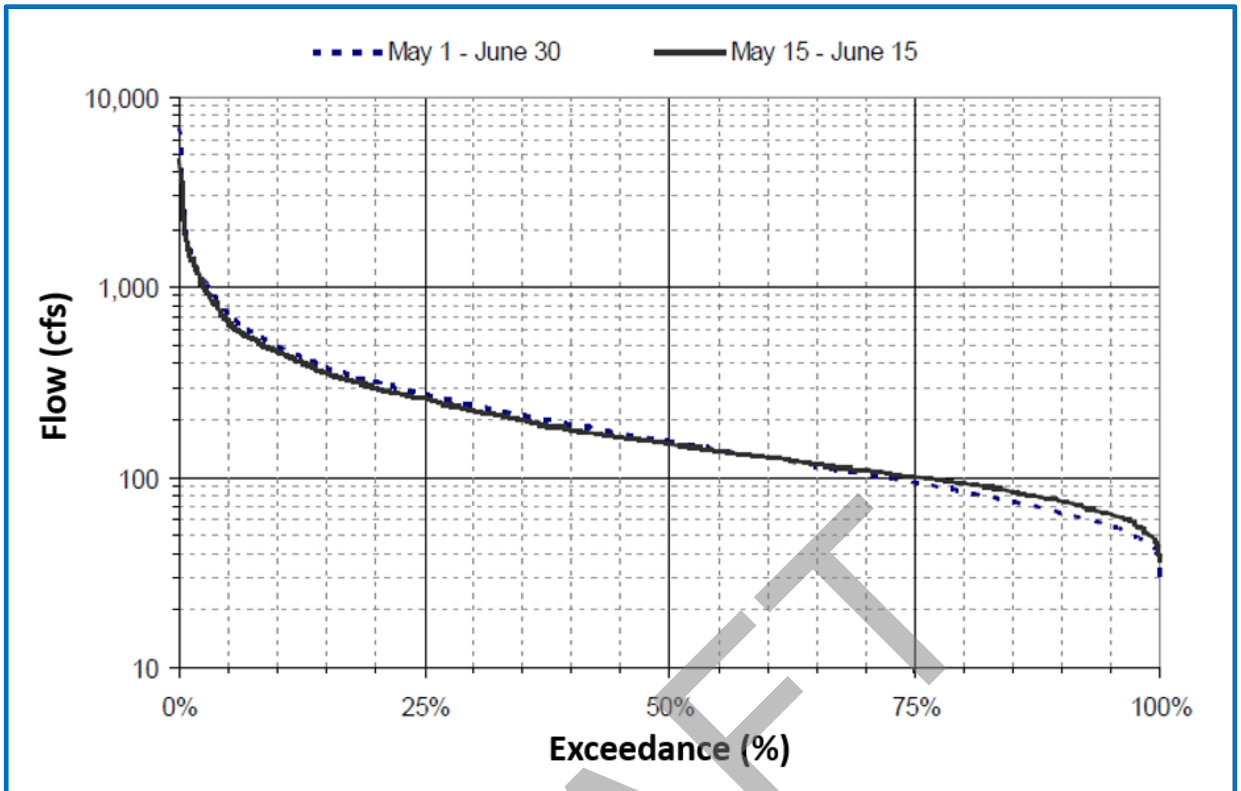


Figure 12: Flow-Duration Curves during May-June Fish Migration Periods

A majority of the flow during these periods (10th to 90th percentiles) is in the range 70 to 500 cfs.

The species of concern are expected to migrate and lay in the spring when the water temperature is between 41 °F and 50 °F.

GZA GeoEnvironmental, Inc. (GZA) (2018) summarized their knowledge of the habitat with respect to fish in the Royal River, noting the obstacles of dams in the river system. The system was clean in the sense that it did not receive any known human waste outflows; moreover, there appeared to have been an effective cleanup of trichloroethene (TCE) from the McKin cleaning and waste storage facility in the upper watershed, following EPA Superfund actions in the 1980s and 1990s, with no TCE detections above the regulatory standard in the Royal River after 2008.

GZA (2018) noted that Denil fishways had been installed in 1974 at the Bridge Street Dam and in 1979 at the Elm Street Dam. Alewives had been stocked upstream in the Sabbathday Lake in 1977. American shad were stocked the following year. Although both species did migrate out, it was noted that by 1981 the shad population had disappeared while, by 1988, the alewife population had fallen to approximately 12% of the 1981 level (6,106 adults in the ascending migration, from an estimated 50,000 population in 1981). The loss of alewife in the years 1981-1988 therefore occurred at a rate of approximately 26% per annum.

GZA (2018) also noted that the Royal River watershed contains poor Atlantic salmon habitat, while gravel and riffle areas were better suited to brook trout and brown trout. The brown trout could be expected to out-compete Atlantic salmon for available space, food, spawning, and nursery areas; these spawning and nursery areas would be convenient to migrating fish that were able to clear the dams in Yarmouth ME (below the natural barriers in upper Gloucester ME). The value of the habitat in the lakes (the dam impoundments) had not been described adequately for a clear understanding of where the fish might lose habitat under changed conditions.

9.0 LITERATURE REVIEW SUMMARY

Recent climate literature indicates that there is evidence of observed, increasing mean air temperature trends in the study region. Winter temperatures may be increasing faster than in other seasons. The literature points to an increasing trend in the number and temperature of extreme heat days. Mean temperatures are projected to rise by 5.3 to 9.1 °F by the end of the 21st century.

Total precipitation and the occurrence of extreme storm events is increasing over time. The NCA4 indicated an 80% increase in high-intensity storm frequency (almost an effective doubling of the frequency), although drier summers were expected to lead to lower summer streamflows and more frequent drought conditions.

Precipitation, especially winter precipitation, is expected to increase. Two studies projected an increase during the 21st century in winter precipitation of 1 inch per month for the months of December to April. Snowmelt and the spring thaw of lake ice have been observed to occur earlier in the year. Despite the observations of increasing precipitation over the 20th century, there is little evidence of significant increases in streamflow over the same period. One study citing results of multiple GCM models and scenarios, could not definitively project a change in expected peak flows in the New England region.

Streamflows are expected to increase in the fall, winter, and spring, but decrease marginally in the summer months.

Streamflows are highest in the April and lowest in August/September, but there is significant variation from one year to the next.

Water temperature changes in the event of a dam removal in Maine are likely mitigated by the cooling effect of groundwater. Landscaping changes (trees in the overbank areas) to shade the exposed river and lake areas might help with cooling in the event that cooling by groundwater proves inadequate for target species.

Fish species are differently suited to the river system in its current state. For example, the fish monitoring record available indicates that both species were overstocked when one upstream lake (Sabbathday) was stocked with these species in the late 1970s, although the shad population declined more quickly than the alewife population.

The USACE literature synthesis findings are summarized in **Figure 13.**

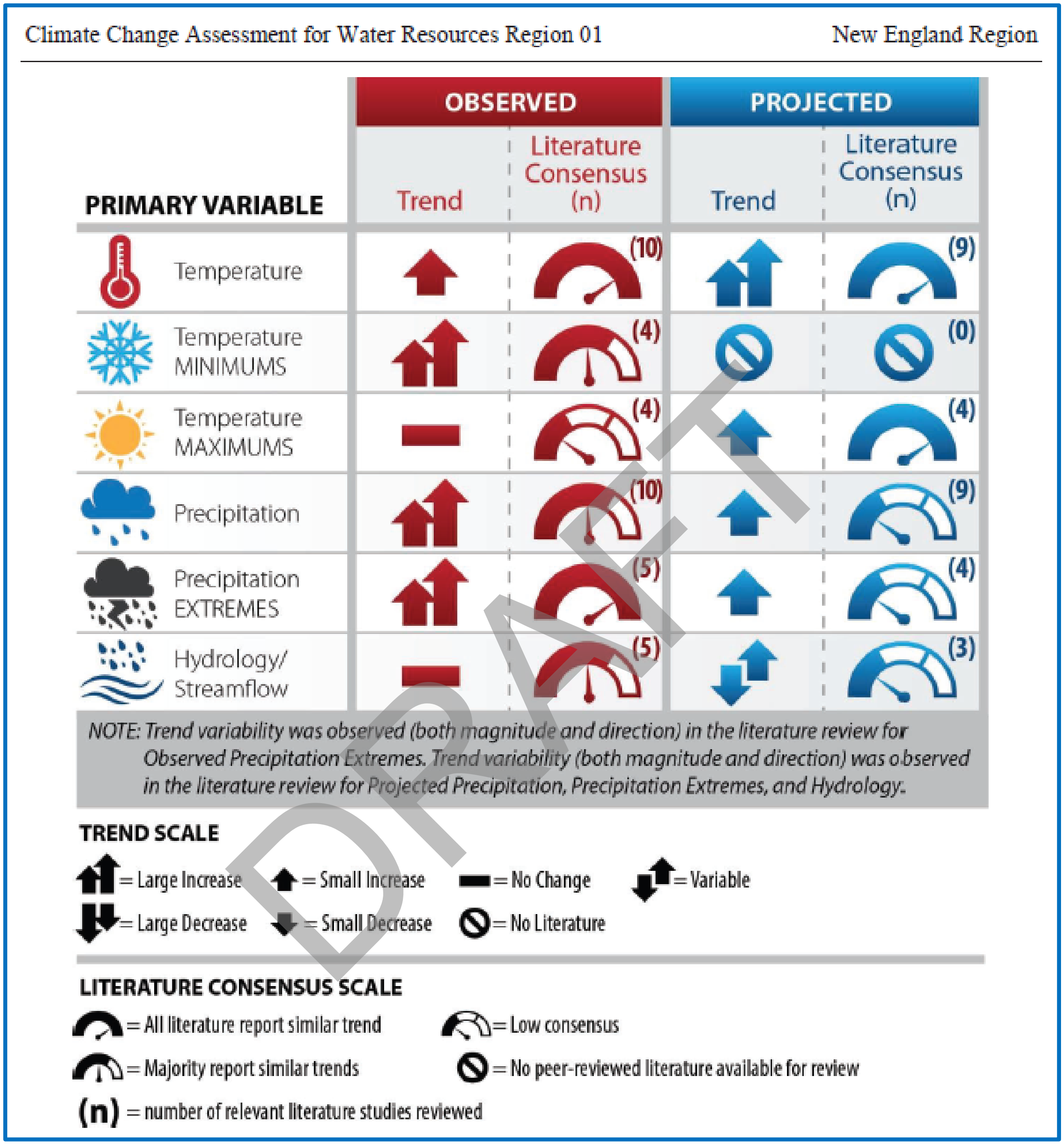


Figure 13: Summary matrix of observed and projected climate trends (USACE 2015)

10.0 NONSTATIONARITY DETECTION AND TREND ANALYSIS

10.1 ROYAL RIVER LOCATION AND USGS DATA

The assumption that discharge datasets are stationary (their statistical characteristics are unchanging) in time underlies many traditional hydrologic analyses. Statistical tests can be used to test this assumption using techniques outlined in Engineering Technical Letter (ETL) 1100-2-3. The Time Series Tool (TST) tool is a web-based tool to perform these tests on datasets of annual peak streamflow at U.S. Geological Survey (USGS) stream gages. The primary objective of this study is to evaluate normal flows and the ecological response to partial or complete removal of blockages on the river, so the focus of this investigation is the medium to low flows best represented by annual and monthly average and median values of streamflows.

For the Royal River in Yarmouth, the drainage basin area is 141.6 square miles. The Climate Hydrology Assessment Tool (TST) was applied based on flows at the penultimate reach of the Royal River. This location is deemed to be tidally influenced, although the bedrock underneath the Royal River rapids in Yarmouth ensures that curves in the river course are likely to endure, and the sinuous river course will prevent most ocean waves from reaching the location. The layout of the Royal River in the wider Presumpscot River hydrological unit is shown in **Figure 14**.

