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Quantitative Assessment of Temperature Sensitivity of the South Fork Nooksack River under Future Climates using QUAL2Kw

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Abstract

The Total Maximum Daily Load (TMDL) program, established by the Clean Water Act, is used to establish limits on loading of pollutants from point and nonpoint sources necessary to achieve water quality standards. One important use of a temperature TMDL is to allocate thermal loads to achieve water temperature criteria established for the protection of cold water fisheries. The pollutant in this case is thermal load and allocations to reduce the load often involve restoration of stream shading, which reduces the solar input. While many temperature TMDLs have been established, the supporting analyses have generally assumed a stationary climate under which historical data on flow and air temperature can serve as an adequate guide to future conditions. Projected changes in climate over the 21st century contradict this assumption. Air temperature is expected to increase in most parts of the US, accompanied in many areas by seasonal shifts in the timing and amount of precipitation, which in turn will alter stream flow. This study evaluates the implications of climate change for the water temperature TMDL developed for the South Fork Nooksack River in northwest Washington by the Department of Ecology, where multiple water body segments exceed temperature criteria established for the protection of cold water salmonid populations (Ecology, 2016). The purpose of this report is to provide a "companion technical methods manual" as documentation for the draft SFNR temperature TMDL developed by Ecology. The TMDL analyses use Ecology's QUAL2Kw stream simulation model in conjunction with an analysis of shading to predict the temperature profile during critical conditions of summer low flow and elevated air temperatures. The modeling shows that restoration of system potential vegetation shading would significantly mitigate increasing water temperature. We reran the QUAL2Kw model for future climate conditions (multiple climate models for the 2020s, 2040s, and 2080s) using gridded downscaled climate data and hydrologic model runoff predictions developed by the Climate Impacts Group at the University of Washington to modify the critical conditions inputs using a change factor approach. Results show that the risk of higher water temperature will accelerate over time. Projected increases in heat inputs and lower summer flows associated with a reduction in the storage of winter snowpack combine to exacerbate summer water temperature extremes and may begin to overwhelm the mitigating impact of increased shading by the 2040s, with a high probability of exceeding cited lethal temperature thresholds under low flow critical conditions. We note, however, that the TMDL focuses on extreme conditions (e.g., 7-day low flow with 10-year recurrence), and predictions are more favorable for less extreme flow conditions – for instance, at a 2-year low flow recurrence water temperatures through the 2080s are generally predicted to remain below lethal thresholds with enhanced shading in place. Indeed, the importance of system potential shading is of even greater importance under future climate conditions. Establishing a mature riparian forest canopy can take 100 years, so it is important to begin planting riparian buffers now to reduce the anticipated climate change impacts on water temperature. Protection and restoration of local cold water refuges is another important adaptation strategy to mitigate the effects of climate change on aquatic life during high temperature events.

Foreword

The U.S. Environmental Protection Agency (EPA) Region 10 and EPA's Office of Water (OW) and Office of Research and Development (ORD) have launched a Pilot Research Project to explore how projected climate change impacts could be considered in the implementation of a Clean Water Act (CWA) 303(d) temperature Total Maximum Daily Load (TMDL,) and influence restoration actions in an Endangered Species Act (ESA) Salmonid Recovery Plan. The Pilot Research Project uses a temperature TMDL being developed by Washington's Department of Ecology (Ecology) for the South Fork Nooksack River (SFNR) in Washington, as the pilot TMDL for climate change vulnerability analysis. An overarching objective of the Pilot Research Project is to support the goals and priorities of EPA's climate adaptation plans.

A range of projected climate change impacts from the Intergovernmental Panel on Climate Change (IPCC) Scenarios were evaluated as a *risk assessment* to thoroughly consider plausible futures of potential impacts to salmonids.

The project consists of two separate research assessments:

The quantitative assessment (this report) provides a comparison of QUAL2Kw modeled stream temperatures, including riparian shading, with and without climate change for the 2020s, 2040s and 2080s. A range of projected climate change impacts from a high, medium and low impact scenario are analyzed for each time period. This assessment discusses and considers the relevant CWA water quality standards developed to protect beneficial uses, including cold water fisheries.

The qualitative assessment (in review) is a comprehensive analysis of freshwater habitat for ESA salmon restoration in the SFNR under climate change. The objective of the qualitative assessment is to identify and prioritize climate change adaptation strategies or recovery actions for the SFNR that explicitly include climate change as a risk.

Together, these two assessments identify comprehensive actions to protect CWA beneficial uses (salmon habitat) and ESA recovery goals under potential climate change.

Stakeholder outreach and Tribal engagement is considered a critical element of this project. Workshops, webinars and working Interdisciplinary Teams have been utilized throughout the life of this project. The result is actionable science and, with the participation of scientists, environmental practitioners and decision makers, supports the co-production of knowledge for climate change adaptation.

Foreword by

One EPA Team:

EPA Region 10

EPA Office of Water

EPA Office of Research and Development

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List of Abbreviations

7-DADMax	Highest 7-day average of the daily maximum temperatures
7-DADMin	Highest 7-day average of the daily minimum temperature
7Q10 flow	7-day average flow with a 10-year recurrence frequency
7Q2 flow	7-day average flow with a 2-year recurrence frequency
AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
CCAP	Coastal Change Analysis Program
CCSM	Community Climate System Model
CFR	*Code of Federal Regulations*
cfs	cubic feet per second
CGCM	Coupled Global Climate Model
CIG	Climate Impacts Group
DOY	Day of Year
DRTT	Dominant River-tracing-based Streamflow and Temperature model
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act
GCM	Global Climate Model *or* General Circulation Model
GIS	Geographic Information System
HADGEM	Hadley Centre Global Environmental Model
HUC	Hydrologic Unit Code
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detecting and Ranging
MIROC	Model for Interdisciplinary Research on Climate
MWMT	Maximum Weekly Maximum Temperature
NAIP	National Agricultural Imagery Program
NCAP	North Cascadia Adaptation Partnership
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NSDZ	Near-stream Disturbance Zone
ODEQ	Oregon Department of Environmental Quality
ORD	EPA Office of Research and Development

OW	EPA Office of Water
PCM	Parallel Climate Model
PNW	Pacific Northwest
QUAL2Kw	The Washington version of a river and stream water quality model (QUAL2K) that is in turn a modernized version of EPA's older QUAL2E model
RMSE	Root Mean Square Error
RPD	Relative Percent Difference
SFNR	South Fork Nooksack River
SNOTEL	"Snow telemetry": Automated system of snowpack and related climate sensors
SOD	Summary of the Day weather station
SPV	System Potential Vegetation
TMDL	Total Maximum Daily Load
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
VIC	Variable Infiltration Capacity hydrologic model
WAC	Washington Administrative Code
WDNR	Washington State Department of Natural Resources
WRIA	Water Resource Inventory Area

Acknowledgements

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We also want to acknowledge and thank the Peer Reviewers (Heather Golden, EPA ORD; Dan Isaak, USFS; Guillaume Mauger, UW-CIG) of this report for their many suggestions and comments that resulted in a much improved product. Lastly, we want to acknowledge and thank Paul Pickett, Washington Department of Ecology for his continued involvement and helpful comments during the life of this project.

Executive Summary

Global climate change has the potential for significant impacts on freshwater ecosystems through changes in both the hydrological and thermal regime. Stream temperatures are projected to increase in most rivers, resulting in increased stress on cold water fish species including salmon. Changes in hydrology, such as reduction in summer baseflows, could potentially exacerbate these impacts.

The South Fork Nooksack River (SFNR) is in an area considered typical of the mountainous, remote, forested landscape of northwest Washington, with minor urban and agricultural land uses along with extensive timber harvest and associated activities. The SFNR and its tributaries provide migration routes and spawning and rearing habitat for several salmon species throughout the year.

The Total Maximum Daily Load (TMDL) program, established by the Clean Water Act, has frequently been used to develop management plans intended to achieve temperature criteria and protect cold water fisheries. Portions of the SFNR and its tributaries are identified as being impaired by elevated temperature on Washington's 2010 Clean Water Act 303(d) list. These segments exceed the temperature criteria established to protect aquatic life uses for the support of cold water salmonid populations. The draft temperature TMDL developed by the Washington Department of Ecology (Ecology) in conjunction with EPA Region 10, the Lummi Nation, and the Nooksack Indian Tribe identifies the issues and outlines the solutions needed to improve river temperatures (Ecology, 2016).

The Quantitative Assessment (this report) provides a comparison of modeled stream temperatures, with and without proposed TMDL allocations such as increased riparian shading, for critical conditions under projected climate conditions for the 2020s, 2040s, and 2080s.

The SFNR temperature TMDL analyses use the QUAL2Kw stream simulation model (Pelletier and Chapra, 2008) in conjunction with an analysis of shading to predict the temperature profile throughout the SFNR during critical conditions of summer low flow and elevated air temperatures. The analyses predict that the SFNR will not fully attain the numeric temperature criteria under current climate during summer low-flow, high-temperature conditions even under full riparian canopy; however, restoration of the "system potential" riparian shade will help mitigate elevated temperatures deleterious to salmon populations.

For this pilot research project, the calibrated QUAL2Kw stream temperature model developed for the TMDL study has been used to estimate the impacts of potential future climate changes on the stream temperature with and without the restoration of riparian vegetation. To evaluate climate change in the SFNR, a new set of climate-modified boundary conditions was developed for the QUAL2Kw simulations.

The Climate Impacts Group (CIG) at the University of Washington has assembled output from multiple Global Climate Models (GCMs) and used statistical downscaling to translate these global model projections to a finer spatial scale over the Pacific Northwest (PNW). CIG has also used the downscaled climate data to predict future hydrology using a grid-based macro-scale hydrologic model known as the Variable Infiltration Capacity (VIC) model. We selected three climate model products that span a range of low impact, medium impact, and high impact for the 2020s, 2040s, and 2080s. By the 2080s, summer average air temperatures are predicted to increase by as much as 6 °C or more over the SFNR watershed, depending on the climate scenario. Presentation of a range of potential impacts provides important information to an iterative risk assessment approach that can support an adaptive management strategy relative to future climate change, as recommended by the National Climate Assessment (Melillo et al., 2014).

The downscaled climate model projections and VIC hydrologic application are still at too coarse a spatial scale to directly drive a local, site-specific model such as the SFNR QUAL2Kw model. Therefore, we applied a delta or change factor method in which the observed historical climate data for the SFNR are modified by the amount of change predicted by the downscaled climate models to obtain a projection of future conditions specific to the SFNR. The climate inputs for which change factors are calculated include several which are analyzed directly from VIC model outputs, such as air temperature and flow, as well as inputs for parameters that are indirectly calculated from VIC output such as dew point, headwater, tributary, and ground water temperatures.

The future climate projections are consistent in predicting an increase in air temperature. For the SFNR, the downscaled climate data, in conjunction with the VIC model, also suggest that summer low flows will decrease significantly. The QUAL2Kw model predicts that this decrease in flow will also contribute to increased water temperatures as the thermal mass of the stream is reduced, amplifying the effects of increased air temperature. The decreases in low flow occur in large part because of a shift from snow to rain during the winter months, which results in less snow melt during the warm season and reduced storage of ground water to support base flows. The net result is less water availability during the summer critical period.

The QUALK2w model simulations suggest that, without restoration of riparian shade, water temperatures during critical summer low-flow conditions could increase by amounts ranging from 3.5 to almost 6 °C by the 2080s. Restoration of full system potential riparian shading can help buffer against temperature increases and mitigate from 30 to 60 percent of the critical period increase; however, even with system potential shade, the critical condition maximum 7-day average stream water temperatures are projected to increase by 1.1 to 3.6 °C by the 2080s. In conjunction with this increase, the percent of stream miles in which critical condition water temperatures are potentially lethal to salmon is predicted by the model simulations to increase dramatically—from about 18 percent at present to a between 60 and 94 percent in the 2080s depending on the climate model analyzed.

The TMDL program intentionally focuses on infrequent, worst-case, or "critical" conditions for the analysis of thermal impairments, using 7-day average low flows that are expected to occur, on average, once in 10 years (7Q10 flows) and the 90th percentile of projected annual 7-day maximum air temperatures, as a way of ensuring that standards are met at all times. To estimate more typical summer periods of maximum stress, additional simulations evaluated responses to the 7-day average low flows that occur, on average, once in two years (7Q2 flow) and the median projected annual 7-day maximum air temperature. Under these less stringent conditions, water temperatures through the 2080s are projected to generally remain below lethal thresholds, with the possible exception of the most downstream reaches of the SFNR.

Because the QUAL2Kw model of the SFNR predicts spatially averaged water temperatures within stream segments of 1-kilometer length, it cannot resolve temperature differences at finer scales or evaluate the availability of cold water refuges. The impact of occasional high-temperature events on salmonids is in large part determined by whether the fish can find sufficient refuges that are cooler than the reach average and within their physiological tolerance ranges. Thus, habitat management at a scale smaller than the spatial scale of the QUAL2Kw model may have an important role in protecting the resource.

In sum, projected changes in future climate in the PNW will result in increased risk of temperature stress on salmon populations in the SFNR. Because projections of the future are uncertain, the resulting analyses should not be treated as forecasts; rather, they are designed to assist managers in defining the potential range of conditions to which adaptation may be needed. Practical implications of the analyses include the following: First, establishing a mature riparian forest canopy can take 100 years, so it is important to begin planting riparian buffers now to mitigate anticipated climate change impacts, as well as to consider the resilience of restored vegetation under future climate conditions. It is also important to recognize that protection and restoration of local cold water refuges may be a key adaptation strategy to mitigate the effects of climate change on aquatic life during high temperature events.

1 Introduction

The Total Maximum Daily Load (TMDL) program is one of the primary frameworks for the nation to maintain and achieve healthy water bodies, implemented pursuant to section 303(d) of the Clean Water Act. The majority of TMDL analyses have been conducted using assumptions of a stationary climate under which historical data on flow and temperature can be assumed to be an adequate guide to future conditions (Johnson et al., 2012).

U.S. Environmental Protection Agency (EPA) Region 10 and EPA's Office of Research and Development (ORD) and Office of Water (OW) are interested in looking beyond these assumptions of stationary climate to identify the range of potential climate change impacts on water temperature, using a temperature TMDL as a pilot study. Knowing that multiple technological approaches are available to assess watershed loading, and that available data can vary dramatically among watersheds, EPA understands that a pilot study in one watershed might have limited applicability in other watersheds. Nonetheless, EPA sees benefits to researching the technological and resource issues that arise during integration of available climate change data into a TMDL project. Already prioritized for TMDL development by the Washington Department of Ecology (Ecology), the South Fork of the Nooksack River (SFNR) is impaired by excess temperature and was chosen as the pilot TMDL for the research project (Ecology, 2016).