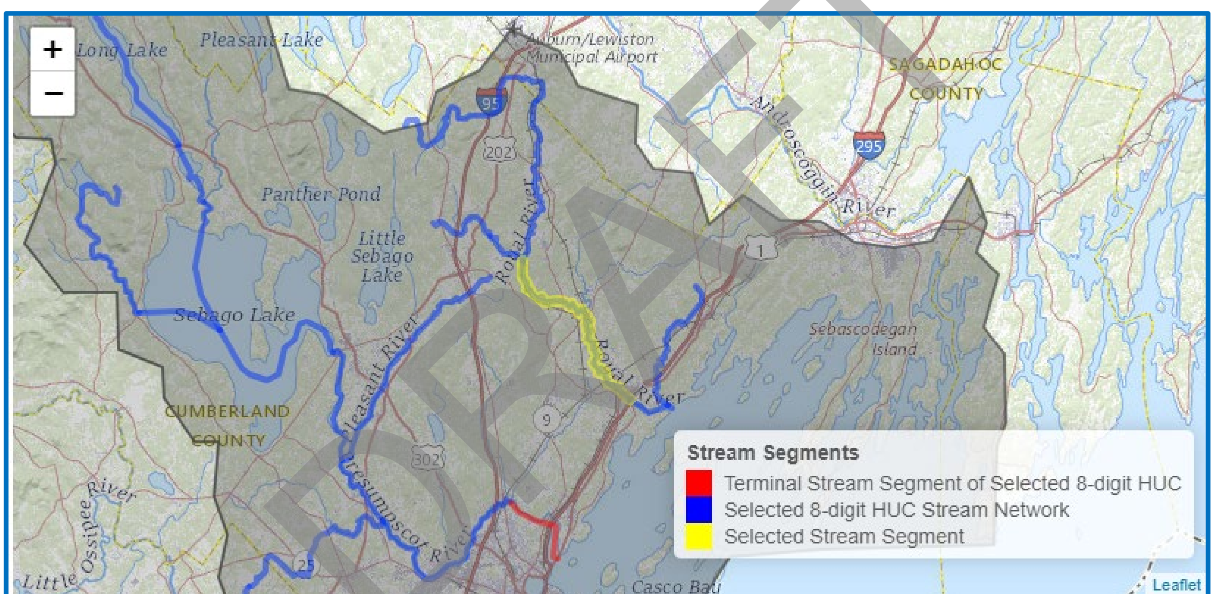


Figure 14: Location of Royal River (Stream Segment 01000915) within the Presumpscot HUC 01060001

For an ecosystem restoration project, typical ("normal") flows, rather than flood flows, were deemed of greater importance than high flows. Practically, annual mean flows and mean monthly streamflows were analyzed with the TST. In keeping with the ecosystem restoration nature of the project, annual average flows and mean monthly flows, rather than peak flows, were analyzed with the CHAT.

The available systematic data included a gap of 17 years from 2003 to 2020. Data for 2021 to 2023 was available, but was of limited value, and so has been discarded for this climate analysis.

10.2 TST OUTLINE OF METHODOLOGY

The Time Series Toolbox Version 2.0 (USACE, 2022) was used to detect the presence of nonstationarities in the mean monthly flow data for the Royal River (Yarmouth, Maine) stream gage. The detection is performed using statistical tests that evaluate for changes in the mean, variance, or distribution in the data. There are 12 different statistical tests available in the tool. The following descriptions of the statistical tests were taken from the tool user guide (Olson et al, 2021):

Mean-Based Tests

1. Lombard Wilcoxon: Test that nests the Wilcoxon score function within the Lombard test statistic to detect both smooth and abrupt shifts in mean by time. It determines the level of significance at which nonstationarities should be detected. It can also be interpreted as the maximum p-value associated with these nonstationarities.
2. Pettit: Nonparametric test that identifies change point in the mean by testing whether two samples come from the same population. The tool returns a single nonstationarity at the point in the dataset where the difference in the mean between the subsets of data prior to and after the nonstationarity has the greatest level of statistical significance or smallest probability of a Type I error.
3. Kolmogorov-Smirnov: Nonparametric test that compares two empirical distributions by evaluating a test statistic of distributional distance.
4. Bayesian CPD: Parametric (Gaussian) test that uses product partitions to identify change points within a sequence using MCMC sampling by assuming a sequence can be broken into partitions with a constant mean, where changes in the mean between partitions are change points.

Variance-Based Tests

1. Mood: A nonparametric case of a Pearson's Chi-test that evaluates change points based on volatility in medians between defined samples.
2. Lombard Mood: Nests the Mood score function within the Lombard test statistic to detect both smooth and abrupt shifts in variance by time.

Distribution-Based Tests

1. Cramer-von-Mises: Nonparametric goodness of fit test that compares two empirical distributions by evaluating a test statistic of distributional distance.
2. Kolmogorov-Smirnov: Nonparametric test that compares two empirical distributions by evaluating a test statistic of distributional distance.
3. LePage: Simultaneously tests the equality of both the location and scale parameters, where an inequality in one suggests distributional shift.
4. Energy Divisive: Nonparametric test based on hierarchical clustering, where change points are iteratively identified and can be diagrammed as a binary tree. The statistical significance is examined by means of a permutation test that combines bisection and multivariate divergence measures.

Smooth versus Abrupt Nonstationarities: The methods are also categorized by whether the nonstationarities they detect represent abrupt or smooth changes in the data. A smooth transition refers to a gradual change in the mean, variance/standard deviation, and/or distribution of the annual instantaneous peak streamflows or stages recorded at a USGS gage site. The only methods in the tool that can detect smooth changes in the statistical properties of the datasets under analysis are:

1. the smooth Lombard Wilcoxon; and
2. the smooth Lombard Mood methods.

Consensus: A nonstationarity that is detected can be considered strong if it is detected by two or more detection methods of the same type (e.g., mean or variance/standard deviation or distribution).

Robustness: A statistically significant nonstationarity can be considered robust when tests targeting changes in two or more different statistical properties (mean, variance/standard deviation and/or overall distribution) are positive.

Magnitude: An identified nonstationarity is also associated with a given magnitude of change in the mean or standard deviation/variance in the datasets prior to and after the identified nonstationarity. Nonstationarities that are produced by greater changes in the statistical properties of the datasets before and after the identified nonstationarities may be important to take into consideration when performing subsequent analysis.

10.3 TST REVIEW OF ANNUAL DATA

The TST does not have an option to select average annual flow as a parameter to be analyzed for nonstationarities. The average annual flow was the intended parameter for an ecosystem restoration project, and so it was necessary to input a data stream obtained directly from the USGS gage, edited to find the annual average flow for a given year.

There were no nonstationarities detected in the resulting data stream 1950 to 2023. A data gap 2004 to 2020 was present in the data set. The data stream was therefore analyzed for the years 1951 to 2004. In both cases, the statistical "heatmap" was completely blank and so is not presented. Although the data did appear to be trending downwards, the trend was not statistically significant. The nonstationarity assessment is summarized in **Figure 15.** The mean annual flow was 270 cfs. The standard deviation was 74.1 cfs. The variance was 5,490 ft^6 s^{-2}.

The trendline assessment is shown in **Figure 16.**

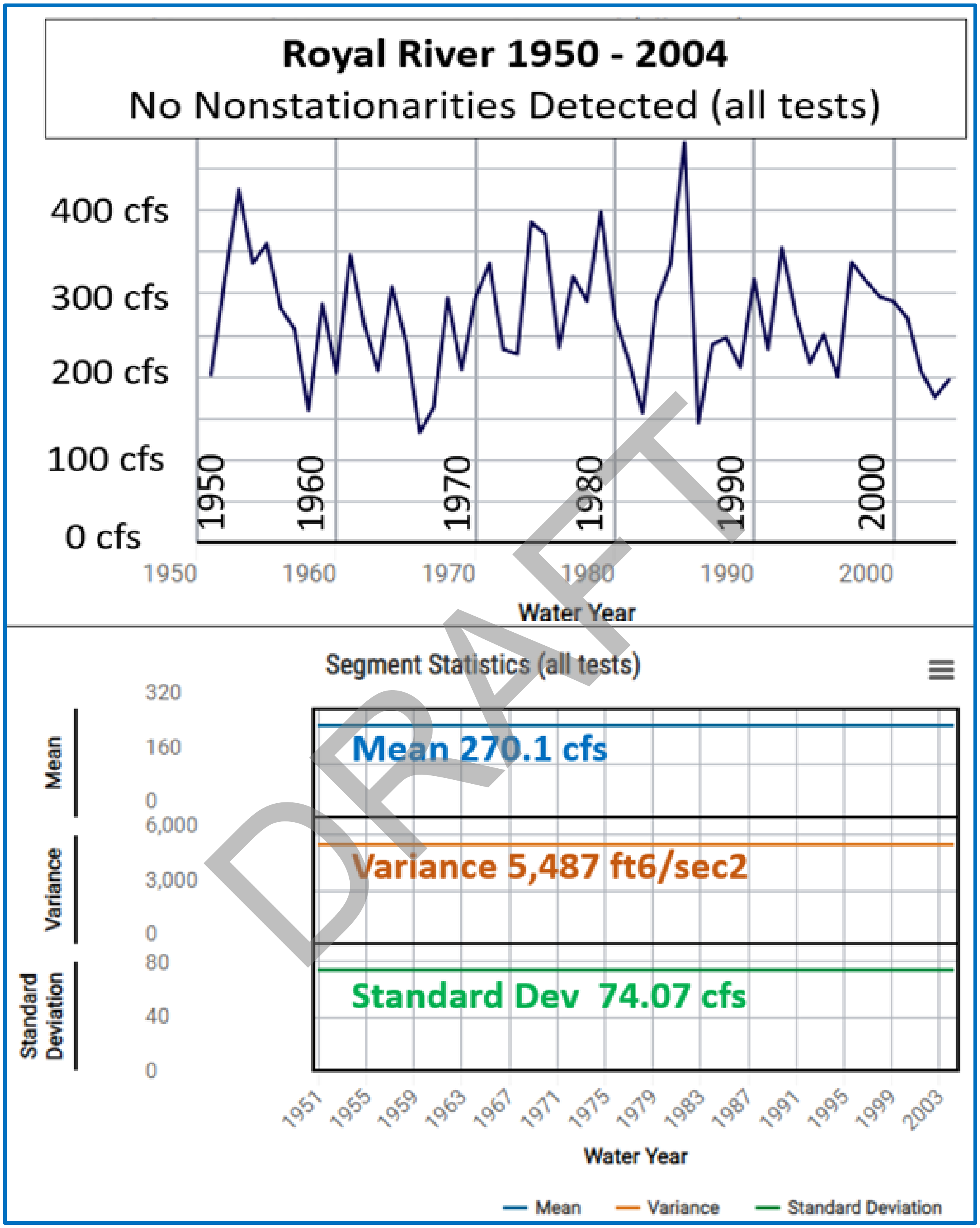
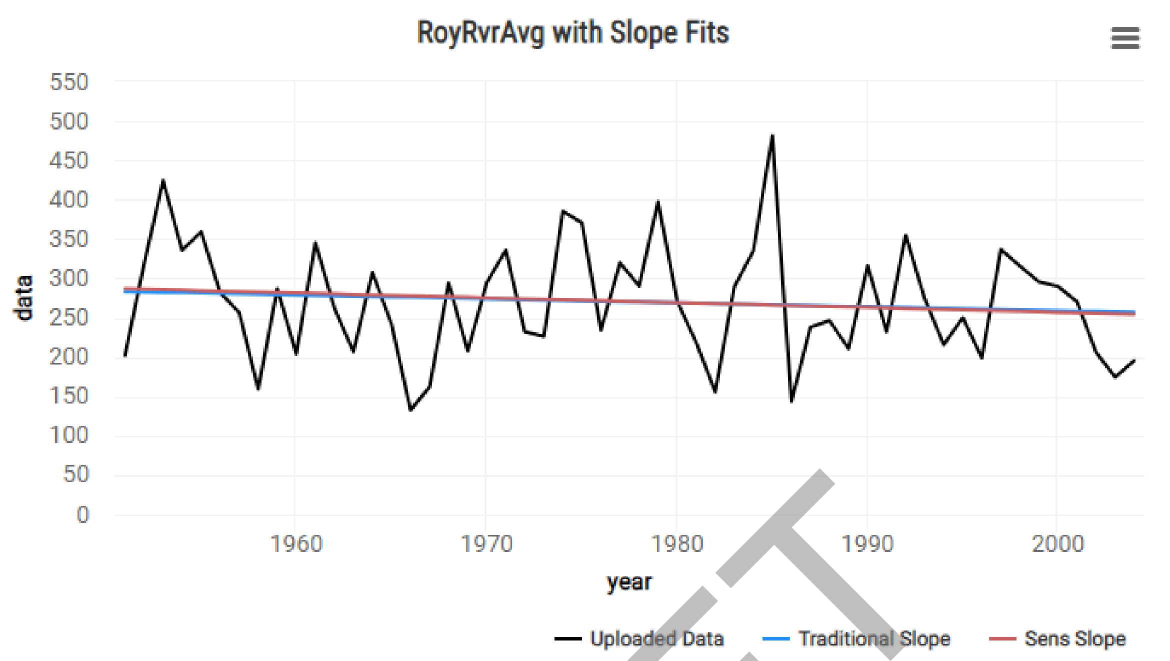


Figure 15: TST Nonstationarity Detection Assessment of Royal River Annual Average Flows 1950-2004



Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-0.496	1251
Sen's Slope	Negative	-0.614	1485

Trend Hypothesis Test

Test	P-Value
t-Test	0.448
Mann-Kendall	0.387
Spearman Rank-Order	0.4

- **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 16: TST Trending Assessment of Royal River Annual Average Flows 1950-2004

10.4 TST REVIEW OF MONTHLY DATA

Monthly streamflow information is reviewed below. The TST nonstationarity detection tool proved sensitive to the shorter time segments (months, not years), with NSD's corresponding to rainy months and no NSD's during the period of a drought during the 1960's.

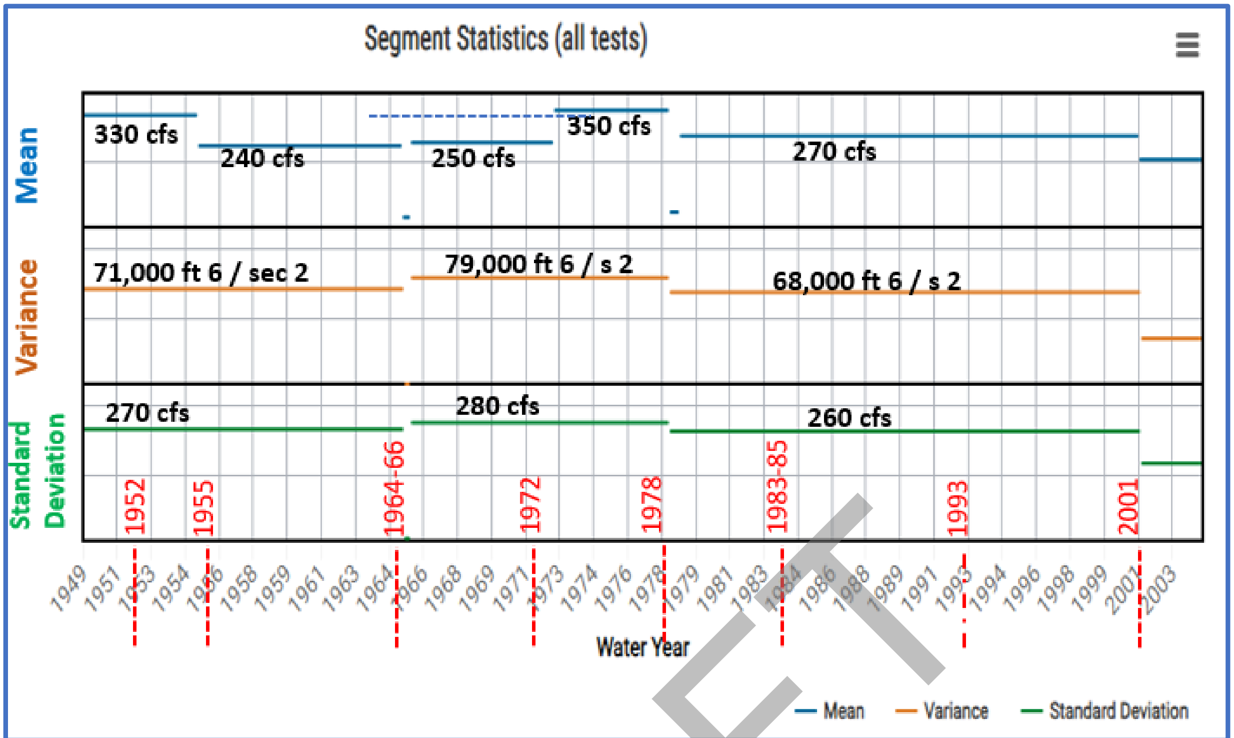


Figure 17: Royal River - Monthly Streamflow Data Summary Statistics 1949 to 2003
(Nonstationarities detected at annotated broken red lines)

After 2001, there was a 2-year period where these statistical records (mean, standard deviation, and variance) were all slightly smaller than previously, but the brief period was not of any statistical value, since the record came immediately before a multi-year gap 2003 to 2020. Similarly, the brief period 2020-2022 was of little statistical value.

It is noted that the monthly mean flows appeared to be falling slightly over time (not a statistical trend, however), in contrast with the observation by Collins (2009), who noted that annual peak flows appeared to be rising (**Table 2**).

Table 2: Royal River Monthly Mean Flows- Summary of Nonstationarity Detections 1949-2005

Dates	Mean-Based NS Detects		Variance/STD-based NS Detects				Distribution-Based NS Detects	Total Significant Detects	Summary
	Kolmogorov-Smirnov	Lombard-Wilcoxon	Cramer-von-Mises	LePage	Mann-Whitney	Energy-Divisive	Mood		
May 1952	1							1	minor 1952
May 1955		1				1		2	**1955**
May 1964						1		1	Y
May 1965			1	1	1			3	Y
June 1965							1	1	Y
Oct 1965			1	1	1		1	4	**1964-1966**
Nov 1966						1		1	Y
Oct 1972	1		1		1			3	**1972**
Nov 1972						1		1	Y
June 1978	1		1	1	1	1	1	6	**1978**
Dec 1978	1		1	1	1			4	Y
Oct 1983	1							1	Y
June 1984	1							1	**1983-1985**
May 1985				1				1	Y
Sept 1985				1				1	Y
June 1993				1				1	minor 1993
June 2001			1		1			2	**2001**
July 2001				1			1	2	Y

NS detections that occur within a short period of time (typically in a period of up to 5 time-steps, typically years) are assumed to demonstrate consensus or robustness as indicated above. In the analyses summarized in **Table 2**, however, the time-step was set as months. The single detection by the Kolmogorov-Smirnov test in May 1952 was weak, since it was not supported by the consensus of the other "mean" test. The detection in May 1955 of a nonstationarity with respect to mean values 1955 did not have consensus (only one test of the mean value was significant), but it was supported by a nonstationarity with respect to the standard deviation, so the NS detection was robust.
Similar reasoning leads to conclusions of NS detections in:

- 1952 (weak detection by only one test of the mean value).
- 1964-66 (consensus on changing variance (8 detections); with robustness, in that the Mood test found a nonstationarity with respect to distribution (detections in both June and October of 1965)
- 1972 (1 NSD based on mean and 3 based on variance), providing robustness (both mean and variance) and consensus (changing variance)
- 1978 (2 NSDs by mean; 7 by variance; 1 by distribution), providing robustness (mean, variance, distribution), and consensus with respect to variance. An argument could be made for consensus with respect to the

mean, but in this case the same test registered a detect in 2 months of the same year.

- 1983-84-85 ((2 NSDs by mean; 2 by variance). Robustness is clear, but consensus is arguable since the same test of the mean yielded a detection in different months of 1983, while the same test of the variance yielded a detection in 1985.
- 1993, although this was a single detection of a variance NS by the lePage method, with no consensus between variance tests and no corroboration from tests for other parameters (not robust)
- 2001, in which 3 different tests for variance NS were positive (yielding consensus) while 1 NS detect for a change in distribution added robustness to the conclusion of a nonstationarity.

The May 1952 observation may have been caused by a storm sequence around that time, since review of high pools at Flood Risk Management (FRM) dams in the nearby Merrimack River Basin in neighboring New Hampshire noted high pools in April 1952 at Edward MacDowell Dam (EMD) and in June 1952 at Franklin Falls Dam (FFD) (USACE NED 1987(a); USACE NED 1987(b)).

A drought in the mid-1960s may have contributed to the finding of a nonstationarity as detected by 10 tests 1964-66. The pools at nearby FRM dams at EMD and FFD did not record any significant high pools during this period (1964 to 1967).

One clear cause of discontinuity/nonstationarity was the removal of the infrastructure at the Third Falls in Yarmouth in 1971, where the TST's statistical tests noted changes in 1972 (the subsequent year).

The observations in June 1984, part of a series of NS detections in 1983-85, was supported by an unusual high pool, recorded in the FRM dam at nearby FFD. Since the basin area for FFD is 1,000 square miles, it is possible that an even wider storm system may have caused this discontinuity, noted as a nonstationarity in the Royal River record at Yarmouth Maine.

Changes in the record could be attributed directly to operations-changes at any of the upstream dams in the Royal River Basin. These potential sources of discontinuity would include operations-changes at (see **Figure 17):**

- Jordan Mills Dam on the Royal River in northern New Gloucester,
- an unnamed dam on Stevens Brook,
- the Pownal State School Dam on Collyer Brook,
- an unnamed dam on the Eddy Brook tributary to Collyer Brook,
- Florida Lake on the Collins Brook tributary to Chandler River,
- Runaround Pond Dam on the Alder Brook tributary to Collins Brook, and
- the existing and former operations on the Royal River at the four sets of rapids in the Town of Yarmouth.

Low bridges could interfere with flow, acting as artificial regulation, so that a series of years with high flows would appear to have added regulation affecting the peak outflow during the stormier years. Bridges that could affect the record in this way are at:

- North Elm Street, at or below the 0.2%, 1%, and 2% AEP (500, 100, and 50-year) Royal River profiles in Yarmouth, 3 miles upstream of the confluence with Casco Bay
- Maine State Route 9, at or below the 0.2%, 1%, 2% and 10% AEP (500, 100, 50, and 10-yr) Royal River profiles, 6 miles upstream of East Elm Street in North Yarmouth
- Maine State Route 231, at or below all four listed Royal River profiles, 7.75 miles upstream of East Elm Street in North Yarmouth in North Yarmouth
- Mill Road, at or below the 0.2%, 1%, and 2% AEP (500, 100, and 50-year) Royal River profiles, 9 miles upstream of East Elm Street
- State Route 26, at or below the 0.2%, 1%, 2% and 10% AEP (500, 100, 50, and 10-year) Collyer River profiles, approximately 8 miles upstream of the Collyer's confluence with the Royal River
- Three farm roads, one private drive, and North Raymond Road, all at or below the four listed Collyer River profiles, at distances from 8.0 to 8.4 miles upstream of the Collyer's confluence with the Royal River.

Flow data since 2004 is necessarily ignored in review of nonstationarities because of a 17-year gap from 2003 to 2020.

Records of high pools at two flood risk management dams in the nearby Merrimack River Basin in New Hampshire occurred at the same time that the Royal River monthly record showed NSDs: May 1952 and June 1984 nonstationarities may have been related to storms at the time of the detections.

Although there was little evidence of an underlying climate change in the record of flows, it is apparent that the various nonstationarities detected in the record of flows in the Royal River could be caused by either climate changes or by upstream infrastructure changes such as the regulatory effect of dams being constructed, operated, or removed, at the locations of at least 10 dams.

There is a similar effect where flows are limited when high flows are held back at bridges at 10 locations on the Royal River and numerous tributaries, or at coffer dam operations during bridge or landscaping construction/ renovations.

11.0 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. It has been programmed to model the hydrological results of one representative river in each HUC-8, with inputs from

32 GCM models, using two different sets of assumptions regarding CO_2 levels as greenhouse gas outputs.

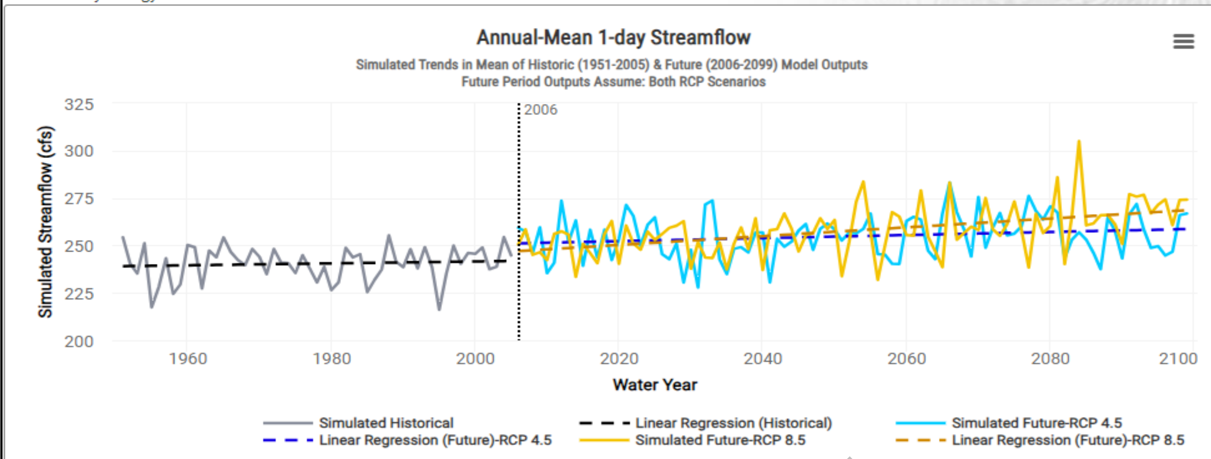
The CHAT displays spatially downscaled, hydrologically simulated and statistically aggregated CMIP5 GCM outputs. CMIP5 GCM outputs are available at daily temporal resolution for calendar years 1950-2099. Baseline historic simulations span the timeframe 1950-2005; these historic simulations assume greenhouse gas emissions to be equivalent to a reconstruction of historically observed greenhouse gas emission levels. Projected future simulations span the timeframe 2006-2099, which represent projected, climate-changed meteorology where various representative concentration pathways (aka "scenarios") (RCP) of greenhouse gas emissions are assumed. CHAT utilizes projected future GCM simulations that were based on accelerated CO_2 levels for RCP 4.5 and RCP 8.5. RCP 4.5 represents rising radiative forcing stabilizing at 4.5 W/m^2 before 2100, and RCP 8.5 represents rising radiative forcing pathway leading to 8.5 W/m^2 in 2100, where radiative forcing expresses the change in energy in the atmosphere due to greenhouse gas emissions.

Projected flows are calculated from a hydrologically modeled derivation of statistically downscaled GCM outputs. Specifically, several GCMs from the CMIP-5 experiment suite were statistically downscaled using the Localized Constructed Analogs (LOCA) method. Those LOCA-downscaled outputs were then applied to drive the Variable Infiltration Capacity Model (VIC) hydrologic model. The LOCA -VIC model outputs employed by CHAT were generated by Scripps Institution of Oceanography (http://loca.ucsd.edu/loca-vic-runs/). The resulting simulated flows depict unregulated, in-channel routed runoff for the VIC model stream segment that most closely represents the cumulative flow from each HUC-8 watershed drainage area.