Climate models used in the Intergovernmental Panel on Climate Change (IPCC) Fourth and Fifth Assessment Reports (IPCC, 2007, 2013) confirm observations of increasing temperatures in the Pacific Northwest (PNW) over the 20th century and consistently project accelerated warming in the 21st century. Across the PNW, the overall average across all analyzed climate models project increases in average air temperature of 2.0 °F (1.1 °C) by the 2020s, 3.2 °F (1.8 °C) by the 2040s, and 5.3 °F (2.9 °C) by the 2080s compared to a baseline of 1970 to 1999 (Mote and Salathé, 2010). Precipitation changes are less certain, but most climate model simulations project changes toward wetter falls and winters and drier summers, with lower flow further increasing summer water temperature maxima. Together these factors could significantly increase temperature stress on salmonid populations. Over the entire PNW, simulations with the DRTT (Dominant River-tracing-based Streamflow and Temperature) model (Wu et al., 2012) project average increases in summer stream temperatures of 1.37 °C by the 2040s and 2.10 °C by the 2080s.

Changes in air temperature and precipitation interact synergistically to shape future stream habitat conditions. Indeed, large reductions in summer flows could have a greater impact on maximum water temperature in some PNW streams than the direct impact of projected increases in 21st century air temperature (Cristea and Burges, 2010; Wu et al., 2012). Of particular importance is the potential shift in overall runoff regime as changes in temperature affect the balance between rain and snow. Hydrologists characterize the PNW as having three runoff regimes: (1) snowmelt dominant, (2) rain dominant, and (3) transient or mixed rain and snow systems (Hamlet and Lettenmaier, 2007). In snow-dominant regimes, much of the winter precipitation is stored in the snowpack, which melts in the spring and early summer, resulting in peak flows in early spring and a continued supply of cold melt water through summer. In contrast, rain-dominant systems have little snowpack, resulting in peak flows in late fall and early winter, lower flows in summer, and greater risk of stream warming (Elsner et al., 2010; Mote and Salathé, 2010). Transient systems receive a mixture of snow and rain and can have large winter-spring flow peaks due to rain-on-snow events. Small changes in winter air temperature can result in a shift from one regime to another. In general, the hydrology of systems currently classified as transient has the greatest sensitivity to changes in climate forcing because these systems are near the current snowline; therefore, small changes in temperature can substantially affect snow accumulation (Mote and Salathé, 2010).

Salmonid populations are at risk from climate change because of a number of factors. Increasing summertime stream temperatures, the focus of the temperature TMDL, are likely to be a key pressure point for many salmon populations, and could be exacerbated if summer flows decrease and limit the extent of cold water refuges (Mantua et al., 2009). In addition, increases in extreme high flows can have a strong negative impact on reproductive success due to washout of redds and fry, as was found in the analysis of climate impacts on ocean-type Chinook in the Snohomish Basin by Battin et al. (2007).

The average changes in climate expected over the PNW can vary substantially at a local scale because of elevation and aspect, as well as local slope, soil, and land cover conditions. The TMDL is a reach-specific estimate of allowable loadings and conditions to protect beneficial uses of a water body. Evaluating the potential impacts of climate change on the TMDL also requires a reach-specific analysis.

This report is one part of a larger research plan that is described in the *EPA Region 10 Climate Change and TMDL Pilot Research Plan* (Klein et al. 2013). An important component of the Pilot Research Plan is a Quantitative Assessment (this document), in which the findings of modeling tools used to develop the temperature TMDL are reevaluated under a range of potential future climate conditions. In the Quantitative Assessment, the calibrated QUAL2Kw stream temperature model developed for the TMDL study is used to estimate the impacts of potential future climate change on critical condition stream temperature with and without enhancement of existing riparian shading to 100-year system potential conditions. The approach first calculates altered boundary conditions for the QUAL2Kw TMDL modeling under the IPCC A1B greenhouse gas emissions storyline (which speculates a balance of fossil and non-fossil fuel energy sources) and for three time horizons (2020s, 2040s, and 2080s). These boundary conditions are then used to conduct additional QUAL2Kw modeling analyses of system response under potential future climate conditions.

Model results provide important information on the potential future response of the system to future climate, with and without the implementation actions called for in the TMDL. The detailed description of the approach used in the SFNR pilot analysis provides insight on how place-based analysis of risk associated with climate change could be incorporated into studies of other watersheds.

2 The Water Temperature Model for the South Fork Nooksack River

The SFNR watershed is located in Whatcom and Skagit counties, northwest Washington, in water resource inventory area (WRIA) 1 and hydrologic unit code (HUC) 17110004 (Figure 2-1). The SFNR watershed covers approximately 186 square miles. It originates east of the Twin Sisters Mountain in the Cascade Mountain Range (Figure 2-2), discharging to the North Fork Nooksack River several miles south of the Middle Fork confluence. The confluence of all forks becomes the Nooksack River mainstem about 36 miles upstream from where the river discharges into Bellingham Bay.

Numerous tributaries feed the SFNR as it flows down from the Twin Sisters. Major tributaries are Wanlick Creek, Howard Creek, Cavanaugh Creek, Skookum Creek, Hutchinson Creek, and Black Slough. The river has an average annual discharge of 1,032 cubic feet per second (cfs) based on Ecology data at gaging station 01F070 (water years 2004–2010) on the left bank of the SFNR at the Potter Road Bridge crossing near the town of Van Zandt.

The SFNR is in an area considered typical of the mountainous, remote, forested landscape of northwest Washington, with minor amounts of urban and agricultural land uses. Forest and shrub land dominate land use in the watershed, with small amounts of agriculture and development in the lower portion (Figure 2-3), including portions of the municipalities of Van Zandt and Acme, WA. The Lummi Nation operates a salmon hatchery and established the Arlecho Creek Preserve in the watershed. The Nooksack Indian Tribe also owns land and other facilities in the watershed. The headwaters are lands managed by the U.S. Forest Service (USFS). A portion of the watershed is dominated by alpine tundra and bare rock of the Twin Sisters summit where vestigial ice fields are present.

The SFNR and its tributaries provide migration routes as well as spawning and rearing habitat for several salmon species throughout the year. To protect these uses, Washington water quality standards establish three temperature criteria for the SFNR, expressed as the highest 7-day average of the daily maximum temperatures (7-DADMax) occurring in a water body. The temperature criteria applicable to the SFNR, as given in the Washington Administrative Code [WAC 173-201A-200; 2003 edition], are listed in Table 2-1 (also shown on Figure 2-1) and are consistent with USEPA (2003):

Table 2-1. Washington State Temperature Criteria for the South Fork Nooksack River Watershed

Use Classification	Numeric Temperature Criteria
Core summer salmonid habitat, spawning, rearing, and migration	< 16 °C 7-DADMax[a,b]
Char spawning and rearing	< 12 °C 7-DADMax[a,b]
Supplemental salmonid spawning and incubation	< 13 °C 7-DADMax[a,b] (Sept 1–Jul 1)

Notes:
[a] 7-DADMax means the highest annual running 7-day average of daily maximum temperatures.
[b] A human-caused variation within the above range of less than 0.3 °C for temperature is acceptable.

The SFNR (Figure 2-1) has 14 mainstem segments and 9 tributary segments identified as impaired by elevated water temperature on Washington's 2010 303(d) list. These segments are documented to exceed the temperature criteria established by Ecology to protect aquatic life use categories (salmonid habitat) and life-stage conditions (spawning and rearing). The temperature TMDL is intended to address these conditions and identify the solutions needed to improve river temperatures and support designated uses.

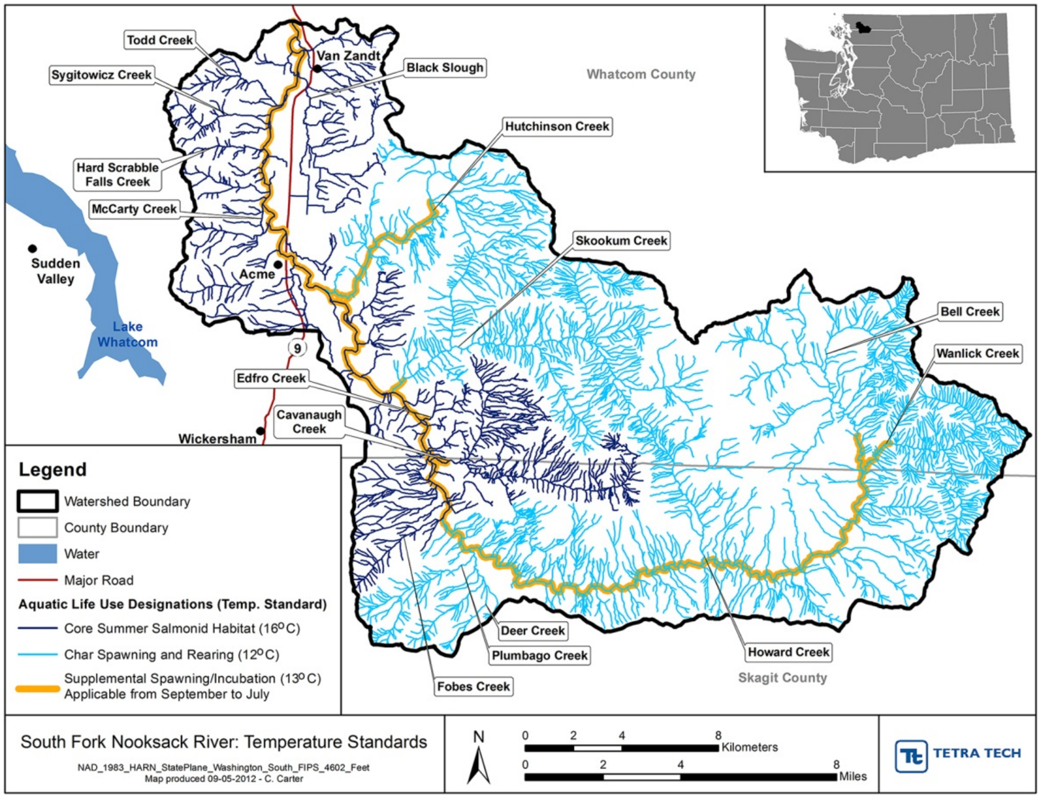


Figure 2-1. The South Fork Nooksack River and Associated Water Temperature Criteria

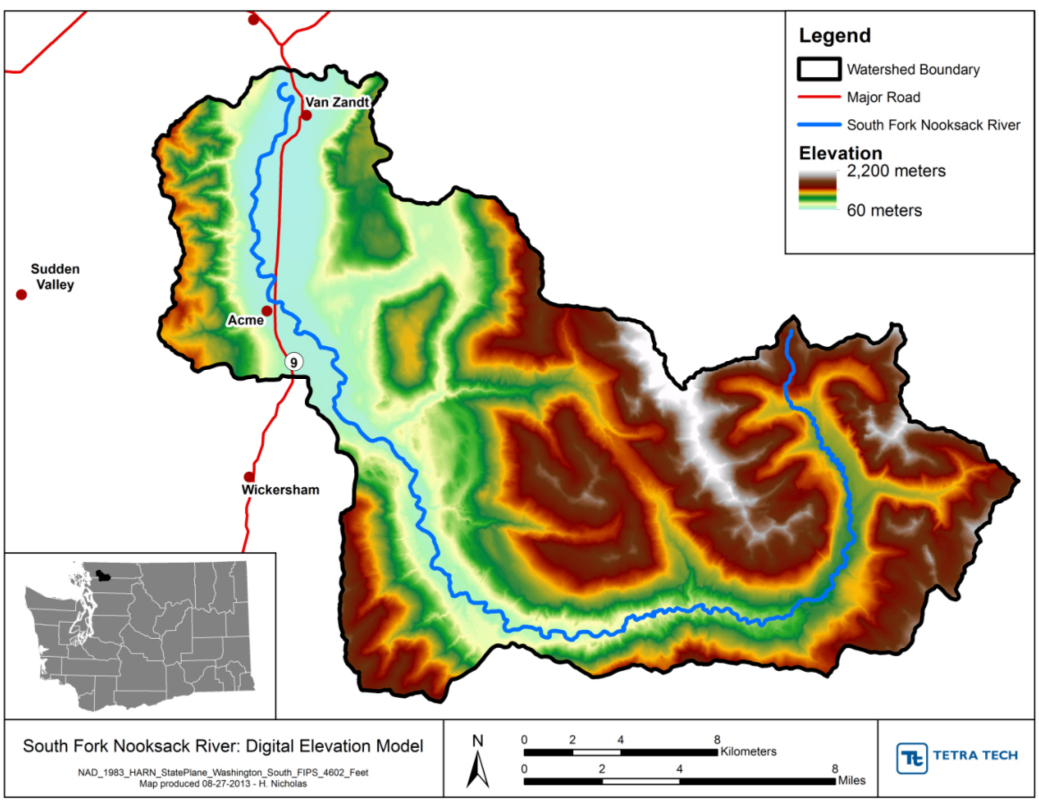


Figure 2-2. Elevation in the South Fork Nooksack River Watershed

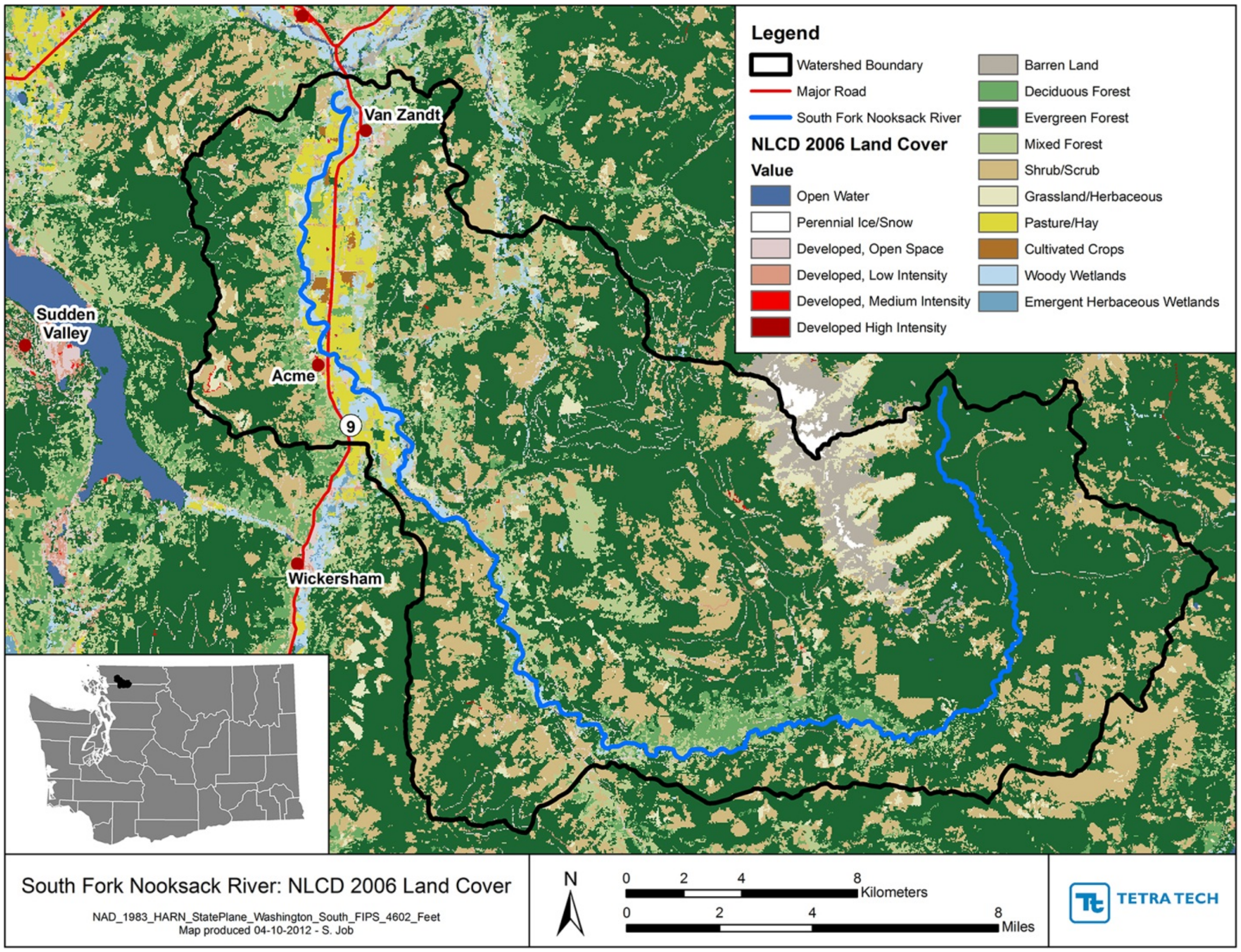


Figure 2-3. Land Use in the South Fork Nooksack River Watershed

Ecology has published the draft *South Fork Nooksack River Temperature Total Maximum Daily Load, Water Quality Improvement Report, and Implementation Plan* (Ecology, 2016). Modeling analyses for the draft TMDL have been completed and those draft results are discussed here for the purpose of evaluating potential climate impacts. The draft Ecology documentation shows all available monitoring data, boundary assumptions, the calibration procedures used, and an evaluation of model predictions versus observed temperatures. The modeling linkage analysis used to estimate the temperature TMDL consists of a Shade model (Ecology, 2003b) linked to the QUAL2Kw water quality model. QUAL2Kw (Chapra and Pelletier, 2003; Ecology, 2003a; Pelletier et al., 2006) is used to simulate in-stream water temperature. The models were developed for 2007 and 2010 summer conditions.

The Shade model was selected to evaluate solar radiation along the streams using watershed-specific geographic information system (GIS)-based data derived with the TTools ArcView extension, developed by Oregon Department of Environmental Quality (ODEQ). TTools uses spatial data to estimate vegetation and topography perpendicular to the stream channel and samples longitudinal stream channel characteristics such as the near-stream disturbance zone (NSDZ), riparian vegetation, and elevation. Ecology's Shade model (Ecology, 2003b) was adapted from a program that ODEQ developed as part of its HeatSource model version 6.

The Shade model quantifies the potential daily solar load and generates the percent effective shade. Effective shade is the fraction of shortwave solar radiation that does not reach the stream surface because vegetative cover and topography intercept it. Effective shade is influenced by latitude and longitude; time of year; stream geometry; topography; and vegetative buffer characteristics, such as height, width, overhang, and density. Vegetation status was determined from a variety of data sources, including Light Detection and Ranging (LiDAR) analyses of vegetation height completed in 2009 (downstream portion of the watershed) and 2005 (upstream portion) by the Puget Sound LiDAR program; classification of riparian vegetation type from the Riparian Function Assessment created by Duck Creek Associates based on aerial photography from 1991 and 1995 and provided by the Nooksack Indian Tribe Natural Resources Department; vegetation type information from the National Oceanic and Atmospheric Administration's (NOAA) Coastal Change Analysis Program (CCAP) based on 2006 satellite imagery; and additional digital ortho-imagery for Whatcom and Skagit counties flow in 2006 and 2009 and obtained from the U.S. Department of Agriculture's (USDA) National Agricultural Imagery Program (NAIP). TTools output serves as input for the Shade model, which is then used to generate longitudinal effective shade profiles. Reach-averaged integrated hourly effective shade (i.e., the fraction of potential solar radiation blocked by topography and vegetation) in turn serves as input into the QUAL2Kw model.

QUAL2Kw is a quasi-steady state model (it assumes steady-state hydraulics but represents the diel heat budget and water quality kinetics) that is Ecology's preferred tool for estimating temperature TMDLs. Model selection for the temperature TMDL is documented in Kennedy and Butcher (2012). The model has also been previously used to evaluate stream temperature response to future climate in the Wenatchee River basin (Cristea and Burges, 2010).

QUAL2Kw is a modernized version of EPA's standard river water quality model, QUAL2E (Brown and Barnwell, 1987) and retains the diel heat budget framework of QUAL2E. The modernized version was first developed as QUAL2K (Chapra et al., 2008), and further updated for use by Ecology as QUAL2Kw. The algorithms used in QUAL2Kw are documented in Pelletier and Chapra (2008) and Pelletier et al. (2006). The model simulates daily temperature and the heat budget with hourly variations in input parameters and boundary conditions. Meteorological conditions have strong influences on water temperature. Parameters included in QUAL2Kw input that affect stream temperature are effective shade, solar radiation, air temperature, cloud cover, relative humidity, headwater and tributary temperature, and hyporheic flow. These parameters are calculated (e.g., effective shade from Shade model), obtained from weather station information, or interpreted from other sources.

For the TMDL, QUAL2Kw was applied to conduct focused analyses of critical conditions (e.g., late summer low flow, clear sky, and high air temperature conditions) that exacerbate temperature impairments, from which TMDL targets can be determined directly. Model inputs for the TMDL simulations include flow, meteorological, and water temperature boundary conditions developed from available data. Section 4 describes these assumptions in the context of developing future climate boundary conditions. The TMDL documentation includes complete details.

2.1 Summary of Water Temperature Model Development

This section summarizes the development of the water temperature model for the SFNR TMDL. Ecology's draft *South Fork Nooksack River Temperature Total Maximum Daily Load, Water Quality Improvement Report, and Implementation Plan* (Ecology, 2016) provides more exhaustive documentation. The model parameters described below are believed to be in final form, but are subject to change until the TMDL is approved.

2.1.1 Shade Modeling

Many factors contribute to warmer in-stream temperatures, including reduced shading from riparian vegetation. Ecology typically evaluates the impacts of restoring system potential vegetation (SPV) and associated shade in stream temperature TMDLs, where SPV refers to the climax tree community expected to be attained on a given soil type. Increased shading typically reduces daily maximum water temperatures, but has lesser impacts on minimum and daily average temperature (Johnson, 2004).

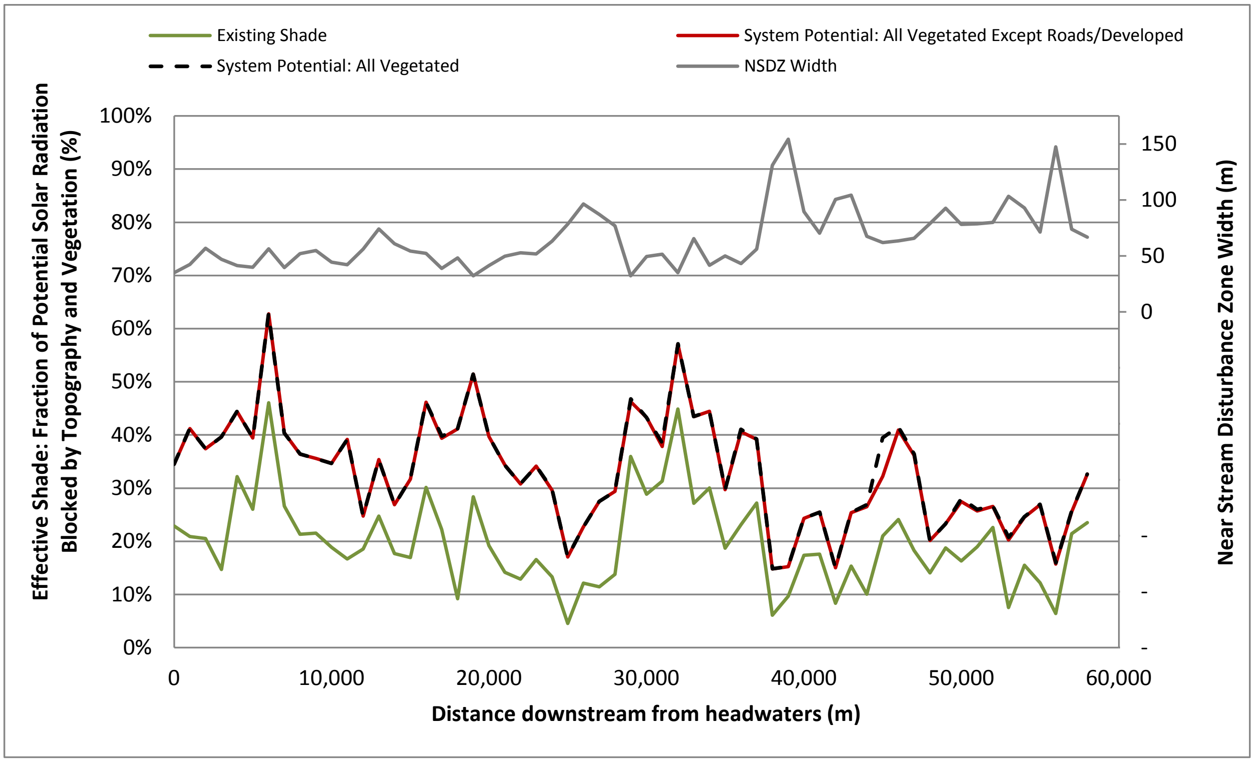
Both existing shade and 100-year system potential shade were estimated using the Shade model, following Ecology protocols (Mohamedali and Stohr, 2011). Key data sources used include digital ortho-imagery from the USDA's NAIP, LiDAR elevation data, land use and land cover data from NOAA's CCAP, and local riparian condition data provided by the Nooksack Indian Tribe.

The riparian corridor was defined for shade analysis as a 150-foot buffer outside of the NSDZ on either side of the river channel. Current vegetation type, height, density, and overhang are measured or estimated within the riparian buffer, which serve as key inputs for the Shade model. In addition to the vegetation information, TTools was also used to sample each 100-meter interval for channel wetted width, NSDZ width, stream aspect, stream elevation, and topographic shade angles in all directions. Where the NSDZ channel width was artificially high because of large tree islands, manual changes were made to the widths before running the Shade model. (Outliers were checked if they were more than two standard deviations away from the mean NSDZ width for the entire reach.) Using this information, effective shade under current conditions was calculated using channel geometry, vegetation, and solar position.

Next, system potential shade was developed. SPV is defined as the 100-year mature riparian vegetation that would naturally occur if the riparian corridor was left undisturbed. The 100-year system potential along the SFNR was determined spatially using a soil GIS coverage provided by the Washington State Department of Natural Resources (WDNR) and Whatcom and Skagit County Soil Survey Reports (Goldin, 1992; Klungland and McArthur, 1989). The WDNR data consists of digitized soil delineations that designate which type of tree would dominate on each soil type in a system potential scenario. Using the dominant soil types in the riparian area, 100-year site indices (i.e., the height of the dominant tree species for a soil type at 100 years of age) were selected for those soil types.

On the basis of these data sources, western hemlock and Douglas-fir are the most common native tree stands that would dominate the soil types in the SFNR. Therefore, the model for 100-year SPV focuses on these two species and their 100-year system potential site index height as representative of the potential for shading in the SFNR watershed. (Note that other species such as western red cedar, red alder, and bigleaf maple dominate in some topographic positions and site-specific prescriptions will be needed in specific restoration projects.) The 90th percentile height for Douglas-fir and western hemlock in Whatcom and Skagit counties from the 100-year site indices for the major riparian soil types is 50.66 meters. This height is used in the 100-year system potential scenario.

The resulting shade from existing vegetation (approximately 2007 conditions) and system potential shade for the SFNR watershed is shown in Figure 2-4 shows the resulting shade from existing vegetation (approximately 2007 conditions) and system potential shade for the SFNR watershed. Note that shade was modeled along the SFNR mainstem only and not for tributaries, which are not explicitly simulated in the QUAL2Kw model. Model scenarios that use SPV are based on the red line below for which the riparian area is allowed to achieve SPV except where roads and houses are currently present.



Note: The figure shows two results, one with all land reaching 100-year system potential, and the other with 100-year system potential vegetation with developed lands (roads and structures) not reaching system potential.

Figure 2-4. Modeled Effective Shade for 2007 Existing Vegetation and 100-year System Potential Vegetation

2.1.2 QUAL2Kw

2.1.2.1 Model Setup

A QUAL2Kw model of the SFNR was developed to determine the components of the heat budget and simulate water temperatures under observed and critical conditions. The model was calibrated to observed conditions for a high-temperature, low-flow day in 2007 (August 2) and model performance was corroborated through a second application to a high-temperature, low-flow day in 2010 (August 16). The QUAL2Kw model was applied by assuming that flow remains constant (i.e., steady flows) at the average flow rate for that day, but key variables other than flow were allowed to vary with time over the course of a day. Solar radiation, air temperature, dew point, cloud cover, shade, headwater temperature, and tributary temperatures were specified as diurnally varying functions. Sensitivity analyses were conducted to determine the model's responsiveness to key parameters. The greatest sensitivities were to temperature boundary conditions (headwater, tributaries, and ground water inputs).

For QUAL2Kw model input, the SFNR was divided into 58 segments of 1 kilometer each (Figure 2-5). The upstream boundary was set at the confluence with Wanlick Creek. Although only the mainstem is modeled directly, tributary inflows (a total of 35) are included. Model configuration also includes direct ground water inputs along the mainstem.