The USBR VIC model is set up to simulate unregulated basin conditions. The selected Royal River 8-digit HUC watershed is in the Presumpscot drainage basin, HUC 01060001, in Stream Segment 010000915. The location is shown in **Figure 14**.

Figure 18 and **Figure 19** show the range of output presented in the CHAT using 64 combinations of GCMs and representative concentration pathways (RCPs) applied to generate the climate-changed hydrology using the USBR VIC model. The information in the figures show results for the selected Royal River reach of the Presumpscot River watershed. For both the earlier 1951-2005 and the later 2006-2099 periods, the range of data is indicative of the uncertainty associated with projected, climate-changed hydrology (each is the result of combined outputs from the 32 models).

Climate Hydrology Assessment Tool v2.3



Simulated Trend Lines

Simulated Historical (1951 to 2005)

0.0516
Traditional Slope

Simulated Future (2006 to 2099)

0.0807
Traditional Slope-RCP 4.5

0.2317
Traditional Slope-RCP 8.5

Statistical Significance Tests (Historical)

Test	p-value
t-Test	0.51
Mann-Kendall	0.722
Spearman Rank-Order	0.649

Statistical Significance Tests (Future)

Test	p-value RCP 4.5	p-value RCP 8.5
t-Test	0.0604	4.02e-07**
Mann-Kendall	0.0608	2.38e-07**
Spearman Rank-Order	0.0744	3.79e-08**

Figure 18: Range of 64 Climate-Changed Hydrology Model Output for HUC 01060001 Presumpscot Stream Segment 01000915 Royal River.

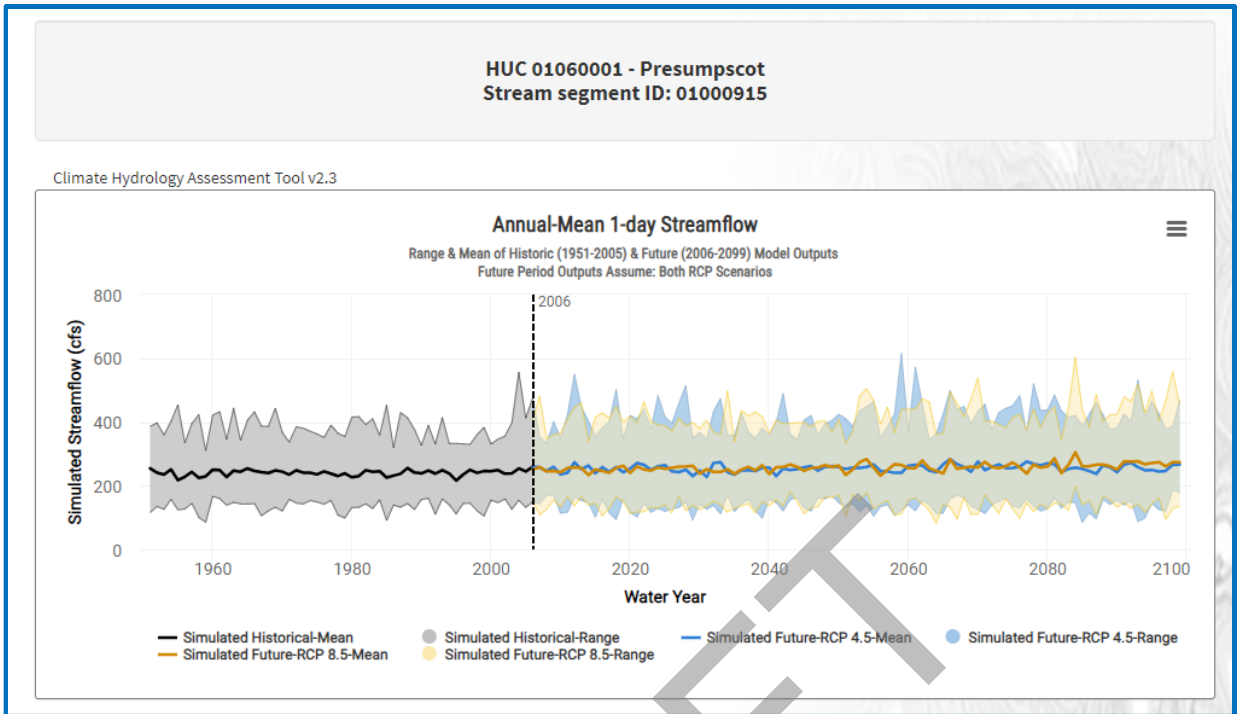


Figure 19: Range of 64 Climate-Changed Hydrology Model Output for HUC 01060001 Presumpscot Stream Segment 01000915 Royal River (*includes projected ranges for all models examined*).

For the selected Royal River reach, both the pre-2005 and post-2006 tests appeared to have a positive slope (on average, more flow from year to year). However, there was significant variance about the computed trendline; in the outputs, the hindcast included pre-2005 statistical significance values (p-values) that far exceeded 0.05; for the RCP 4.5 projection, the test values fell between 0.05 and 0.10 (failed at the USACE standard 95% confidence level, but passed at the less stringent 90% level); while the RCP 8.5 case reported p-values smaller than E-6 (greater than 99.9999% confidence that the slope was non-zero), with an estimated slope of 0.23 cfs/year.

It should be noted that the changes appear smaller in **Figure 18** than in **Figure 17** because the scale has been adjusted in **Figure 18** to include the full range of model results, and so the trends are less easily detected by eye.

Figure 20 has been prepared as a graphical presentation of the flow data shown in **Figure 18** and **Figure 19**.

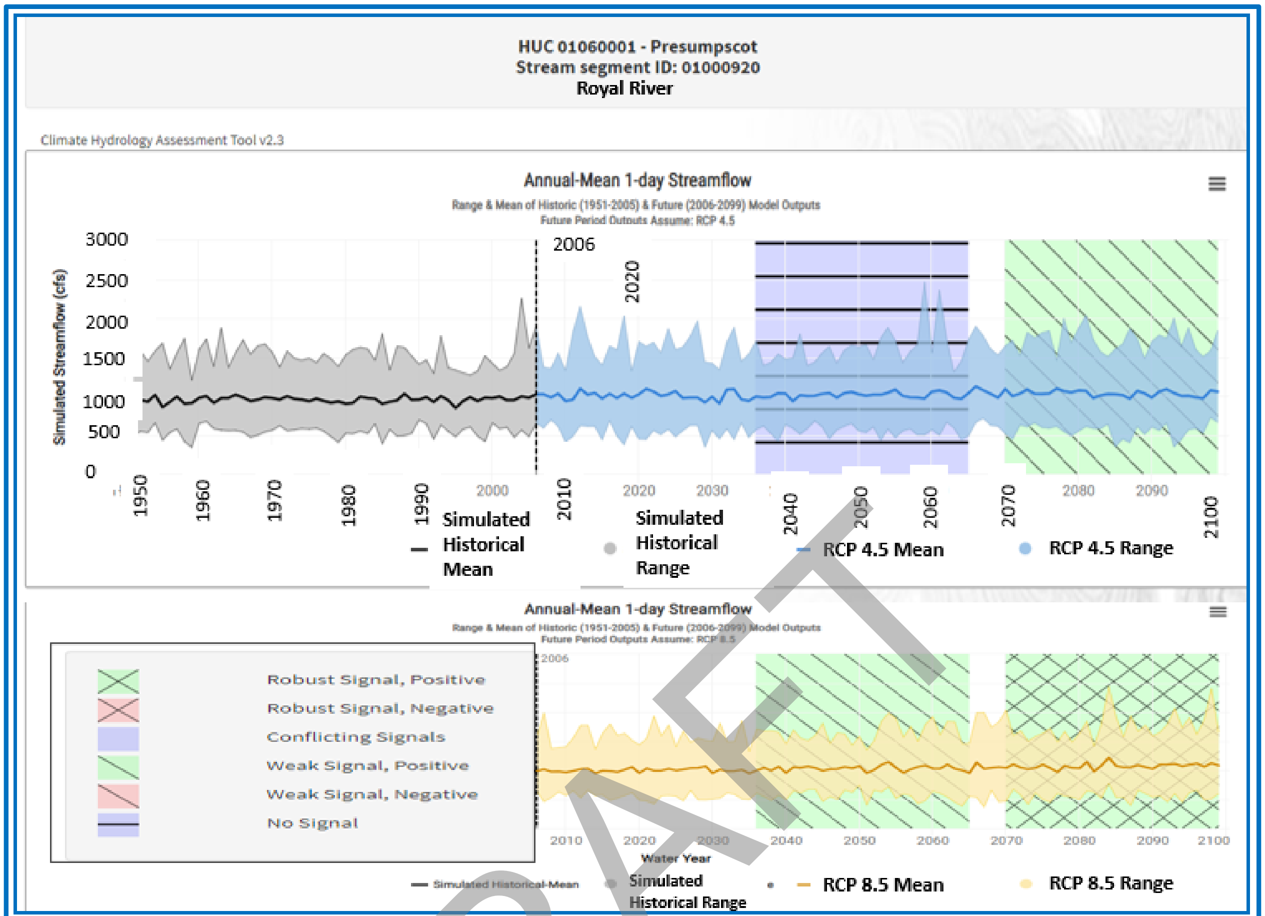


Figure 20: Royal River Summary of Projected Simulated Flows under RCP 4.5 and RCP 8.5 Rates of Climate Change

The figure illustrates that a rising annual mean streamflow under the RCP 8.5 scenario, becoming statistically significant in the period 2070-2100. Under the RCP 4.5 scenario, however, the rising pattern was not detected until the period prior to 2070, and the increasing (positive) pattern is not yet statistically significant in the period 2070-2100.

In summary, average flow in the Royal River is definitely projected to increase during the 21st century under the RCP 8.5 warming scenario. There is a smaller projected increase under the RCP 4.5 scenario, but the statistical confidence is smaller than 95%.

With respect to temperature-change and precipitation-change, the same features of the CHAT were used to generate **Figure 21** and **Figure 22**. For these figures, the annual mean precipitation and the annual mean 1-day temperature were selected.

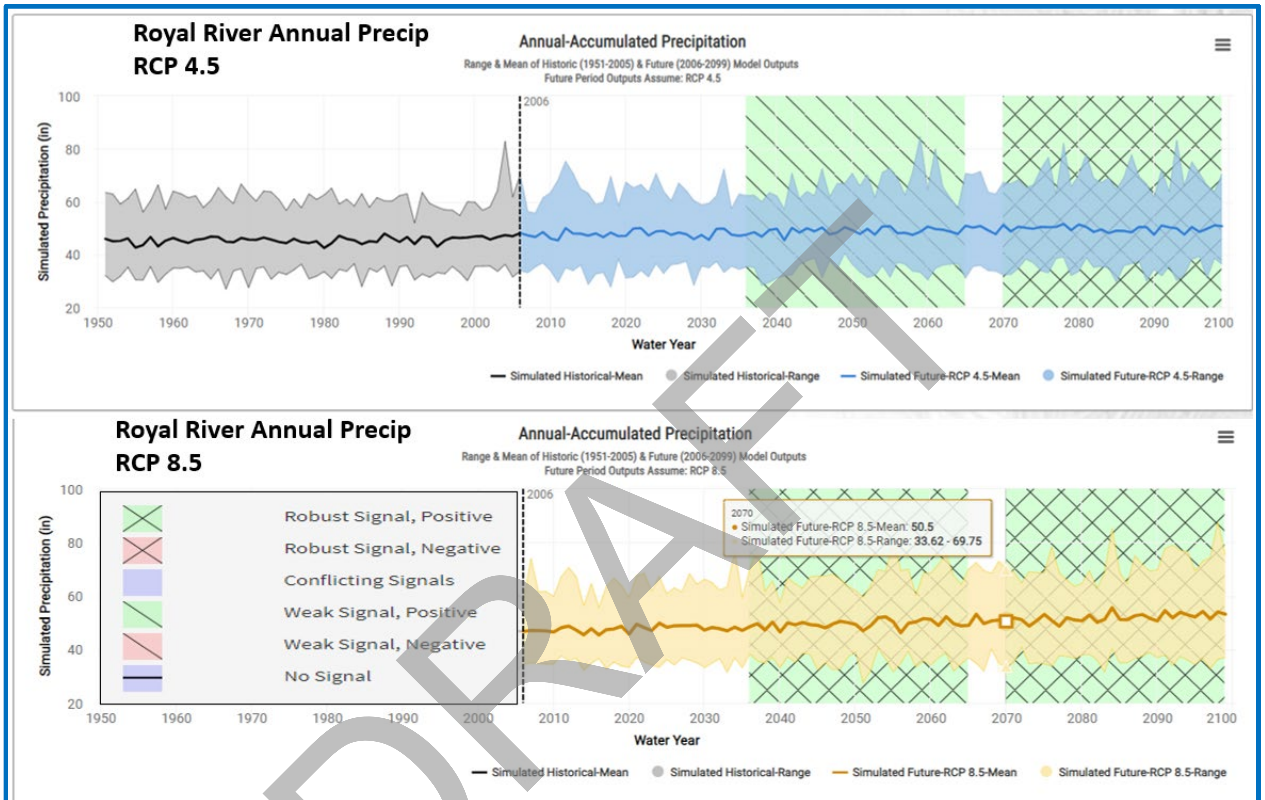


Figure 21: Selected Royal River Reaches: RCP 4.5 and 8.5 Precipitation Simulations

Under both RCP 4.5 and RCP 8.5 scenarios, the models used in the CHAT indicate increasing annual precipitation. Under RCP 4.5, the positive signal is weak in the years 2035 to 2065, but robust for the years 2070 to 2100. Under RCP 8.5, the signal is robust from 2035 through 2100. The mean annual precipitation rises from approximately 48 inches in 2006 to approximately 51 inches by 2100, judged by consensus of the models using the RCP 4.5 scenario, or to approximately 53 inches by 2100 under the RCP 8.5.