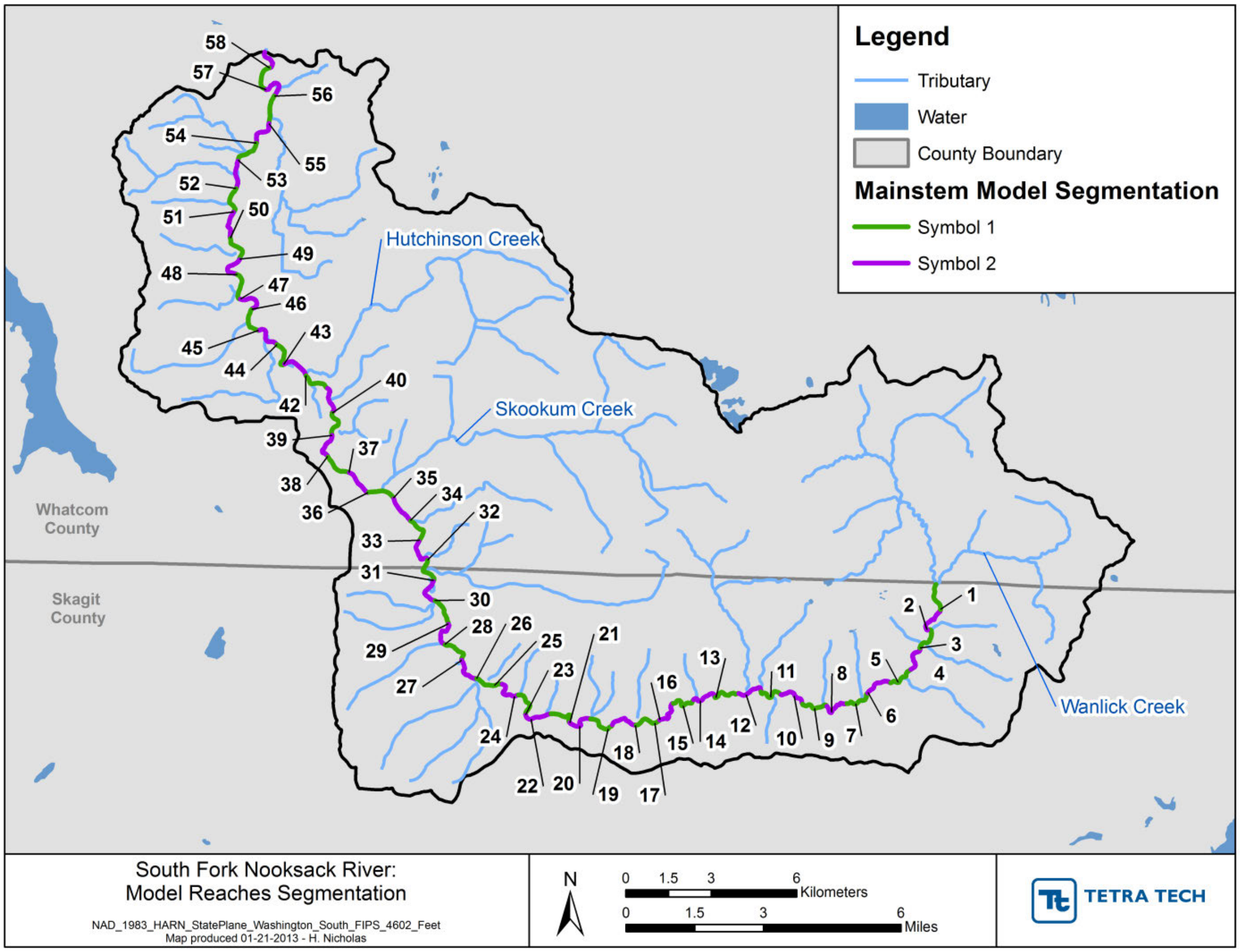
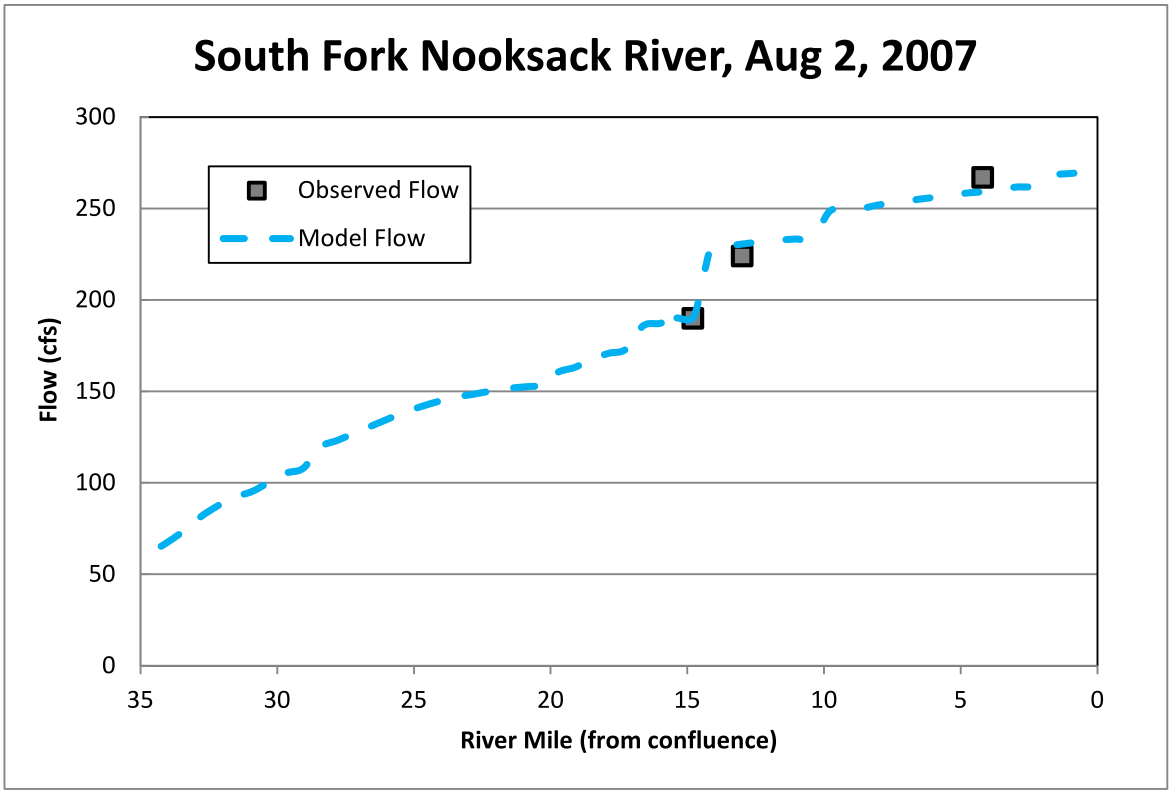


Figure 2-5. South Fork Nooksack River Model Segmentation by 1-kilometer Reach

Daily flow boundary conditions for the headwater, tributary, and ground water inputs were based on steady-state flows during low-flow conditions in the calibration and corroboration periods. Observed flow data in the watershed included a limited amount of data from U.S. Geological Survey (USGS) and Ecology gages; much of the mainstem and tributaries are not gaged. Flow values, therefore, were estimated throughout the watershed using regression equations from Curran and Olsen (2009), with adjustments to account for differences between observed flow at the gages during the simulation days and the low-flow statistic assumed to represent those days. Curran and Olsen performed an in-depth analysis of low-flow hydrology and statistics for 25 gaging sites in the Nooksack River basin and developed regional regression equations for estimating 12 critical low-flow statistics at ungaged locations. Modeled flows match available in-stream flow observations well (Figure 2-6).



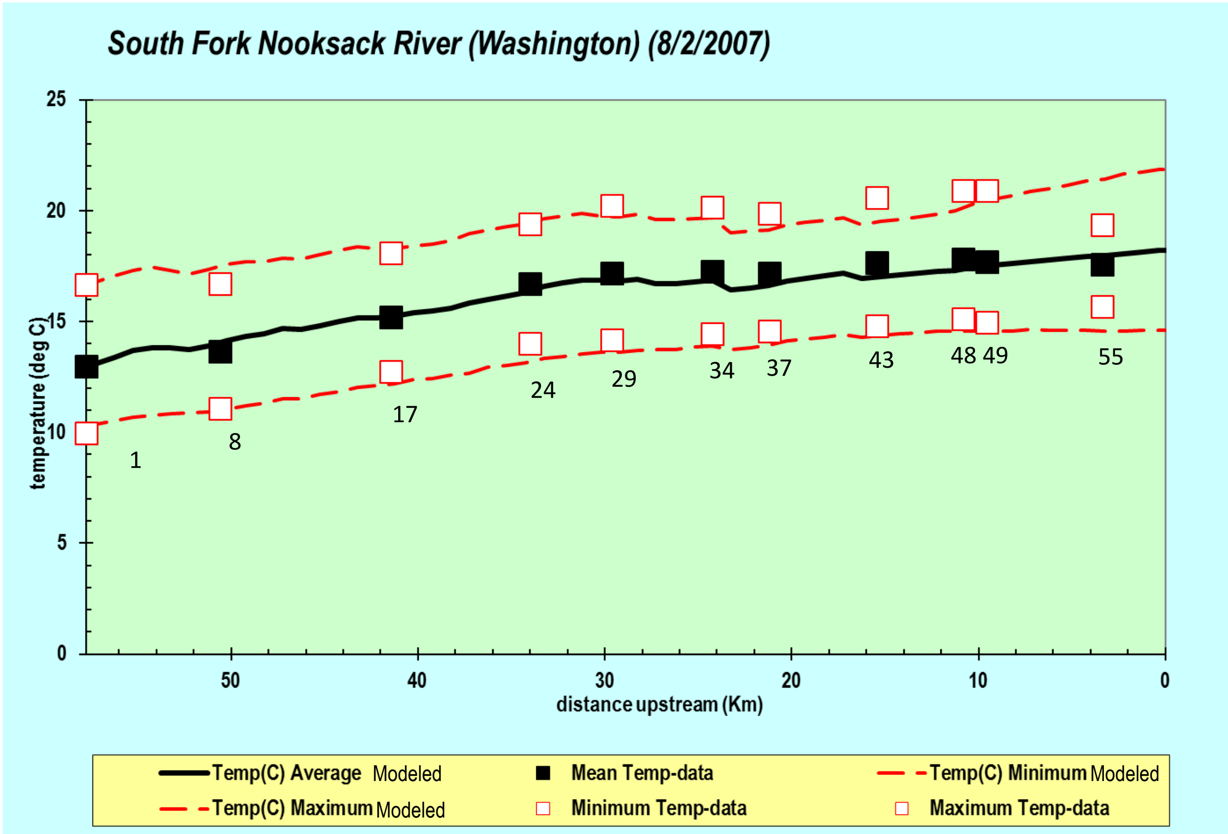
Note: The figure was adapted from the draft of Ecology's *South Fork Nooksack River Temperature Total Maximum Daily Load, Water Quality Improvement Report, and Implementation Plan* (Ecology, 2016).

Figure 2-6. Comparison of Observed and Simulated Flows for the Calibration Period

In addition to hourly shade provided by the Shade model and flow boundary inputs, other major inputs to the QUAL2Kw model included reach hydraulic parameters, hourly meteorology time series, and boundary stream temperatures. Hydraulics inputs were developed using LiDAR and aerial imagery used in the Shade work and data from a late 1990s USGS seepage study. Meteorology input data were based on a variety of weather stations that were chosen on the basis of proximity to the watershed, data availability for both calibration and validation dates, and reported quality assurance. Tributary and headwater temperatures were based on the available monitoring data. Temperature for direct ground water inputs were derived based on average annual air temperature with some adjustment during calibration.

2.1.2.2 Calibration, Validation, and Sensitivity

To conduct the model calibration process, a visual comparison of temperature along with a set of statistical measures was used to compare model predictions and observations along the mainstem of the SFNR (Figure 2-7). Two primary statistical measures were used: root mean square error (RMSE), a commonly used measure of model variability, and relative percent difference (RPD) as a measure of bias. The average RMSE for model calibration (2007) and validation (2010) of maximum temperatures was less than 0.5 °C. Model bias evaluation showed no evidence of systematic over- or under prediction of temperature. The TMDL report provides additional details.



Notes: Solid and dashed lines show model results; open and closed squares show observed temperature data. The figure was taken from the draft of Ecology's *South Fork Nooksack River Temperature Total Maximum Daily Load, Water Quality Improvement Report, and Implementation Plan* (Ecology, 2016). The chart shows model segment numbers for observations.

Figure 2-7. Temperature Calibration for QUAL2Kw Model of South Fork Nooksack River

A sensitivity analysis was conducted to test the calibrated model's response to key inputs. Changes in boundary temperature inputs (e.g., headwater, tributaries, and ground water) had the greatest impact on water temperature. Air temperature had the second-largest impact on the model predictions for water temperature. The second- and third-largest impacts on maximum predicted water temperature were from boundary flow and bottom width. Changes in Manning's *n* and shade had the least impact on the model outputs.

2.2 TMDL Modeling Scenarios

Using the 2007 calibration model as a foundation, a series of modeling scenarios were developed to evaluate stream temperatures on the mainstem of the SFNR realized under various typical and critical summer conditions. TMDL modeling scenarios were constructed using Ecology's standard assumptions and protocols for temperature TMDLs. These include typical low-flow conditions (7Q2 flow – the 7-day average flow with a 2-year recurrence frequency) and critical low-flow conditions (7Q10 flow – the 7-day average flow with a 10-year recurrence frequency) coupled with typical and critical 7-day average maximum temperatures, as explained below. These conditions are selected to correspond to the water quality criterion for temperature expressed as 7-DADMax. For each of these flow and temperature regimes, scenarios using shade provided by existing vegetation and 100-year SPV were developed. Those scenarios that incorporate system potential shade also included a microclimate effect, which is discussed further below.

2.2.1 Scenario Flows and Air Temperature

Flow inputs for TMDL critical condition scenarios were based on calculated 7Q2 and 7Q10 statistics from Curran and Olsen (2009) for three of the gaged sites in the SFNR watershed using various standard USGS methods, as shown in Table 2-2. Figure 2-8 shows flow gages and air temperature monitoring stations used for boundary condition development.

Table 2-2. Calculated 7Q2 and 7Q10 Flows Compared to Calibration Conditions

Location	Gage ID	Flow (cfs)		
		Calibration	7Q2	7Q10
Skookum Creek	12209490	44	20.6	15.3
South Fork Nooksack at Wickersham	12209000	190	102	75.8
Hutchinson Creek	01C070	7.9	4.92	4.37

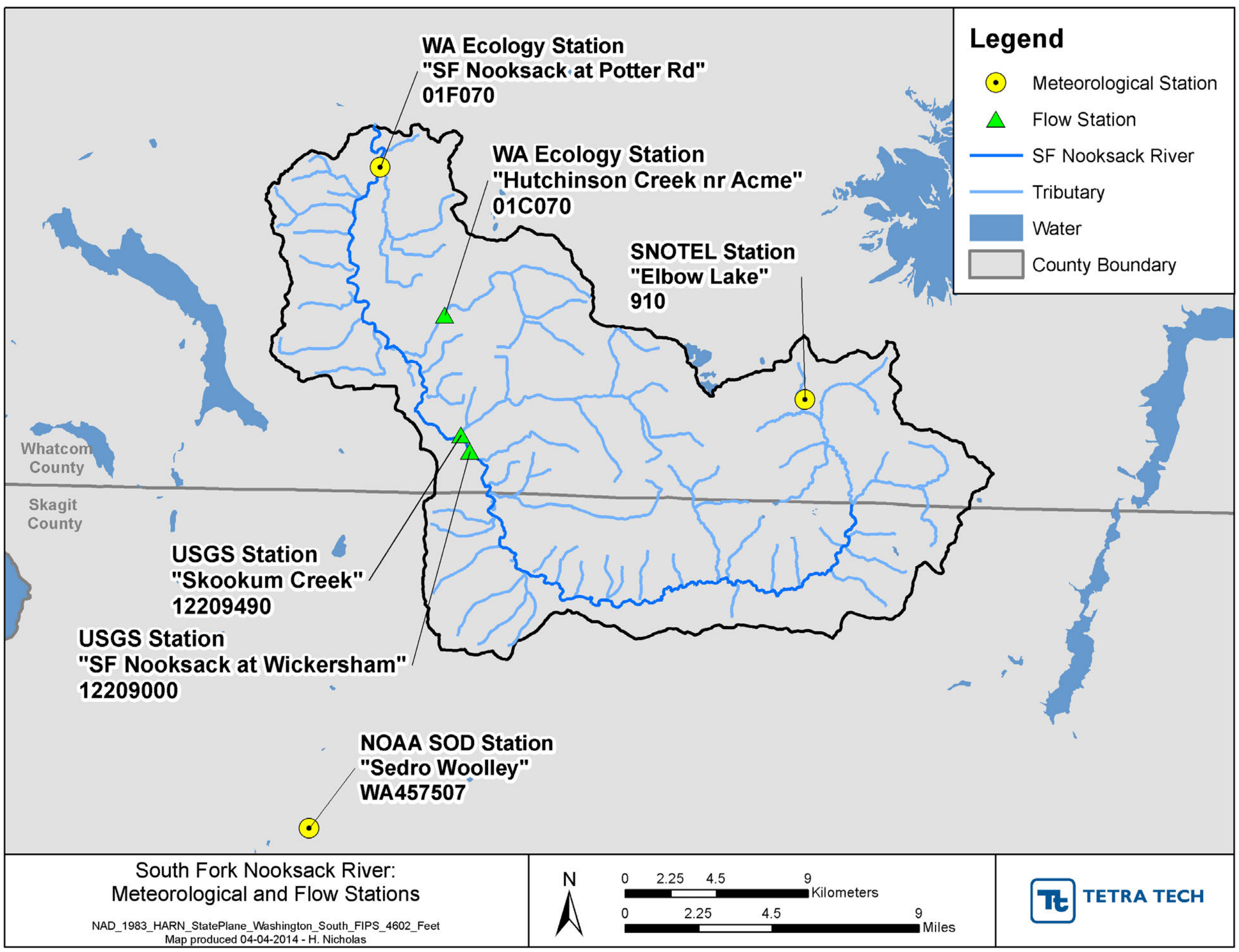


Figure 2-8. Flow Gages and Air Temperature Monitoring Stations used for Boundary Condition Development

The 50th percentile air temperatures are calculated as the median of the series of annual maxima based on annual rolling 7-day average maximum temperatures. The 90th percentile temperature is similarly calculated from the series of annual maxima. The air temperature analysis used historical records from two meteorological stations, representing lower and upper elevations. Elbow Lake Station 910 (a Snow Telemetry or "SNOTEL" station) with available data from August 1995 through 2012 was used as the upper elevation station. Ecology station 01F070 was used to represent lower elevations during model calibration, but had a much shorter period of record beginning in 2003. Therefore, an alternate station, Sedro Woolley Station WA457507 (NOAA Summary of the Day [SOD] Program), farther downstream in the town of Nooksack, was selected to represent lower elevations in the TMDL analysis. Linear interpolation on elevation between the high and low stations was used to adjust the daily maximum and minimum air temperatures for each model reach. Using the period of record at SNOTEL 910 and data from 1959 to 2009 at WA457507, 50th and 90th percentiles were calculated from the series of hottest annual 7-day average maximum temperatures (Table 2-3). The WA457507 values were then scaled by 0.47 °C to adjust for the difference relative to station 01F070 (determined using the average difference between air temperatures from July and August of paired years between the two stations). The same procedure was used to establish the appropriate percentile of the maximum 7-day average daily minimum temperature, while the hourly distribution of temperatures within the day was scaled to follow the same pattern between the maximum and minimum as observed in the calibration data set for August 2, 2007.

Table 2-3. Air Temperature Statistics for the South Fork Nooksack Region

Condition	SNOTEL Station 910 (1996-2012)		Adjusted SOD Station WA457507a (1959-2009)	
	Max 7-DADMin °C	Max 7-DADMax °C	Max 7-DADMin °C	Max 7-DADMax°C
90th percentile of annual max 7-day series[b]	17.56	28.69	15.39	30.07
50th percentile of annual max 7-day series[b]	15.21	26.77	13.64	28.01

Notes:
[a] Observations at WA457507 are adjusted to 01F070 by adding 0.47 °C.
[b] Results are shown for the maximum 7-day average of daily temperature minima (7-DADMin) and the maximum 7-day average of daily temperature maxima (7-DADMax).

Ecology protocols for temperature TMDLs consider a microclimate effect. The microclimate effect, incorporated into all the SPV scenarios, reflects a cooling of air temperature near the stream channel as a result of the presence of mature riparian vegetation. Brosofske et al. (1997) reported that a buffer width of at least 150 feet was required to maintain natural riparian microclimate environments in small forest streams in western Washington in Douglas-fir and western hemlock forests. The average impact of clear cutting on ambient mean daily air temperature was an increase of 2 °C according to a literature review provided in Bartholow (2000). Using the aggregated results of this study, Ecology concluded that an opposite impact could be expected from reforesting an area, such that the full microclimate impact of a mature riparian forest would decrease ambient air temperature by 2 °C. (Because much of the SFNR is wider than the streams studied by Brosofske et al. (1997), the validity of this assumption is uncertain.) As specified by Ecology, this microclimate effect is simulated by a drop in air temperature of 2 °C at every hour of the day for scenarios in which SPV is present. The presence of a mature forest canopy could actually lead to less radiative cooling and warmer nighttime air temperatures; however, a fixed decrease in air temperature at all hours was applied to be consistent with Ecology's TMDL modeling practices (e.g., Stohr, et al., 2011). As was done in the Lower Skagit temperature TMDL (Lawrence, 2008), dew point was held at 90th percentile conditions during microclimate runs for 7Q10 flows (unless it exceeded air temperature) to preserve increased relative humidity expected during the microclimate scenarios (Zalewsky and Bilhimer, 2004).

2.2.2 Modeling Results

Table 2-4 summarizes the results for the draft modeling scenarios for typical low-flow and weather conditions and critical low-flow and weather conditions. Figures showing the simulations are not reproduced here; however, the results of the modeling scenarios for existing climate are shown in conjunction with the climate scenario results in Section 5.

Table 2-4. Modeling Scenario Results for Typical Low-Flow and Critical Low-Flow and Air Temperature Conditions

Scenario	Condition	Maximum Stream Temperature (°C) (averaged across select reaches)		
		All Reaches	Headwaters to Reach 28[a]	Reach 28[a] to Outlet
Typical Low-Flow Conditions (7Q2 flows; 50th percentile air temperature)				
1	Current Shade Conditions: 7Q2	19.0	18.4	19.6
2	System Potential except where developed: 7Q2 [b]	16.9	16.2	17.5
Critical Low-Flow Conditions (7Q10 flows; 90th percentile air temperature)				
3	Current Shade Conditions: 7Q10	21.0	20.1	21.8
4	Current Shade Conditions with cooler tributaries[b]: 7Q10	20.7	19.6	21.6
5	System Potential Vegetation with microclimate effect except where developed, cooler tributaries[b]: 7Q10	18.7	17.8	19.6
6	System Potential Vegetation with microclimate effect everywhere, cooler tributaries[b]: 7Q10	18.7	17.8	19.6

Notes:
[a] From the headwaters to reach 28 the summer water quality criterion is 12 °C. For reach 28 to the mouth the water quality criterion is 16 °C.
[b] Tributaries are set at current temperatures or water quality criteria temperatures, whichever is cooler.

During both typical low-flow (Scenario 1) and critical low-flow (Scenario 3) conditions, and corresponding meteorological conditions in the summer, the model estimates that the SFNR exceeds the numeric water quality criteria of 12 °C (headwaters to reach 28) and 16 °C (reach 28 to outlet) in nearly all mainstem river segments. Maximum temperatures estimated for Scenario 1 averaged 18.4 °C and 19.6 °C for the upstream and downstream reaches, respectively, and exceed the numeric criteria by 3.6 °C to 6.4 °C.

To estimate the stream temperature profile under conditions of maximum potential shade, the models were run with 100-year SPV, associated microclimate effects, and with tributaries and headwaters at or below the numeric water quality criteria. Under both typical and critical 100-year system potential scenarios (Scenarios 2 and 5), the model predicts that the stream will continue to exceed the numeric water quality criteria. Averaged over reaches upstream of Fobes Creek, the predicted temperatures are 4.2 °C and 5.8 °C above the criterion for the 7Q2 and 7Q10 scenarios. Below the point where the numeric criterion changes to 16 °C (for the simulation dates) the predicted water temperatures are 1.5 °C to 3.6 °C above the criterion. On average, the impact of system potential shade with the microclimate effect on critical condition stream temperatures was a cooling of about 2.21 °C relative to stream temperatures under the current shade scenarios. The addition of 100-year SPV in the developed areas under critical conditions (Scenario 6) did not have a noticeable effect because the change applied to a relatively small area (1.6 percent) of the riparian buffer.

Additional model runs investigated response to critical conditions for the September through July time period, when the supplemental spawning criterion of 13 °C applies to the entire mainstem of the SFNR, using September 11, 2007 meteorology. Lower thermal inputs for September result in lower simulated water temperatures than are predicted for the summer critical conditions run. The scenario with shading and tributary temperatures equal to those for TMDL Scenario 5 yield an average maximum stream temperature of 13.3 °C, slightly greater than the criterion. The summer critical condition analysis is thus more limiting on thermal load allocations.

Scenario 5 uses shade levels provided by 100-year SPV to estimate water temperatures occurring under system potential shade at critical low-flow and high air temperature conditions. This is interpreted as a natural limit on what can be attained under existing climate. This limiting condition then becomes the applicable temperature water quality criterion under the natural conditions provision for the water quality criteria, WAC 173-201A-070(2), which states, "Whenever the natural conditions of said waters are of a lower quality than the criteria assigned, the natural conditions shall constitute the water quality criteria."

2.2.3 Evaluation of Historical Conditions

Several supplemental modeling scenarios undertaken for the TMDL analysis investigated possible stream temperature responses during critical conditions with inferred natural, historical conditions for the watershed land cover and stream channel geometry. These scenarios evaluated (1) a 20 percent reduction in headwater and tributary temperatures, (2) decreased channel width representative of conditions prior to land use disturbance, (3) shade associated with full climate vegetation (assumed height of 290 feet) attained everywhere within a wider, 218-foot stream buffer, (4) greater hyporheic exchange, and (5) combined impacts of all four individual factors. These analyses suggest that, under historical conditions, stream temperatures in response to 7Q10 critical conditions could be up to about 16 percent lower than predicted for Scenario 5, with the predicted average maximum stream temperature over all reaches dropping from 18.7 to 15.8 °C.

2.2.4 Draft TMDL Results

The general goal of the TMDL, however, is to develop allocations of thermal load such that the sum of these allocations does not exceed the water body's loading capacity. The loading capacity provides a reference for calculating the amount of pollutant reduction needed to bring water bodies into compliance with water quality standards. EPA defines *loading capacity* as, "the greatest amount of loading that a water can receive without violating water quality standards" [Title 40 of the *Code of Federal Regulations* (CFR) 130.2(f)]. The loading capacity for the mainstem of the SFNR can be approximated using the 100-year system potential shade scenario (Scenario 5) under critical low-flow (7Q10) and air temperature conditions (90^{th} percentile of the series of hottest rolling 7-day average of daily maximum temperatures from each year of record). This scenario also assumes water temperatures within the tributaries and headwaters are at or below the numeric water quality criteria. Thermal loading under these conditions can provide the basis for TMDL load allocations.

3 Climate Change Modeling

The climate-altered boundary conditions for the QUAL2Kw modeling of the SFNR are derived from the work conducted by the Climate Impacts Group (CIG) at the University of Washington (Hamlet et al., 2010; Hamlet et al., 2013; Mauger and Mantua, 2011; Mote and Salathé, 2010). CIG focuses on the consequences of a warming climate in the PNW. Among their key products is the Washington Climate Change Impacts Assessment (Miles et al., 2010), a comprehensive assessment of the impacts of climate change on the state of Washington, developed under mandate of the Washington State legislature. Figure 3-1 provides a general schematic of the relationships between CIG climate products and the TMDL model, with details in the following sections.