The models' projected increase 2006 to 2100 is thus 3 to 5 inches per annum of increased precipitation for the assumptions that were used.

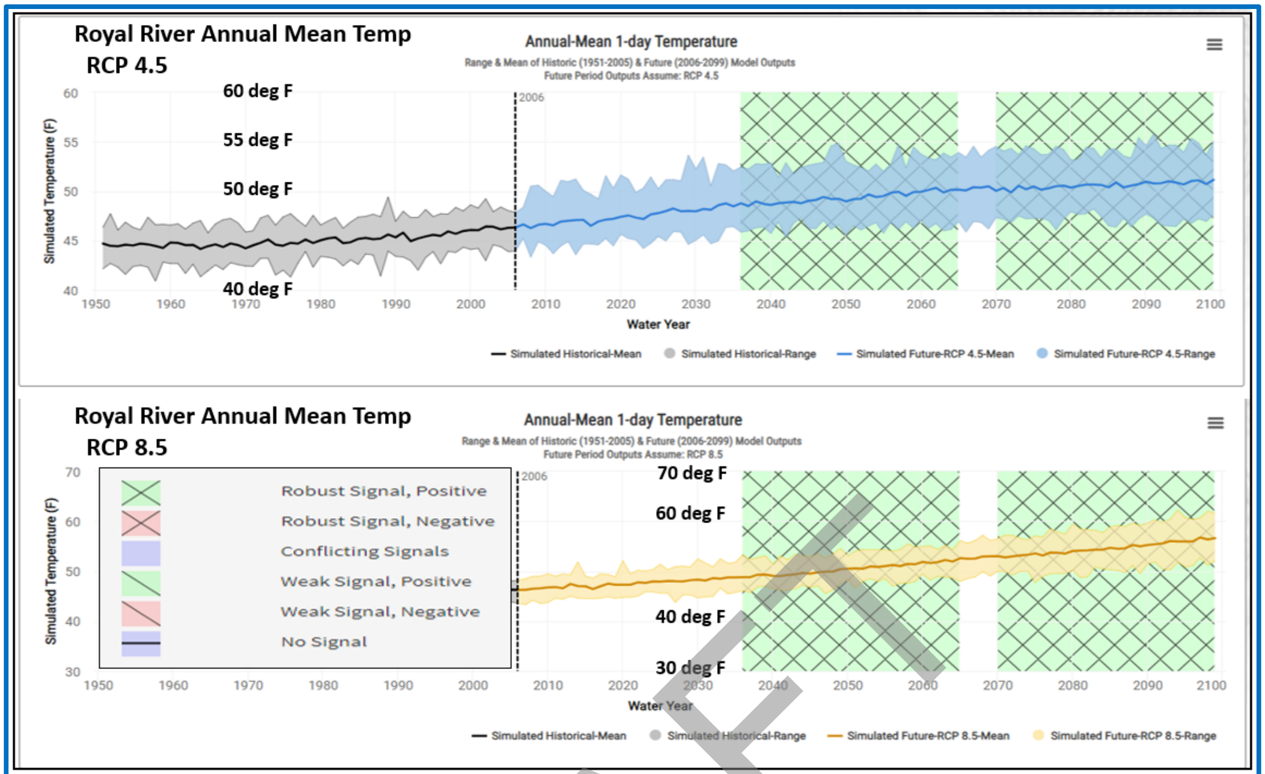


Figure 22: Selected Royal River Reaches: RCP 4.5 and 8.5 Precipitation Simulations

both RCP 4.5 and RCP 8.5 scenarios, the models used in the CHAT indicate increasing temperatures. In both cases, the positive signal is robust from 2035 through 2100. The mean temperature rises from approximately 48 °F in 2006 to approximately 52 °F by 2100, judged by consensus of the models using the RCP 4.5 scenario, or to approximately 56 °F by 2100 under the RCP 8.5.

The models' projected increase 2006 to 2010 is thus 4 to 8 degrees Fahrenheit for the assumptions that were used.

12.0 SEA LEVEL CHANGE

12.1 BACKGROUND

Global sea level change (SLC) is often caused by the global change in the volume of water in the world's oceans in response to three climatological processes: 1) ocean mass change associated with long-term forcing of the ice ages ultimately caused by small variations in the orbit of the earth around the sun; 2) density changes from total salinity; and most recently, 3) changes in the heat content of the world's oceans, which recent literature suggests may be accelerating due to global warming. Global SLC can also be caused by basin changes through such processes as seafloor spreading. Thus, global sea level, also sometimes referred to as global mean sea level, is the average height of all the world's oceans.

Relative (local) SLC is the local change in sea level relative to the elevation of the land at a specific point on the coast. Relative SLC is a combination of both global and local SLC caused by changes in estuarine and shelf hydrodynamics, regional oceanographic circulation patterns (often caused by changes in regional atmospheric patterns), hydrologic cycles (river flow), and local and/or regional vertical land motion (subsidence or uplift).

12.2 USACE GUIDANCE

In accordance with ER 1100-2-8162, potential effects of relative sea level change (RSLC) were analyzed over a 50-year economic period of analysis and a 100-year planning horizon. USACE guidance states "the period of analysis shall be the time required for implementation of the lesser of 1) the period of time over which any alternative plan would have significant beneficial or adverse effects 2) a period not to exceed 50 years" (ER 1105-2-100). However, because infrastructure often stays in place well beyond the economic period of analysis, a 100-year adaptation planning horizon is used to address robustness and resilience in the time of service of the project that can extend past its original design life. Research by climate science experts predict continued accelerated climate change for the 21st century and possibly beyond, which could cause a continued or accelerated rise in global mean sea level. ER 1100-2-8162 states that planning studies will formulate alternatives over a range of possible future rates of SLC and consider how sensitive and adaptable the alternatives are to SLC.

ER 1100-2-8162 requires planning studies and engineering designs to consider three future sea level change scenarios: low, intermediate, and high. The historic rate of SLC represents the low rate. The intermediate rate of SLC is estimated using the modified National Research Council (NRC) Curve I. The high rate of SLC is estimated using the modified NRC Curve III. The high rate exceeds the upper bounds of Intergovernmental Panel on Climate Change (IPCC) estimates from both 2001 and 2007 to accommodate the potential rapid loss of ice from Antarctica and Greenland but is within the range of values published in peer-reviewed articles since that time.

12.3 HISTORICAL SEA LEVEL CHANGE

The nearest long-term tide station to the mouth of the Royal River at Callen Point is NOAA Station 8418150 in Portland, approximately 10 miles southwest. The Portland gauge has a 112-year (1912-2024) record with a historical rate of RSLC of (1.96 mm/yr or 0.64 ft/yr). The full historical record with the 5- and 19-year moving averages is shown in **Figure 23**. It is apparent that over long timescales (19 years) mean sea level is steadily increasing. However, over shorter timescales mean sea level may increase or decrease. The monthly mean sea level (blue), for instance, goes up and down every year capturing the seasonal cycle in mean sea level. The 5-year moving average (cyan) captures the interannual variation (2 or more years).

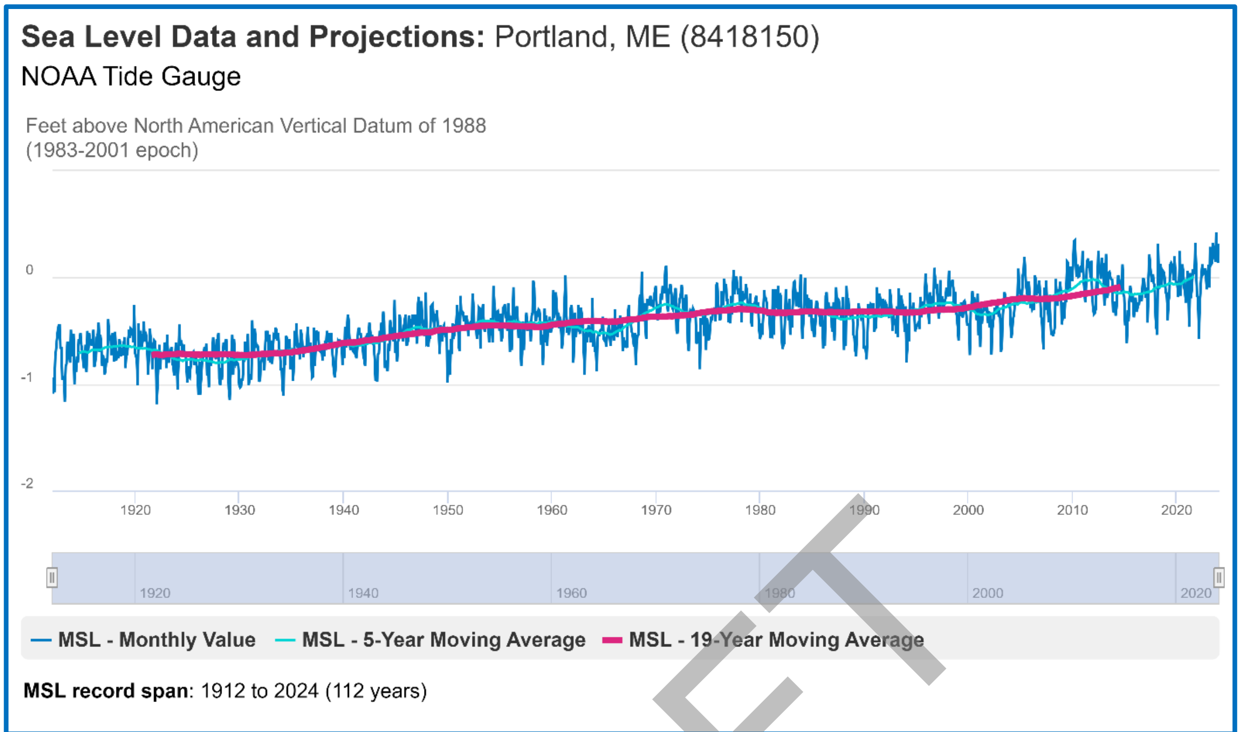


Figure 23: Historical RSLC at Portland, ME NOAA tide gauge

The USACE Sea Level Analysis Tool (SLAT) was also used to visualize historical SLC relative to the three USACE sea level change curves. **Figure 24** shows the historical record for the most recent 40 years with the three USACE SLC curves which originate in 1992, the midpoint of the present National Tidal Datum Epoch (1983-2001).

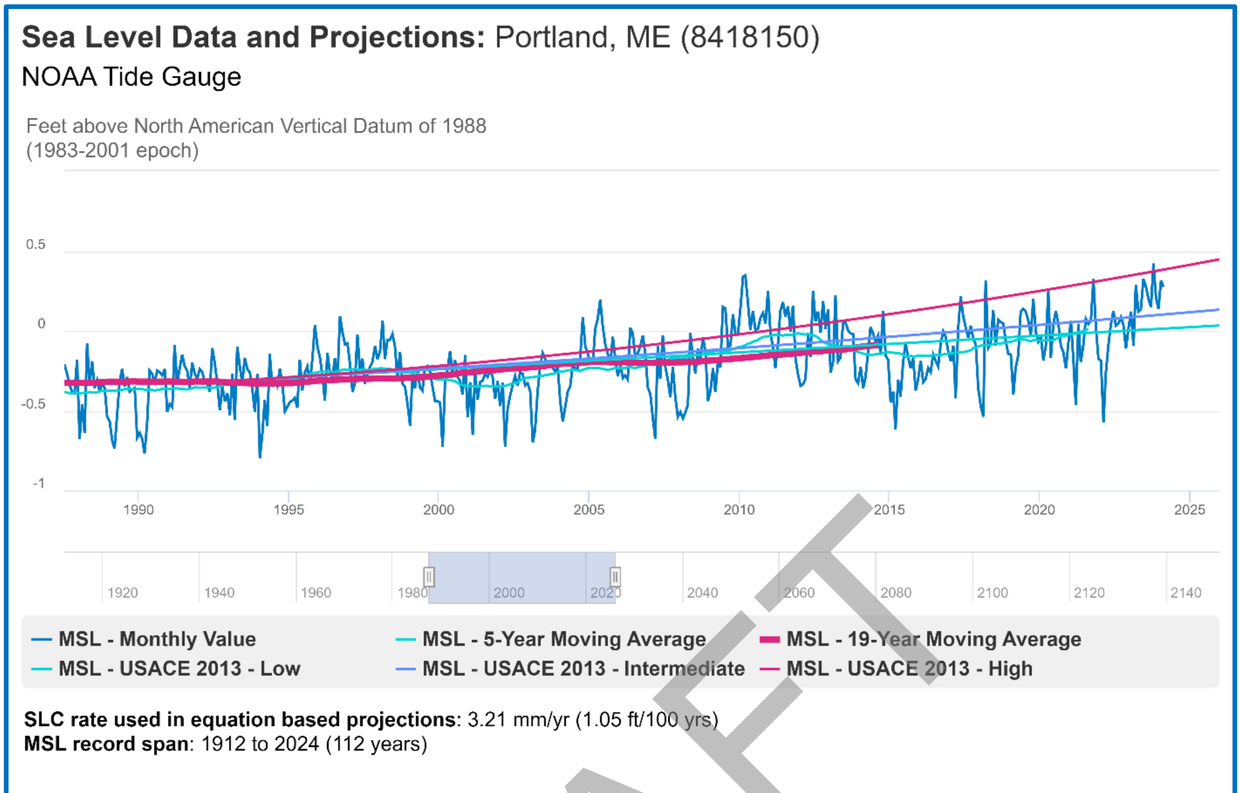


Figure 24: Historical RSLC at Portland, ME with three USACE SLC curves

12.4 USACE SLC SCENARIOS

USACE low, intermediate, and high SLC scenarios through the 100-year planning horizon at Portland, ME are presented in **Table 3** and **Figure 25**. It is anticipated that the dam removal would be complete by 2028. Using projections for the year 2030, it is estimated that mean sea level will be between 0.40 and 0.94 feet higher than the current National Tidal Datum Epoch (NTDE). At the end of the 50-year period of analysis, mean sea level is projected to be between 0.93 and 3.80 feet higher than the current NTDE.