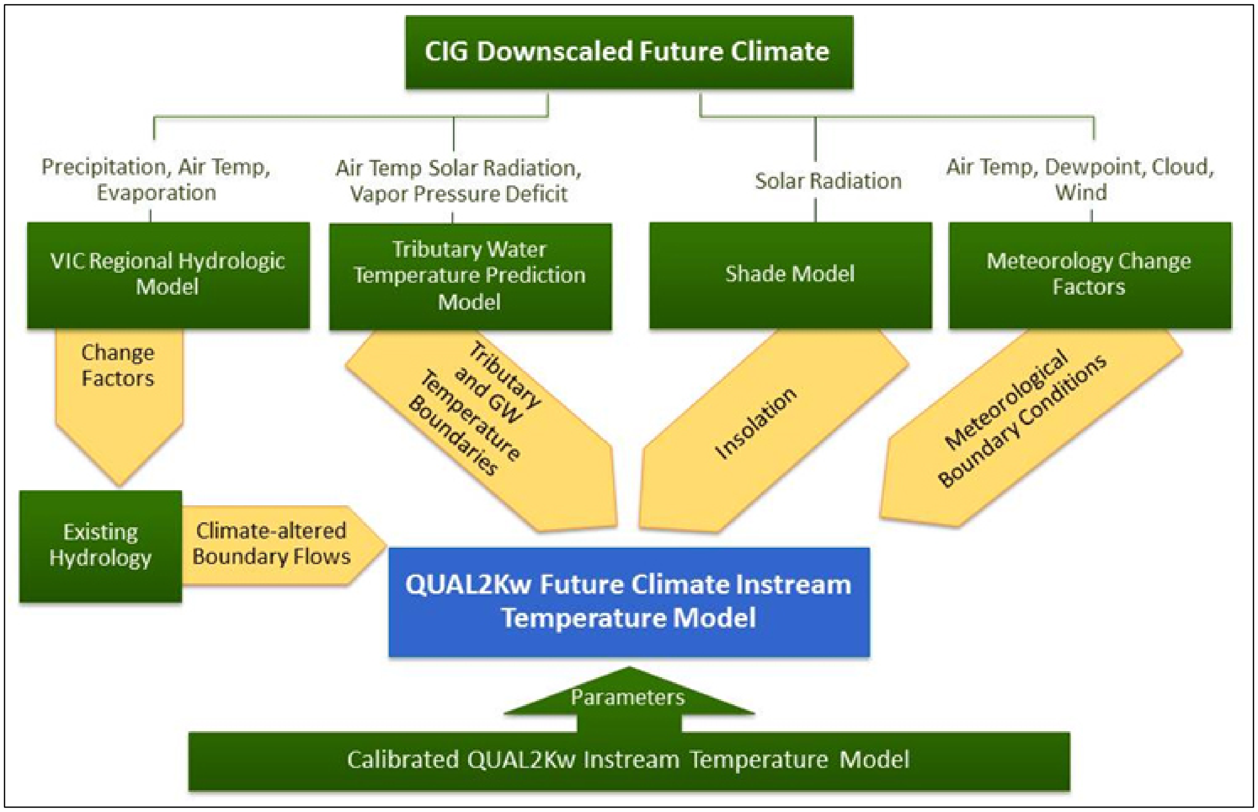


Figure 3-1. Schematic of Model and Climate Data Integration for the Quantitative Assessment

3.1 Climate Model Applications for the Pacific Northwest

3.1.1 CIG Climate Projections

The basis of the CIG climate change assessment is a common set of simulations using 21 Global Climate Models (GCMs) coordinated through the IPCC as part of the Fourth Assessment Report (AR4) and described in the IPCC 2007 report (Randall et al., 2007). These models are global in scope, and therefore the spatial resolution across the state of Washington is coarse (i.e., only a few grid cells cover the state).

Overall, the suite of models from AR4 provide a credible representation of observed climate in the PNW, reproducing both the observed seasonal cycle and 20^{th} century warming trend of 0.8 °C (Randall et al., 2007). The large-scale GCMs, however, provide a coarse representation of local climate because the scale of these model results precludes fine-scale resolution of local elevation effects and the details of land-sea interactions. For this reason it is important to use the models to inform the potential for *relative* changes at the local scale, rather than use climate model output directly. Mote and Salathé (2010) evaluated GCM performance in simulating historical climate over the PNW as a whole by comparing the regional average model output over the PNW to 0.5° gridded data for 1970–1999 obtained by assimilating observed data into the Climate Research Unit weather prediction model (Mitchell et al., 2004). This adjusts for the uneven distribution of weather stations, especially in high terrain, and yields a direct basis for comparison. The GCMs are in a general sense consistent with observed spatial and temporal patterns of climate in the PNW. On detailed comparison for 1970–1999, Mote and Salathé found that most of the GCMs have a cold bias (mean and median of -1.8 °C) on average over the whole PNW region. The models also all have a wet bias, with a mean bias of +0.6 centimeters per month.

The spatial scale of the global models is too coarse for evaluating the hydrologic and water quality response of even moderate-size watersheds because it does not resolve local elevation and local land-water interactions well. For more local analysis it is necessary to downscale the global predictions to finer-scale local predictions. Downscaling can be accomplished in two general ways: by running a more detailed regional climate model that is forced by the global model (dynamical downscaling) or through using statistical relationships between GCM output and local climate variations (statistical downscaling). The two approaches can yield different results and both have limitations. Statistical downscaling assumes that spatial patterns of weather remain unchanged under future climate, which might not be true, while regional climate models used in dynamical downscaling are themselves subject to high levels of uncertainty and might not fully resolve local topographic effects. CIG used a statistical downscaling approach and has taken projected time series from GCMs and downscaled the meteorological output to a $1/16^{th}$ degree (approximately 26. 7 km^2 or 6,600 acres at this latitude) resolution for the PNW (see Hamlet et al., 2013; Polebitski et al., 2007). This has been done for 10 GCMs and multiple emission scenarios for the period through 2099. Downscaling is also done in two different ways: using a composite delta method in which there is a single average change (delta) for each month calculated from a time slice of the GCM for the region that is applied to every day in that month, and a hybrid delta approach that uses statistical bias correction to maintain the probability distribution.

CIG has also produced gridded estimates of surface runoff and baseflow at the 1/16 degree scale, using the Variable Infiltration Capacity or VIC model (Elsner et al., 2010; Gao et al., 2010; Liang et al., 1994). Both the downscaled GCMs and VIC output are available for calendar years 1915 through 2006 as well as future climate projections based on the hybrid delta method modifications of the 1915–2006 historical climate series.

Seventy-nine climate scenario products from AR4 are available from CIG covering the SFNR watershed. These products incorporate a range of greenhouse gas emissions scenarios as interpreted through multiple GCMs. This project focuses on a limited subset of model results for the IPCC A1B emissions scenario. The A1B scenario is considered to provide a robust data set for a moderate emission scenario. Other IPCC emission scenarios predict greater warming, but there are only small deviations among scenarios until the latter half of the 21^{st} century, and the range of models using the A1B scenario covers most of the A2 (high emission) scenario range through the 2080s. The upper bound of the suite of GCMs using the A1B scenario projects an average annual air temperature increase for 2080 that is only 0.6 °C lower than the upper bound from the A2 scenario.

The IPCC recently began releasing updated GCM results for the Fifth Assessment Report (AR5). The climate models perform similarly to the AR4 projections for the PNW and have the same climate sensitivities. Differences in projected results are primarily due to differences in greenhouse gas emission scenarios. Work funded by the Northwest Climate Science Center is ongoing to develop downscaled hydrologic projections for the PNW using AR5, but results are not yet available at fine resolution comparable to the AR4 results.

3.1.2 Time Horizons for Analysis

Climate models are not of sufficient spatial resolution to resolve watershed-scale processes and are furthermore subject to biases in their simulation of climate. It is therefore standard practice to use a "delta" or "change factor" approach in which future climate time series are represented by perturbing historical climate time series in accordance with the differences between future and historic climate indicated by the downscaled GCMs. This approach preserves realistic temporal sequencing and minimizes bias present in the GCM simulations (Elsner et al., 2010). The GCMs themselves predict continuous changes in climate over time as a result of the changing concentrations of greenhouse gases and natural variations in climate. To minimize the impact of random and cyclic fluctuations in climate, the change analysis is typically based on the average change assessed over 30-year windows.

Downscaled climate projections produced by CIG are the result of bias correction of global models, spatial downscaling, and translation to a future time frame (Hamlet et al., 2013). The first step is implemented by comparing the historical simulations of the GCMs with observations, and then applying monthly differences, or "change factors" to the full GCM record to correct for spatial bias. In other words, the GCM output is adjusted to match observed data (CIG used data from 1950-1999 for the spatial bias analysis), and these same adjustments are applied to the remainder of the GCM time series. These adjustments are applied separately for each calendar month.

The bias correction and statistical downscaling steps are first applied to model output for 1915–2006, resulting in a 92-year time series that represents historical conditions and their variability.

Future climate products from CIG are also provided as 92-year time series, although relying on the average differences between two 30-year time windows. The future climate series are based on modification of the historic, 1915–2006 time series using a hybrid delta approach. The hybrid delta approach uses cumulative distribution functions to adjust the historical time series based on the change in the probability distribution of temperature and precipitation projected by the bias-corrected GCMs (see Hamlet et al., 2010 and Hamlet et al., 2013, Chapter 4). This step relies on the comparison of cumulative distribution functions between the future period of interest (e.g., 2070–2099) and a chosen historical window (specified as 1970–1999, which matches the historical time window chosen by Mote and Salathé (2010)). These change factors are then applied to the 92-year historical time series (1915–2006) to produce a perturbed time series that has the same time series characteristics of the historical record but a probability distribution that is shifted to match the change projected by GCMs. Using the 92-year historic time series has two principle advantages: (1) it provides a more accurate representation of local spatial and temporal weather variability than is provided by the climate models and (2) using a longer time series allows for better sampling of cyclic natural variability in the climate system, such as El Niño and the Pacific Decadal Oscillation. Despite being constructed based on specific 30-year windows, the downscaled projections are referred to using the shorthand "time horizon" names listed below (refer to Table 3-1):

Table 3-1. Time Horizons for the Climate Analysis

Time Horizon	Cumulative Distribution Basis	Resulting Time Series
Historic (1980s)	1970–1999	1915–2006, bias corrected and statistically downscaled
2020s	2010–2039	1915–2006 shifted by relationship of 2010–2039 to 1970–1999
2040s	2030–2059	1915–2006 shifted by relationship of 2030–2059 to 1970–1999
2080s	2070–2099	1915–2006 shifted by relationship of 2070–2099 to 1970–1999

From Table 3-1 it will be noted that a climate time series referred to as the "2020s time horizon" is actually a 92-year time series that is created by modifying the 1915–2006 historical time series based on the difference between the 2010–2039 projected results (centered at 2025) and those for 1970–1999 conditions (centered at 1985). In addition to the climate shift between these two periods, the resulting series also incorporates the variability in climate (whether of natural or anthropogenic origin) experienced over the 1915–2006 historical data. Therefore, it is more appropriate, for instance, to refer to the “2080s time horizon” than to the specific year 2085 for future scenarios.

The shift expected under future climate is calculated by CIG based on comparison to historic conditions centered at 1985, not 2013. Because the TMDL is based on calibration to conditions observed in 2007 with subsequent adjustment to the 90th percentile of 7-day maximum air temperatures observed from 1995–2012 there is likely some additional margin of safety in the analysis due to the difference between the 30-year distribution function of temperatures centered at 1985 and the underlying distribution statistics that would be appropriate to conditions centered at about 2003.

3.1.3 Climate Scenarios Selected for the South Fork Nooksack River TMDL

As discussed above, Mote and Salathé (2010) evaluated biases in the global-scale climate model predictions for the PNW. No single GCM fell into the best five of the GCMs for prediction of both temperature and precipitation; likewise, no GCM fell into the worst five for both temperature and precipitation. It is thus not appropriate to select a specific GCM based on its perceived prediction skill for the area; instead, the suite of GCMs is more appropriate for analyzing the potential ensemble range of future climates (Mote et al., 2011). This is consistent with findings of Knutti et al. (2010) and Pierce et al. (2009) that attempts to cull the best GCMs yields little difference in representing likely future change relative to a randomly selected subset of GCMs.

We evaluated three time horizons (2020s, 2040s, and 2080s) using the hybrid delta results from GCMs under the A1B scenario for the South Fork Nooksack watershed. We selected three GCMs for the analysis that are anticipated to produce the least warming of air temperature (model low-impact scenario), medium warming (medium-impact scenario), and highest warming (high-impact scenario), resulting in 3 climate models x 3 time horizons = 9 runs. This addresses the project objective of evaluating the ensemble *range of outcomes* from one IPCC emission scenario for the climate change risk assessment.

Selection of specific GCMs also considered factors other than average increase in annual air temperature. Maximum risk would be expected to coincide with increases in summer temperatures accompanied by decreases in summer baseflow. The USFS North Cascadia Adaptation Partnership (NCAP) has suggested a general storyline for impacts on aquatic habitat that includes the following components:

- Longer duration, higher stream temperatures, and lower summer baseflow.
- Transitions among the three basic PNW streamflow patterns (snowmelt-dominated, transient (mixed snow and rain runoff), and rain-dominated hydrographs). The lower SFNR is now classified as transient, but is expected to transition to rain-dominated by the 2020s under A1B. The upper reaches of SFNR are currently snowmelt-dominated, but are expected to transition to transient as early as the 2020s.
- Precipitation is expected to increase on an annual basis due primarily to increased winter rainfall and earlier, more intense fall rainfall. This is likely to increase winter flooding in sensitive transient river basins such as the SFNR.

Selection of specific GCMs is complicated by the fact that rankings switch for different time periods. Nonetheless, we have identified three GCMs that meet the general criteria for low, medium, and high warming while also demonstrating consistency with the NCAP storyline. These are as follows:

Low-Impact Scenario: This scenario uses the CGCM3.1_t47 or Third Generation Coupled Global Climate Model (CGCM) from the Canadian Centre for Climate Modelling and Analysis (www.ec.gc.ca/ccmac-cccma/default.asp?n=1299529F-1). Across the entire Columbia Basin this scenario shows the least warming by the 2040s and remains below the average through the 2080s. Temperature results for the grid cells intersecting the SFNR watershed are consistent with low warming. This scenario also shows a strong increase in total annual precipitation and a small decrease in summer precipitation compared to other scenarios, and is consistent with low impact in the NCAP storyline. CGCM3.1_t47 was also found to have the best performance across the 1970–1999 historical data set on evaluation of combined performance in predicting air temperature, precipitation, and sea level pressure (Mote and Salathé, 2010).

High-Impact Scenario: This scenario uses HADGEM1 (the Hadley Centre Global Environmental Model) from the Hadley Centre in the UK (Johns et al., 2006). Across the entire Columbia Basin this scenario has the second greatest increase in air temperature for the 2040s (and the highest increase of those available in the VIC model output) and the greatest increase in air temperature for the 2080s (+5.39 °C). Results for the SFNR are similar to findings for the Columbia Basin. This GCM also predicts a large decrease in summer precipitation and is consistent with high impact under the NCAP storyline. HADGEM1 exhibits average biases across the PNW that are near the ensemble mean for both air temperature and precipitation.

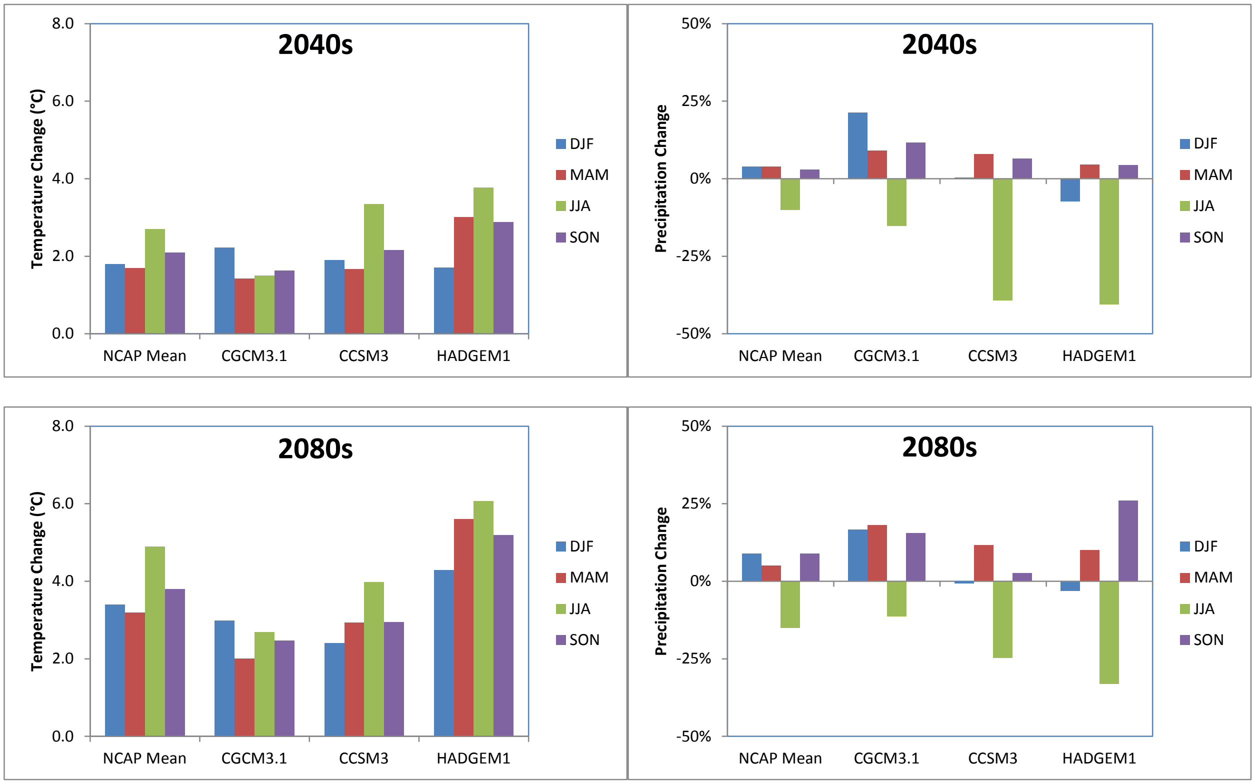
Medium-Impact Scenario: We chose to use a single GCM rather than a composite of multiple GCMs to represent a medium-impact condition because of concerns that a composite might not correctly reproduce correlations between air temperature, humidity, and other variables that jointly influence water temperature extremes. No GCM exactly follows the central trend of the ensemble of models on both temperature and precipitation; however, CCSM3 (the Community Climate System Model) provides a good compromise and is used for this purpose. CCSM3 is supported by the National Center for Atmospheric Research in Boulder, CO (Collins et al. 2006). This model falls near the average on temperature change for the PNW in both the 2040s and 2080s. There is a relatively large predicted decrease in summer precipitation, although not as extreme as the high warming scenario. Using this model could help distinguish between impacts due to air temperature and those due to precipitation changes. CCSM3 also exhibits biases on the historical 1970–1999 data sets that are near the ensemble mean (Mote and Salathé, 2010).

Table 3-2 compares predicted temperature and precipitation for the three selected GCMs for the SFNR to the minimum, mean, and maximum predictions from a 10-model ensemble identified in NCAP's draft (May 2013) North Cascadia Vulnerability Assessment (http://www.northcascadia.org/). Figure 3-2 provides a graphical comparison of the selected GCMs and the NCAP ensemble mean.

Table 3-2. Comparison of Selected SFNR Climate Scenarios to 10-model Ensemble for the North Cascadia Region

Period	Month	PCM1 (NCAP least warming)	SFNR Model Low-Impact CGCM3.1_t47 (least warming)	NCAP 10-model ensemble mean (moderate warming)	SFNR Model Medium-Impact CCSM3	MIROC 3.2 (NCAP most warming)	SFNR Model High-Impact HADGEM1 (most warming)
Temperature change relative to 1970–1999 baseline (° C)							
2040s	DJF	2.0	2.2	1.8	1.9	2.7	1.7
	MAM	1.3	1.4	1.7	1.7	3.0	3.0
	JJA	1.9	1.5	2.7	3.3	2.8	3.8
	SON	2.0	1.4	2.2	1.7	2.4	3.0
	Annual	1.8	1.6	2.1	2.2	2.7	2.9
2080s	DJF	3.2	3.0	3.4	2.4	4.6	4.3
	MAM	2.0	2.0	3.2	2.9	4.8	5.6
	JJA	3.3	2.7	4.9	4.0	4.9	6.1
	SON	2.4	2.2	3.9	2.5	4.3	4.8
	Annual	2.7	2.5	3.8	3.0	4.6	5.2
Precipitation change relative to 1970–1999 baseline (percent)							
2040s	DJF	-8	21	4	0	6	-7
	MAM	10	9	4	8	1	5
	JJA	-3	-15	-10	-39	-8	-41
	SON	-6	12	3	6	17	4
	Annual	-2	13	0	1	4	-4
2080s	DJF	9	17	9	-1	9	-3
	MAM	5	18	5	12	9	10
	JJA	-19	-12	-15	-25	-30	-33
	SON	-13	16	9	3	14	26
	Annual	-5	14	2	1	0	6

*N*ote:
PCM: Parallel Climate Model; MIROC: Model for Interdisciplinary Research on Climate; DJF: December, January, February; MAM: March, April, May; JJA: June, July, August; SON: September, October, November. Results are weighted averages across model grid cells covering the SFNR watershed.



Note: Results are weighted averages across all climate model grid cells intersecting the SFNR watershed. DJF = December, January, February; MAM = March, April, May; JJA = June, July, August; SON = September, October, November.

Figure 3-2. Climate Scenario Changes in Precipitation and Temperature Compared to North Cascadia (NCAP) Ensemble Mean

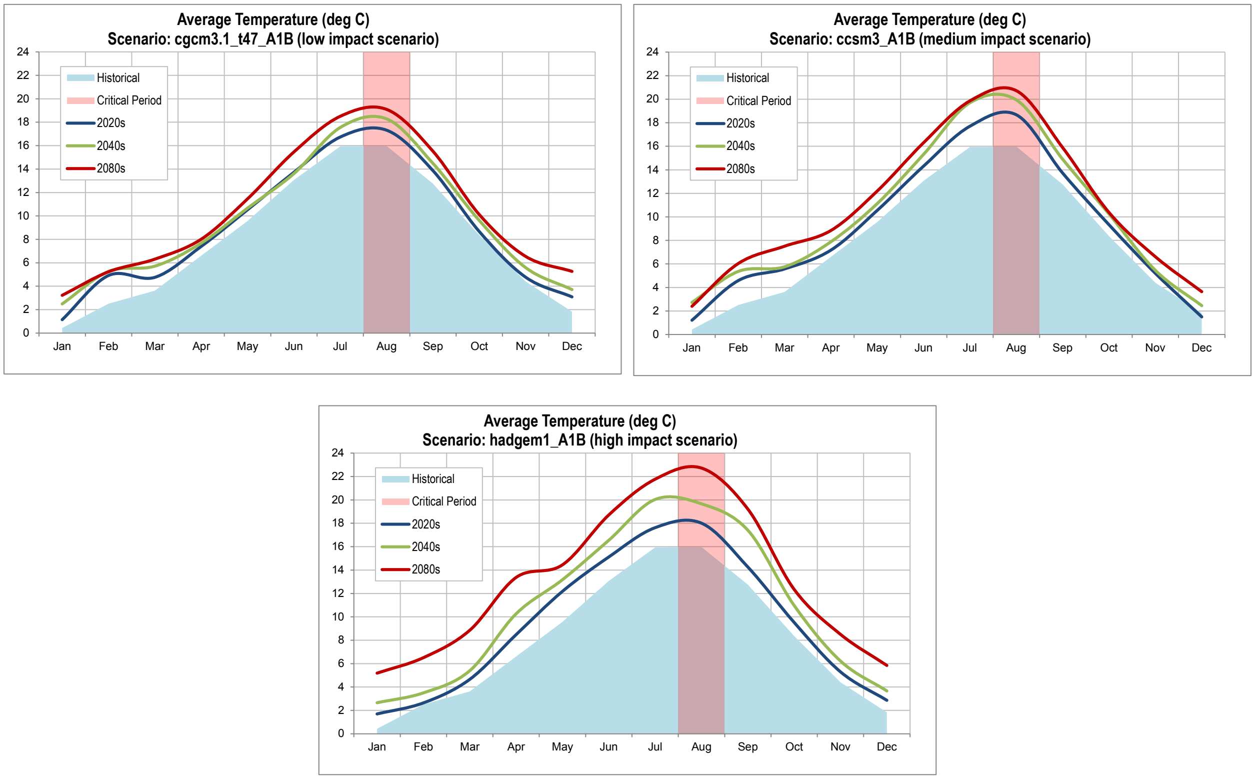
3.2 Future Climate Estimates for the SFNR

Model predictions for future air temperature, precipitation, and other climate variables from the low, medium, and high-impact GCMs are summarized below for the grid cells intersecting the SFNR watershed. Projections reported here for the SFNR are generally consistent with those reported in draft form by Mauger and Mantua (2011) for the North Cascades area (Omernik ecoregion 77), which contains the SFNR watershed. Their analysis of CIG GCM modeling products reports monthly average air temperature in the 2080s rising by about 2.8 ºC in the winter and 4.6 ºC in the summer, with precipitation varying widely among models, but tending on average to increase by about 19 percent in the winter and decrease by about the same percentage in the summer. As a result of temperature increases, potential and actual evapotranspiration is also predicted to increase in the summer, further reducing summer flows.

3.2.1 Air Temperature

Figure 3-3 shows air temperature projections area-weighted and spatially averaged over the downscaled grid cells intersecting the SFNR watershed and temporally averaged over the 91-year time series associated with each climate time horizon. (Note that in this and similar subsequent figures, the monthly averages are connected by smoothed lines to improve legibility.) The results are generally consistent with the average changes for the PNW reported by Mantua et al. (2010): By the 2080s the average summer (July–September) air temperature is projected to rise by amounts ranging from 2.81 ºC (CGCM3) to

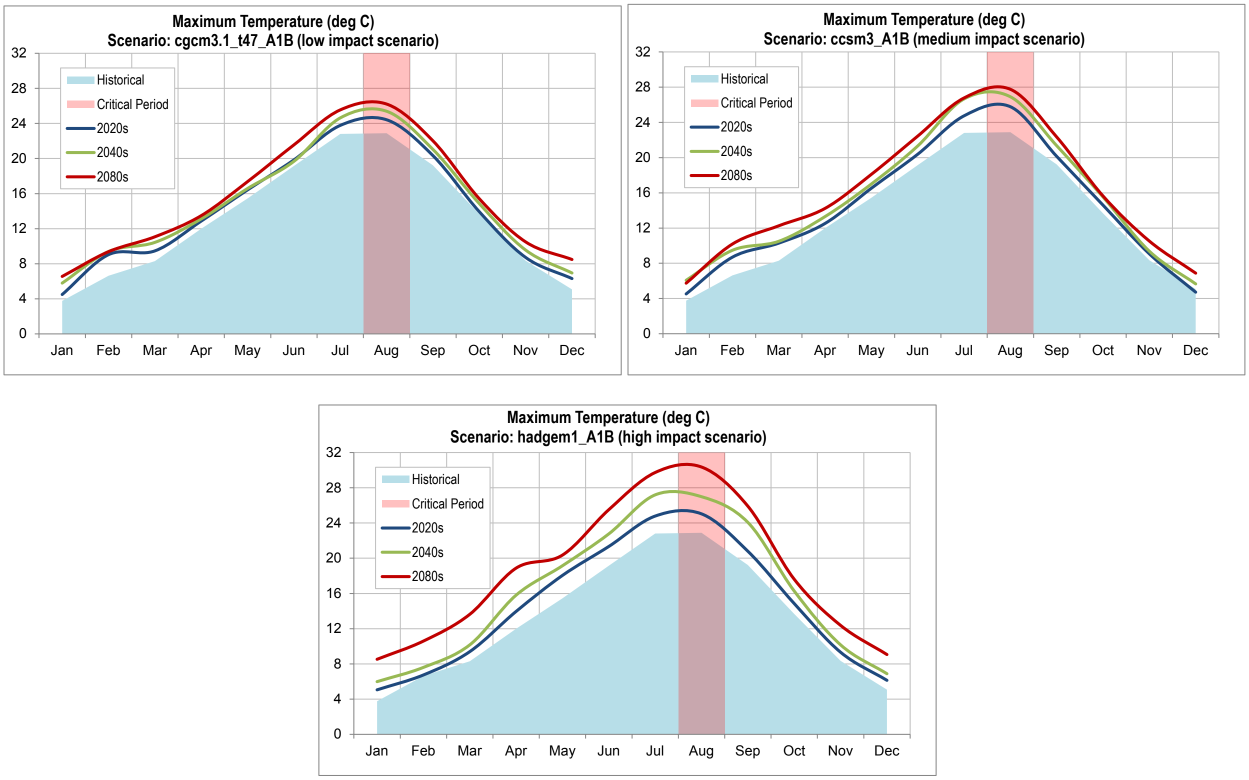
6.31 ºC (HADGEM1), while the average winter (December–February) air temperature is projected to rise by amounts ranging from 2.44 (CCSM3) to 4.28 ºC (HADGEM1).



Note: Results shown are medians across all the CIG grid cells intersected by the SFNR watershed. August is highlighted as a critical period because it typically combines the highest air temperatures and lowest precipitation.