Table 3: USACE Sea Level Projections: Portland, ME

Year	Low	Intermediate	High
1992	-0.32	-0.32	-0.32
2020	-0.02	0.04	0.27
2030	0.08	0.21	0.62
2040	0.19	0.39	1.04
2050	0.29	0.59	1.54
2060	0.4	0.81	2.11
2070	0.5	1.04	2.76
2080	0.61	1.3	3.48
2090	0.71	1.57	4.27
2100	0.82	1.85	5.14

Year	Low	Intermediate	High
2110	0.92	2.16	6.08
2120	1.03	2.49	7.1
2130	1.13	2.83	8.19

Units: Feet above NAVD88 (1983-2001 epoch)

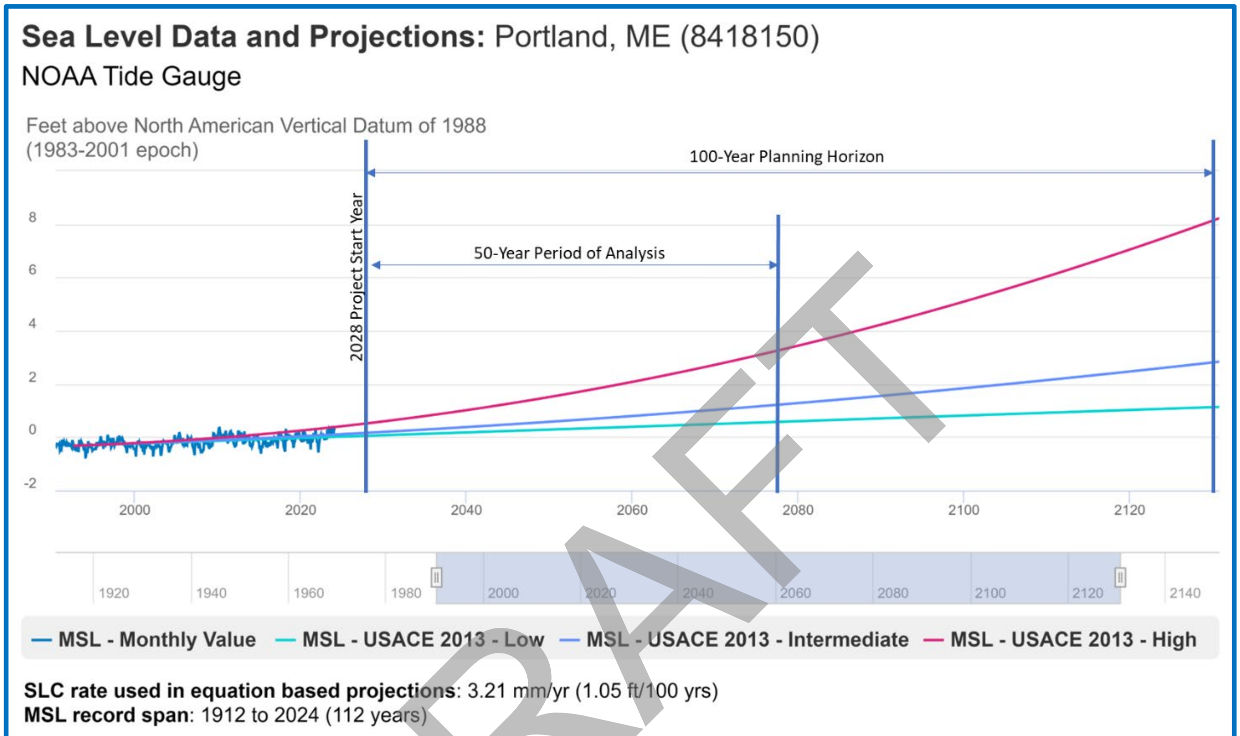


Figure 17: USACE Sea Level Projections for Portland, ME

12.5 SEA LEVEL CHANGE IMPACTS

The Royal River is currently tidally influenced below the First Falls. Elevations just upstream of the Falls rise to approximately 10 feet NAVD88, whereas the present NTDE Mean Higher High Water (MHHW) reaches 4.85 feet NAVD88. With SLC, tides are predicted to rise, approaching the First Falls, as shown in **Figure 26**. MHHW is not projected to exceed 10 feet NAVD88 and extend upstream of First Falls within the 50-year period of analysis. Under the high SLC scenario, MHHW is projected to reach 10 feet NAVD88 in the year 2099. However, MHHW is not projected to exceed First Falls under the low and intermediate SLC scenarios within the 100-year planning horizon.

Similarly, extreme astronomical tides and storm surges will also reach the First Falls and extend upstream more frequently with SLC. **Figure 27** shows how a range of present-day annual exceedance frequency event water levels, from 1-year to 100-year events, will change due to SLC. The likelihood of First Falls to be reached under storm events will increase with SLC and what is currently a lower probability event will become more frequent. However, given that the base of the first dam is at 24 feet NAVD88, astronomical tides and surges are not projected to extend that far upstream within the 50-year period of analysis or the 100-year planning horizon.

Ultimately, as sea level change occurs, water levels will deepen. This will have a positive effect on the project as it will ease fish passage and the ability for fish to move upstream.

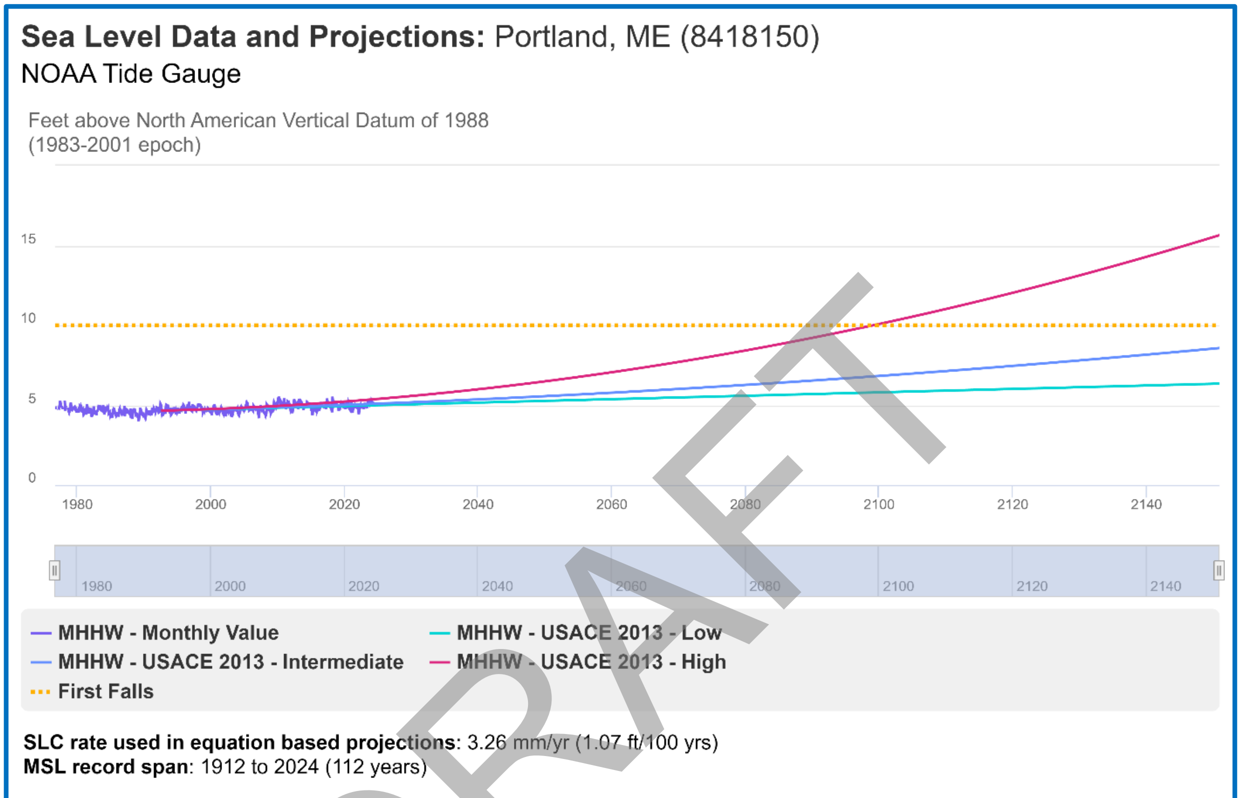


Figure 26: Mean Higher High-Water Projections with SLC relative to First Falls

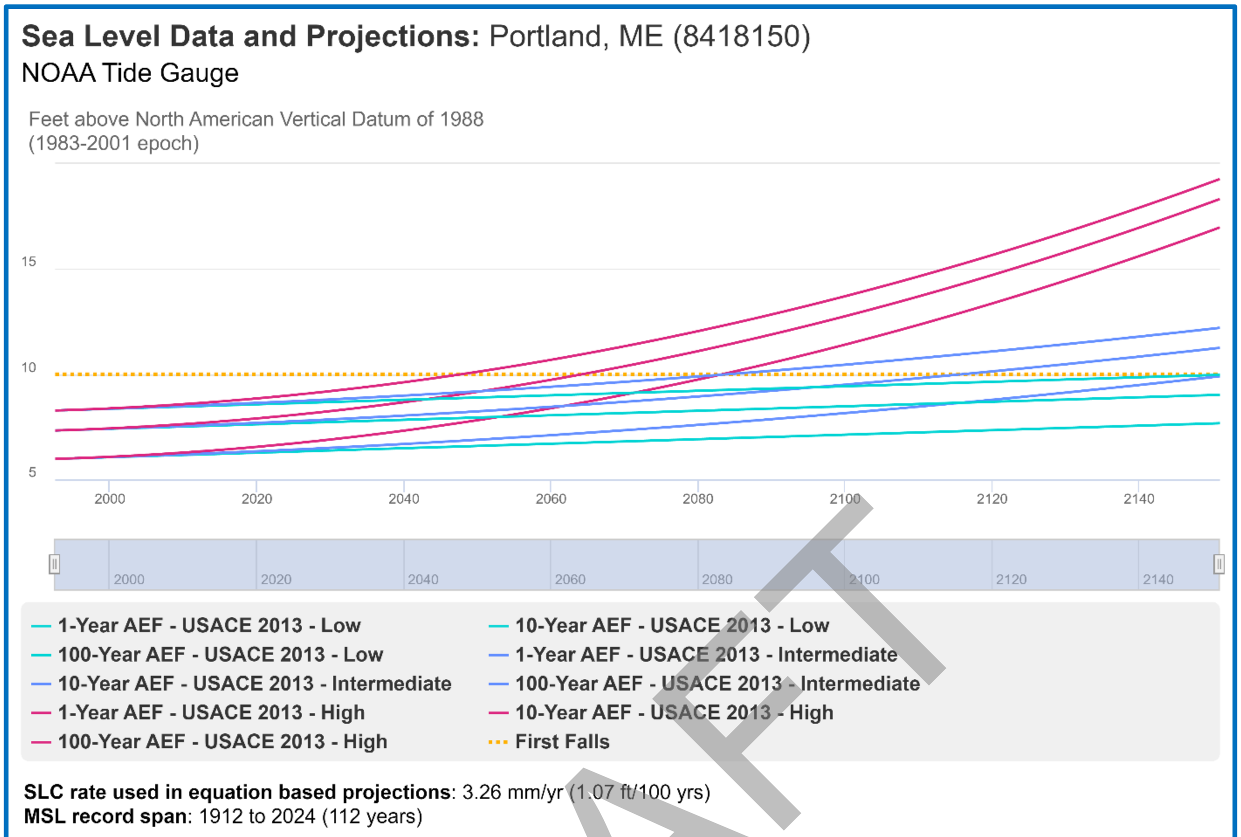


Figure 27: Annual Exceedance Frequency (AEF) Event Water Levels with SLC relative to First Falls

13.0 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.

As shown in **Figure 28**, the Saco River Basin (HUC 0106) watershed is not considered vulnerable to climate change impacts for the ecosystem restoration business line, since it is not among the 20% most vulnerable watersheds for this business line in the CONUS (202 HUC04s). This is true for both the wet and dry scenarios and both the 2050 and 2085 epochs. Although the HUC 0106 watershed is not considered vulnerable in a relative sense to impacts from climate change, it may still be vulnerable in an absolute sense.

The primary drivers of ecosystem restoration vulnerability assessment for wet scenarios under the two epochs are indicators 8 At-Risk Freshwater Plants and 227 the Runoff-Precipitation Ratio. Other indicators were: 65L Mean Annual Runoff, 156 Sediment, 221C Monthly Covariance (a measure of short-term variability in the region's hydrology: it is the 75th percentile of annual ratios of the standard deviation of monthly runoff to the mean of monthly runoff, and it includes upstream freshwater inputs), 297 Macroinvertebrates (the sum of six scores 0-100 for: taxonomic richness, taxonomic composition, taxonomic diversity, feeding groups, habits, and pollution tolerance) 568C Flood Magnification, 568L Flood Magnification, 700C Low Flow Reduction (change in low runoff as the ratio of 570C monthly runoff exceeded 90% of the time, including freshwater inputs, to 570C in the base period). 568C is a ratio of flood runoff to monthly runoff exceeded 10% of the time; 568L is the same ratio, but it does not include upstream watershed.

In both projected epochs, and for both the wet and dry scenarios, the VA/WOWA score remained below the level of the top 20% of vulnerabilities. The score for the wet scenarios was marginally (2% or less) greater than for the dry scenarios in each epoch. The scores increased by approximately 2% between the earlier and the later epochs, for the dry scenarios, but were essentially the same for the wet scenarios. The increases over time indicate that there might be a later epoch (than the late 21st century) in which the vulnerability of the Saco Basin (HUC 0106) to climate change impacts with respect to the ecosystem restoration business line would result in a "vulnerable" assessment, scored in comparison to other HUC-4 basins. The scores are summarized in **Table 4**, and the indicators themselves are listed in **Table 5**.

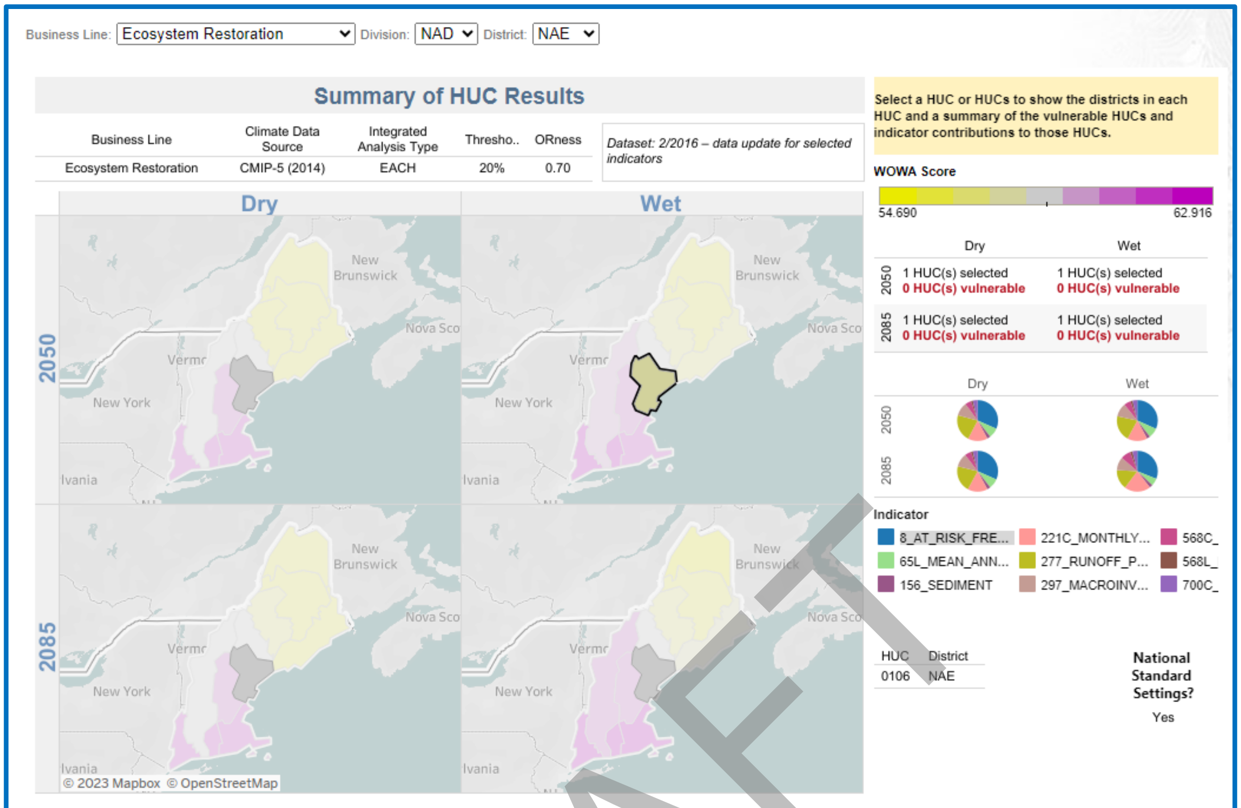


Figure 28: Output of VA Tool for the Saco River Basin Watershed (HUC 0106)

The VA Tool indicates the Saco River Basin watershed (HUC 0106) is not among the 20% most vulnerable CONUS watersheds for the Ecosystem Restoration business line under wet and dry scenario projections in both the 2050 and 2085 epochs (**Figure 26**).

Table 4: Projected Vulnerability with Respect to Ecosystem Restoration

HUC4 Watershed	Projected Vulnerability with Respect to Flood Risk Reduction			
	Ecosystem Restoration Vulnerability Score			
	2050 Dry	2050 Wet	2085 Dry	2085 Wet
Saco River Basin (0106)	58.389	58.245	58.357	59.237

Table 5: Comparison of Different Indicators for the Saco River Basin

Saco River Basin (0106)				
Indicator	**Indicator Contributions to WOWA Flood Risk Reduction Vulnerability Score (percentages)**			
	2050 Epoch		**2085 Epoch**	
	Dry	**Wet**	**Dry**	**Wet**
8 At-Risk Freshwater Plant Score – Percentage of wetland and riparian plant communities that are at risk of extinction, based on remaining number and condition, remaining acreage, threat severity, etc.	31.61	31.63	31.69	31.08
65L Mean annual runoff	7.88	7.85	7.81	5.86
156 Sediment (ratio of the change in the sediment load in the future to the present load).	2.64	2.64	2.64	2.59
221C Monthly Covariance: Measure of short-term variability in the region's hydrology: 75th percentile of annual ratios of the standard deviation of mean monthly runoff to the mean of monthly runoff. Includes upstream inputs (cumulative).	15.55	15.84	15.78	20.78
277 Runoff Precipitation – Median of: deviation of runoff from monthly mean times average monthly runoff divided by deviation of precipitation from monthly mean times average monthly precipitation	21.51	20.95	20.52	15.54
297 Macroinvertebrate: Macroinvertebrate score as the sum of six scores 0-100 for: taxonomic richness, taxonomic composition, taxonomic diversity, feeding groups, habits, and pollution tolerance)	10.68	10.68	10.70	10.50
568C Flood Magnification – change in flood runoff: ratio of indicator 571C (monthly runoff exceeded 10% of the time, including upstream inputs) to 571 in base period. *See Footnote*	4.89	5.11	5.47	7.94
568L Flood Magnification – change in flood runoff: ratio of indicator 571L (monthly runoff exceeded 10% of the time, excluding upstream freshwater inputs) to 571L in base period. *See Footnote*	1.49	1.55	1.66	1.86

Saco River Basin (0106)				
Indicator	**Indicator Contributions to WOWA Flood Risk Reduction Vulnerability Score (percentages)**			
	2050 Epoch		**2085 Epoch**	
	Dry	**Wet**	**Dry**	**Wet**
700C Low Flow Reduction (change in low runoff as the ratio of 570 C monthly runoff exceeded 90% of the time, including freshwater inputs, to 570C in the base period)	3.75	3.75	3.73	3.85
Footnote: The 568C and 568L *indicator values* are the same, but their *importance weights* are not. The overall WOWA score (vulnerability score) accounts for the *indicator value* and the *importance weights* to compute the vulnerability score. This is why the WOWA scores listed in the VA tool have different values. "Some indicators are more directly relevant to a business line than others, so giving every indicator the same weight would be inappropriate – Instead, the tool uses subjective weights that assign more weight to indicators that are highly relevant or important." – VA User Manual				

14.0 CONCLUSION

The purpose of the Royal River study is to facilitate fish migration in the river, with a view to reintroducing migrating species that have been unable to migrate past the dams in Yarmouth. The selected plan notes potential suitable habitat in small regional tributaries and, if dams are removed, in the currently impounded areas, although the nature of these areas is less well known.

Output based on both historical observed hydrometeorological data and projected, climate-changed hydrometeorological data is reviewed to support qualitative statements about how to incorporate resilience to climate change impacts over the duration of the 21st century. Projections have extended through the 2100 and, with respect to sea-levels, through 2125.

Recent climate science literature indicates observed trends of rising mean and extreme temperatures. The literature indicates observed precipitation mean and likely also peak values showing rising trends. The literature is equivocal, however, on projected stream runoff trends. As a result, projections of future streamflows are mixed and depend on the climate model and its assumptions. Observed trends in streamflow vary by season, but some evidence exists of earlier and likely larger flows in the spring and smaller flows in the late summer.

The nonstationarity analysis indicated multiple nonstationarities in the monthly streamflow record (eight clusters of non-stationarity observations in the years 1949 to 2003, with a significant gap in the record 2004 to 2020). The changes could have been caused by changes in operation at multiple upstream dams, by effective regulation of flows at bridges, or possibly due to underlying climate change. Trend analysis showed a slight decreasing pattern, but this was not statistically significant.

The CHAT HUC-8 review of simulated annual mean 1-day streamflow indicated, however, that the annual mean flows in the Royal River (HUC 01060001, Stream Segment 01000915) were increasing over time, with significance that approached the significance cut-off using the RCP 4.5 assumptions (92% to 94% certainty, not quite "significant" for USACE's 95% purposes), to greater than 99.9% confidence for the RCP 8.5 assumptions.

There were, however, no nonstationarities detected with respect to annual average streamflow. The average annual streamflow was seen to be reducing slightly over time, but the trend was not significant at the 95% level.

As a result, projections of future streamflows are mixed and depend on the climate model and its assumptions.

Sea-level is known to be rising, although there is not yet consensus about the rate of change. The higher relative sea level for this ecosystem restoration project would promote fish passage from the Atlantic to upstream spawning locations. The possibility of non-native species, such as fish, shellfish and aquatic plants, entering the watershed would be aided by the rising water, and possibly also by rising temperatures. Removing dams increases typical velocities at the dam sites, creating a barrier to upstream passage for weak-swimming species; this effect is limited by rising sea-levels. Warmer weather promotes non-native species such as shellfish which could compete with native species for habitat.

The watershed is not vulnerable, in the ecosystem-restoration business line, relative to other CONUS watersheds (not in the top 20% list of vulnerable watersheds). The watershed may still be vulnerable to the impacts of climate change in an absolute sense.

As indicated in **Table 6**, high flows occasioned by more intense rainfall would lead to greater velocities along the Royal River and its tributaries. Partial or complete removal of dams would accentuate this effect. In general, flows are projected to increase in three seasons, but would be slightly smaller in the summer months. Intense storms are expected to become more frequent during the 21st century. The table outlines how the main proposed changes to the system might be affected by changes in inflow patterns. The regional (HUC-specific) data do not indicate a clear climatic change underway for the basin, but there are clearly signs of increasing temperature, projected seasonal changes in precipitation, observed changes in seasonal flows, with a longer growing season and with earlier spring snowmelt and associated high flows.

Based on this assessment, the effects of climate change are likely to lead to increases in overall flow and spring flow. Temperatures will rise. Summer flows will likely decrease. Evidence supporting projected changes in temperature, precipitation and streamflow has become stronger from the NCIA (Frumhoff 2007), through the USACE 2015 summary, the NCA4 (2018) and NCA5 (2023). Site-specific observations support the increases in 1-day maximum precipitation, while the CHAT indicates that for RCP8.5, monthly average flow will rise, although the lower RCP4.5 case leads to a projected increase in flow that is less certain (confidence in the trend is less than 95%, at only 93 to 94%).

Mitigation for the inland streamflow effects (warmer, drier summers and falls) is therefore likely to be needed.

Although residual risk to the ecosystem restoration objectives of the project due to climate change is classified as moderate (the signs and projections of change are clear), it is likely that design of fish passage structures and shading of any exposed riverbanks can mitigate these concerns.

The recreational concern of dam removal generating increased sediment load and additional nuisance shoaling at the downstream boat docks is unlikely to be valid, based on the hard rock riverbed and minimal sediment available, and by comparison with dam removals described at the nearby Penobscot River.

Table 6: Residual Risk to Royal River Ecosystem Restoration due to Climate Change

Residual Risk to Royal River Ecosystem Restoration due to Climate Change				
Feature or Measure	**Trigger**	**Hazard**	**Harm**	**Qualitative Likelihood**
1 - RED - Fish Passage (Ladder and Side Channel Options)				
2 - BLUE - Dam Removal or Partial Dam Removal Options				
1. Addition of Fish Ladders, promotes fish passage especially upstream during spring migration season. **Side Channel for Fish.**	**1.1 Higher temperatures.**	With warming, migrating fish tire more easily, and so would need more resting areas within the ladder(s) than current best-practice assumes. Low flows in warmer summers could strand juvenile fish. Higher temperatures lead to less dissolved oxygen. New non-native species compete with the target species. Invasive weeds reduce the DO in the water.	Target species, resting longer before attempting upstream migration, become prey to mammals and birds. Target species declines due to competition with different species or due to low dissolved oxygen in the warmer water. Fish populations decline due to low dissolved oxygen because of new plants (such as hydrilla).	**Likely**. Fish ladder design has been shown to be effective, but research is continuing to establish how to deal with exotic weeds (hydrilla) elsewhere in New England. **Adaptive note:** Appropriate landscaping (trees) at the stream banks might be needed to provide cooler areas for fish habitat.

Residual Risk to Royal River Ecosystem Restoration due to Climate Change				
Feature or Measure	**Trigger**	**Hazard**	**Harm**	**Qualitative Likelihood**
1 - RED - Fish Passage (Ladder and Side Channel Options)				
2 - BLUE - Dam Removal or Partial Dam Removal Options				
1. Addition of Fish Ladders, promotes fish passage especially upstream during spring migration season. **Side Channel for Fish.**	**1.2 More intense precipitation and river flows.** **Earlier snowmelt, flows, and upstream migration season.**	Rain on reservoir introduces oxygen during storm events; rain in the drainage basin introduces runoff that includes debris and sediment, which potentially limit the dissolved oxygen in the lakes/reservoirs. Earlier snowmelt means the surge in cold spring runoff may occur before there are fish attempting to swim upstream. Warmer runoff means reduced capacity for dissolved oxygen.	Low oxygen levels in the water lead to fish-kills. Rainfall changes lead to changes in flow, causing more, and more abrupt, changes in stream velocity. Sediment from the drainage basin during storm events reduces the oxygen content in the streams and reservoirs, leading to fish-kills.	**Likely.** **Adaptive note:** Careful monitoring, maintenance and landscaping adjacent to the streambanks could curtail the sediment loading and oxygen deficits during storms.

Residual Risk to Royal River Ecosystem Restoration due to Climate Change				
Feature or Measure	**Trigger**	**Hazard**	**Harm**	**Qualitative Likelihood**
1 - RED - Fish Passage (Ladder and Side Channel Options)				
2 - BLUE - Dam Removal or Partial Dam Removal Options				
1. Addition of Fish Ladders, promotes fish passage especially upstream during spring migration season. **Side Channel for Fish. Essentially, this is a fish ladder**	**1.3 STREAMFLOW.** **Higher peak flows for much of the year.** **Lower flows are projected in a typical summer.**	Upstream migration season has increased flows with greater velocities. The temperature rises in the lower-flow stream systems and lakes: increased temperatures reduce the oxygen-carrying capacity of the water. In an extended drought period, the fish are in shallower water and so more exposed to predators (fish and mammals). Runoff from rain immediately after a dry period would likely carry a sediment load, potentially reducing the oxygen-carrying capacity of the river/lakes.	Fish are less able to migrate upstream during the spring (May-June) season due to high velocities. Summer fish-kills. If there are multiple species, it is possible that there would be competition for areas that are more sheltered within the lakes and streams. The target species may not be favored in the competition.	**Neutral.** The higher flows are projected, but the outcome will be a marginal change in how long fish need to wait before attempting the upstream migration. The lower flows are likely, but it is unclear which species will gain from the competition in the upstream rivers and lakes. Shallower, faster flows in summer is affected more directly by atmospheric oxygen, tending to increase dissolved oxygen in the water. **Adaptive notes:** Fish passage design can accommodate the anticipated flow velocities. Introduction of river-side shading such as trees might promote fish habitat. Landscaping measures could minimize the introduction of sediment loads when storms occur.

Residual Risk to Royal River Ecosystem Restoration due to Climate Change				
Feature or Measure	**Trigger**	**Hazard**	**Harm**	**Qualitative Likelihood**
1 - RED - Fish Passage (Ladder and Side Channel Options)				
2 - BLUE - Dam Removal or Partial Dam Removal Options				
1. Addition of Fish Ladders, promotes fish passage especially upstream during spring migration season. **Side Channel for Fish.**	**1.4 Sea-level rise**	SLR may promote encroachment of non-native species of fish and plants. Hydrilla would lead to low DO in the lakes and/or river.	The non-native species would compete with target species until a new equilibrium is reached. This might include a much smaller target-species population than projected. Weeds could cause fish kills (too little dissolved oxygen for fish to breathe).	**Likely.** (1 to 4 ft rise over the 21st century is expected; the new species are likely to follow). ERDC has a project to investigate an invasive weed (hydrilla) in the Connecticut River, also in New England but south of Maine, and this is now seen as far as 40 miles upstream from the coast where there is still a tidal influence. **Adaptive notes:** Ongoing monitoring and maintenance might be needed. It is likely that the plants can be treated with herbicides, but permits would be needed. Stations to clean off boat hulls and public awareness campaigns might be needed. Fish ladders/channels could be designed with target species in mind.

Residual Risk to Royal River Ecosystem Restoration due to Climate Change				
Feature or Measure	**Trigger**	**Hazard**	**Harm**	**Qualitative Likelihood**
1 - RED - Fish Passage (Ladder and Side Channel Options)				
2 - BLUE - Dam Removal or Partial Dam Removal Options				
2. Partial or complete removal of Dam(s), likely removes the entire reservoir, but retains some potential reservoir storage during extremely large storms. **The temperature-buffering in a reservoir is lost** **The higher temperatures are partly offset by groundwater inflows.** **Shallower water makes fish more susceptible to predators (birds, mammals).**	**2.1 TEMPERATURE** **Higher temperatures** **Lower summertime flows exacerbate temperature increases in the former lake(s).**	Loss of target fish species due to predation and low oxygen content in the water. Combination of ideal flow (80 to 400 cfs) with ideal water temperatures (41 °F to 50 °F) in May-June changes the upstream migration season – fish arrive too early/too late and become prey for mammals and birds. **Too early** – not yet strong enough for the upstream migration; **too late** – need to compete for spawning locations in the upstream river locations. New weeds reduce the DO in the water.	Target species population is reduced. • Fish are more exposed to predators during upstream migration. • Fish are more easily fatigued during upstream migration. • Target species fish are outcompeted by stronger swimmers. • Fish kill due to low oxygen content in the water.	**Neutral:** Temperatures will likely rise, but all fish species will be affected. Buffering of temperatures from groundwater is expected. Greater velocities when reservoirs are removed will likely introduce more oxygen from eddies/ripples. **Adaptive notes:** Monitoring for hydrilla might be needed; monitoring to know when and how to restock upstream reservoirs might be needed. Landscaping options (trees near riverbanks) would provide cooler locations along the river. Monitoring and removal of predators might be needed.

Residual Risk to Royal River Ecosystem Restoration due to Climate Change				
Feature or Measure	**Trigger**	**Hazard**	**Harm**	**Qualitative Likelihood**
1 - RED - Fish Passage (Ladder and Side Channel Options)				
2 - BLUE - Dam Removal or Partial Dam Removal Options				
2. Partial or complete removal of Dam(s), likely removes the entire reservoir, but retains some potential reservoir storage during extremely large storms. The temperature-buffering in a reservoir is lost, but the higher temperatures are partly offset by groundwater inflows. **Shallower water makes fish more susceptible to predators (birds, mammals).**	**2.2 RAINFALL:** **More intense precipitation and faster river flows in general.** **Earlier snowmelt and flows, earlier upstream migration season** **Lower summertime precipitation leads to low dissolved oxygen.**	Upstream migration is more difficult (greater velocities, less effective fish passage). More frequent departures from "average" flow favor hardier species. Combination of ideal flow (80 to 400 cfs) with ideal water temperatures (41 °F to 50 °F) in May-June changes the upstream migration season – fish arrive too early/too late and become prey for mammals and birds. Low rainfall in summer leads to low DO and fishkill before the downstream migration occurs.	Fish population dwindles due to losses as: • Fish are more exposed to predators during upstream migration. • Fish are more easily fatigued during upstream migration. • Target species fish are outcompeted by stronger swimmers. • Low DO in the summer.	**Neutral:** Dam removal has limited effect on reservoir storage because there is so little volume behind these run-of-river dams; but weak swimmers would struggle through the rapids to get to calmer waters farther upstream. Increased precipitation will enhance entrainment of oxygen during runoff events, favoring fish survival through spawning, laying, and fingerling stages. Conversely, less precipitation is expected in the summer, so juvenile fish may be subject to low dissolved oxygen. The combined temp-range-with-flow-range and its repercussions are not well understood. **Adaptive notes:** Monitoring might be needed to remove predators from time to time.

Residual Risk to Royal River Ecosystem Restoration due to Climate Change				
Feature or Measure	**Trigger**	**Hazard**	**Harm**	**Qualitative Likelihood**
1 - RED - Fish Passage (Ladder and Side Channel Options)				
2 - BLUE - Dam Removal or Partial Dam Removal Options				
2. Partial or complete removal of Dam(s), likely removes the entire reservoir, but retains some potential reservoir storage during extremely large storms. The temperature-buffering in a reservoir is lost	**2.3 STREAMFLOW** **Annual peak flows are expected to increase. This typically occurs in upstream migration season.** **Summer flows are expected to decrease.**	Upstream migration is more difficult (greater velocities, less effective fish passage). Especially in stormy conditions, fish are forced to wait longer before attempting the upstream migration through the rapids. More frequent departures from "average" flow favor hardier species. Lower summer flows lead to higher water temperatures and lower dissolved oxygen for young growing fish.	Fish population dwindles due to losses as: • Predators find the fish while they are waiting to attempt the upstream migration. • Fishkill occurs from low DO in slow-moving or stagnant water. • Predators find lethargic (oxygen-deprived) young fish more easily in shallower water.	**Neutral to likely:** Unlikely that dam removal materially affects reservoir storage because there is so little volume behind these run-of-river dams; but during upstream migration weak swimmers would struggle through the rapids. **Adaptive notes:** Mitigation might require fish ladders or channels for upstream migration; and landscaping such as trees to limit high summertime day-time temperatures. Monitoring and restocking might be necessary to fine-tune target species populations. Predators might need to be removed on occasion.

Residual Risk to Royal River Ecosystem Restoration due to Climate Change				
Feature or Measure	**Trigger**	**Hazard**	**Harm**	**Qualitative Likelihood**
1 - RED - Fish Passage (Ladder and Side Channel Options)				
2 - BLUE - Dam Removal or Partial Dam Removal Options				
2. Partial Removal of Dam(s), likely removes the entire reservoir, but retains some potential reservoir storage during extremely large storms. The temperature-buffering in a reservoir is lost. **Complete Dam Removal(s), removes the reservoir.**	**2.4 Ocean warming and Sea-Level Rise.**	Fish disease increases. Fewer target species fish return for spring migration. More species compete with the target species for habitat in the river.	New species outcompete the target species, and so the target species population falls. Algal blooms occur more frequently and all fish species populations decrease.	**Likely to very likely:** Increased disease rates are already seen in shrimp, shellfish and migratory fish. SLR has been observed and is projected to increase by 1 to 4 feet in the 21st century. The reduction in swimming effort from sea level to river level will help more species, although the native target species are likely better suited to the river environment. **Adaptive notes:** Mitigation via fish passage structures could be designed to favor particular (target) species.

Residual Risk to Royal River Ecosystem Restoration due to Climate Change				
Feature or Measure	**Trigger**	**Hazard**	**Harm**	**Qualitative Likelihood**
1 - RED - Fish Passage (Ladder and Side Channel Options)				
2 - BLUE - Dam Removal or Partial Dam Removal Options				
2. Partial Removal of Dam(s), likely removes the entire reservoir, but retains some potential reservoir storage during extremely large storms. The temperature-buffering in a reservoir is lost. **Complete Dam Removal(s), removes the reservoir.**	**2.5 Increased sediment load passes into Casco Bay.**	Sediment collects in the bay.	Boating community in the bay experiences sedimentation that affects navigation issues in the harbor.	**Unlikely:** Experience with dam removal at Great Works Dam and Veazie Dam on the Presumpscot River in the same HUC 8 (01060001) indicates the sediment load is small. Collins et al 2020 indicated small grain sizes are likely to favor wide dispersal of any liberated sediments (clumping less likely). Exploratory borings in 2023 indicate the quantity of loading is much smaller than initially estimated. **Adaptive notes:** Monitoring immediately after dam removal may indicate a need to move sediment in the bay, but this is unlikely to be necessary.

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