Figure 3-3. Climate Model Projections of Monthly Average Air Temperature in the SFNR Watershed for Low-, Medium-, and High-Impact Climate Scenarios

The increase in the maximum daily average temperature might be even greater than the increase in the monthly average, as shown in Figure 3-4. The spatial median maximum air temperature for the SFNR, which occurs in August, is projected to increase by 3.32 ºC (CGCM3) to 7.74 ºC (HADGEM1).



Note: Results shown are medians across all the CIG grid cells intersected by the SFNR watershed.

Figure 3-4. Climate Model Projections of Monthly Maximum of Daily Average Air Temperature in the SFNR Watershed for Low-, Medium-, and High-Impact Scenarios

The pattern of projected air temperature increases is similar across the SFNR watershed; however, the absolute magnitude of the temperature decreases at higher elevations (Figure 3-5).

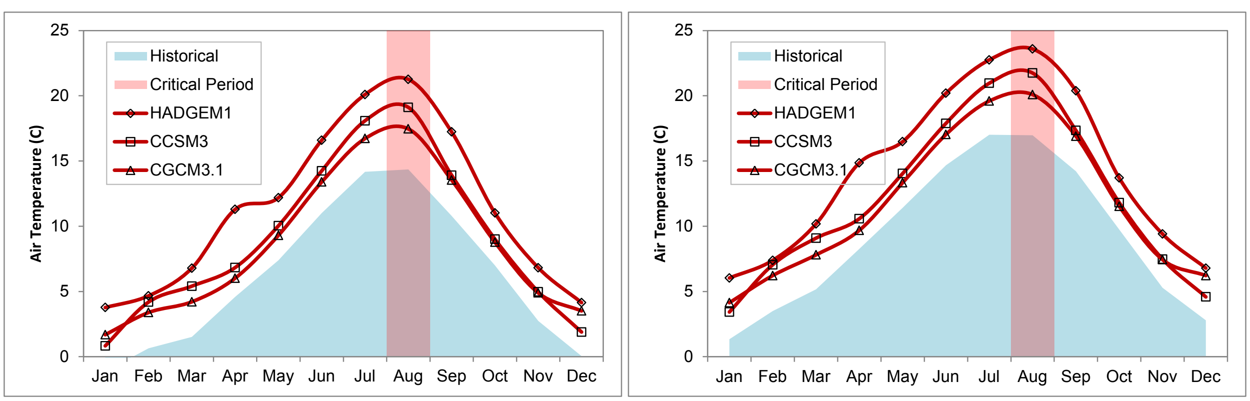
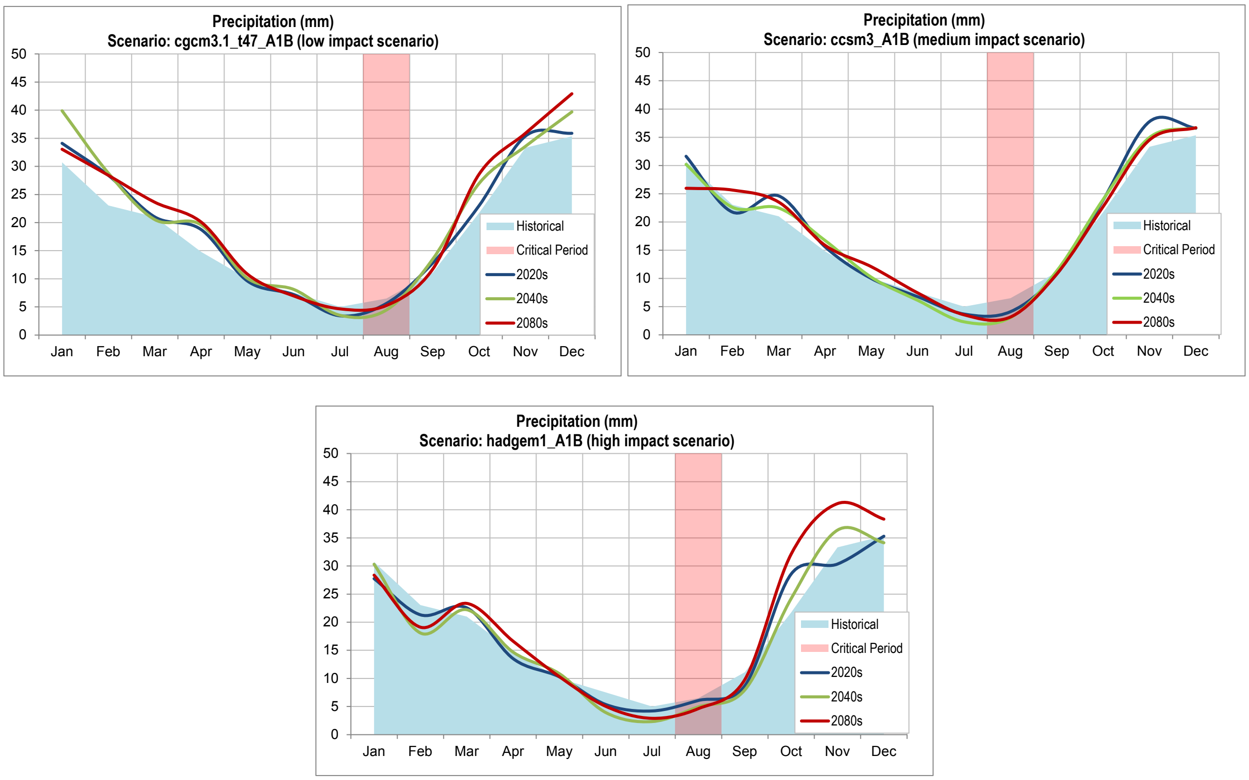


Figure 3-5. 2080s Climate Model Projections of Average Air Temperature in the SFNR Watershed at the Headwaters (left) and Outlet (right)

3.2.2 Precipitation

Projected changes in future precipitation (Figure 3-6) are less dramatic than changes in air temperature. All three GCMs predict an increase in fall precipitation by the 2080s accompanied by a small decrease in summer precipitation. The low-impact scenario (CGCM3) projects an increase in winter-spring precipitation, while the high-impact scenario (HADGEM1) suggests a decrease in January-February precipitation. The spatial distribution of 2080s precipitation is shown in Figure 3-7.



Note: Results shown are medians across all the CIG grid cells intersected by the SFNR watershed.

Figure 3-6. Climate Model Projections of Monthly Median Precipitation in the SFNR Watershed for Low-, Medium-, and High-Impact Scenarios

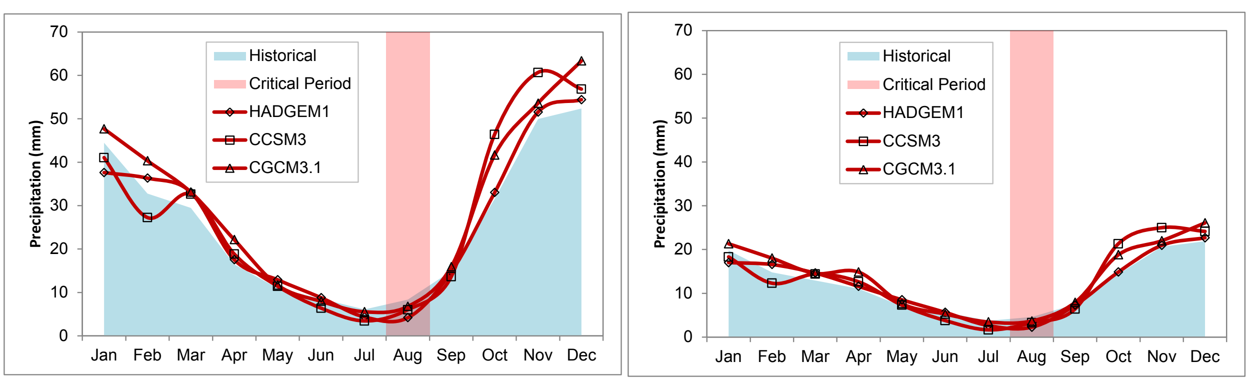
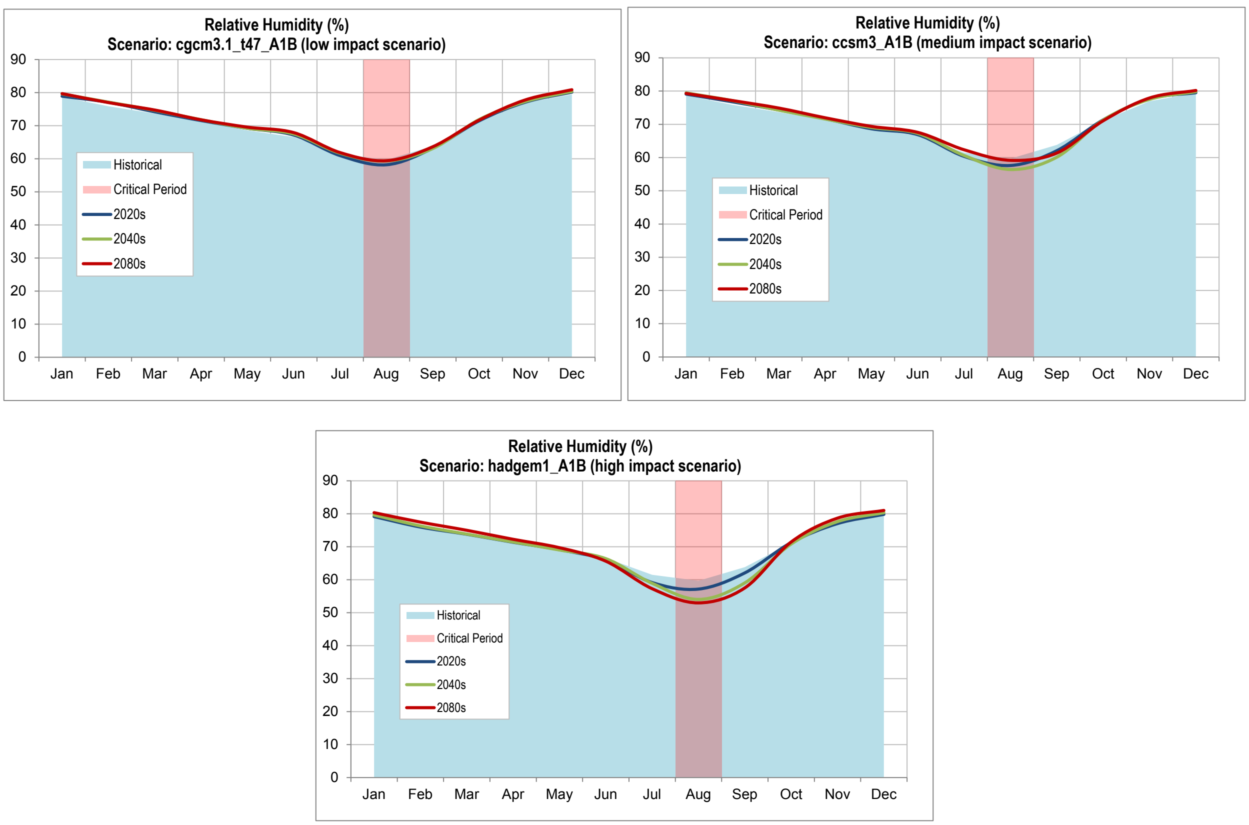


Figure 3-7. Climate Model Projections of 2080s Average Precipitation in the SFNR Watershed at the Headwaters (left) and Outlet (right)

3.2.3 Relative Humidity, Dew Point, and Vapor Pressure Deficit

Evaporative cooling can be an important component of the stream heat balance under low-flow conditions. The evaporation rate depends on the moisture content above the air-water interface and wind mixing. Ground-level atmospheric moisture is summarized via the relative humidity (percent of the saturation vapor concentration), dew point temperature (temperature of saturation), and vapor pressure deficit (the absolute difference between saturation and ambient vapor pressure, in Pascals). The VIC output from CIG includes estimates of relative humidity and vapor pressure deficit; however, these estimates do not come directly from the GCMs but rather were calculated in a preprocessing step within the VIC model. Both are based on empirical relationships to the average and daily range of air temperatures and so could omit important responses to changes in forcing conditions (Guillaume Mauger, Climate Impacts Group, personal communication, March 28, 2014). The relative humidity results project only a small change, with a potential decrease in summer relative humidity under the high-impact scenario (Figure 3-8).



Note: Results shown are medians across all the CIG grid cells intersected by the SFNR watershed.

Figure 3-8. Climate Model Projections of Monthly Average Relative Humidity in the SFNR Watershed for Low-, Medium-, and High-Impact Scenarios

While changes in relative humidity are small, calculated estimates of dew point temperature show a large increase as a result of increases in air temperature. This is significant for thermal modeling because the dew point temperature tends to control the daily minimum air temperature and thus affects the amount of nighttime cooling of water temperature that can occur.

VIC model results for all three of the GCMs project increases in vapor pressure deficit by the 2080s, with larger increases at lower elevations (Figure 3-9). This might in turn drive greater evaporation and increased evaporative cooling, providing some buffering against the projected air temperature increases.

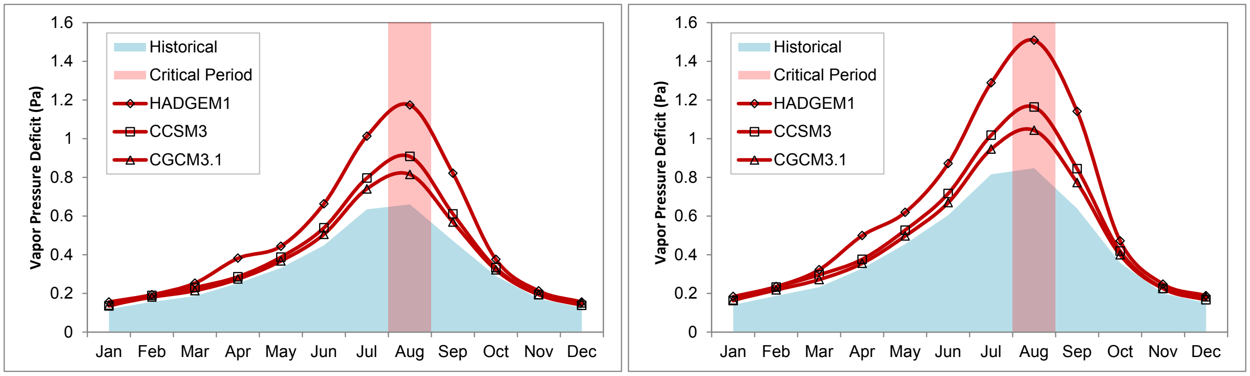
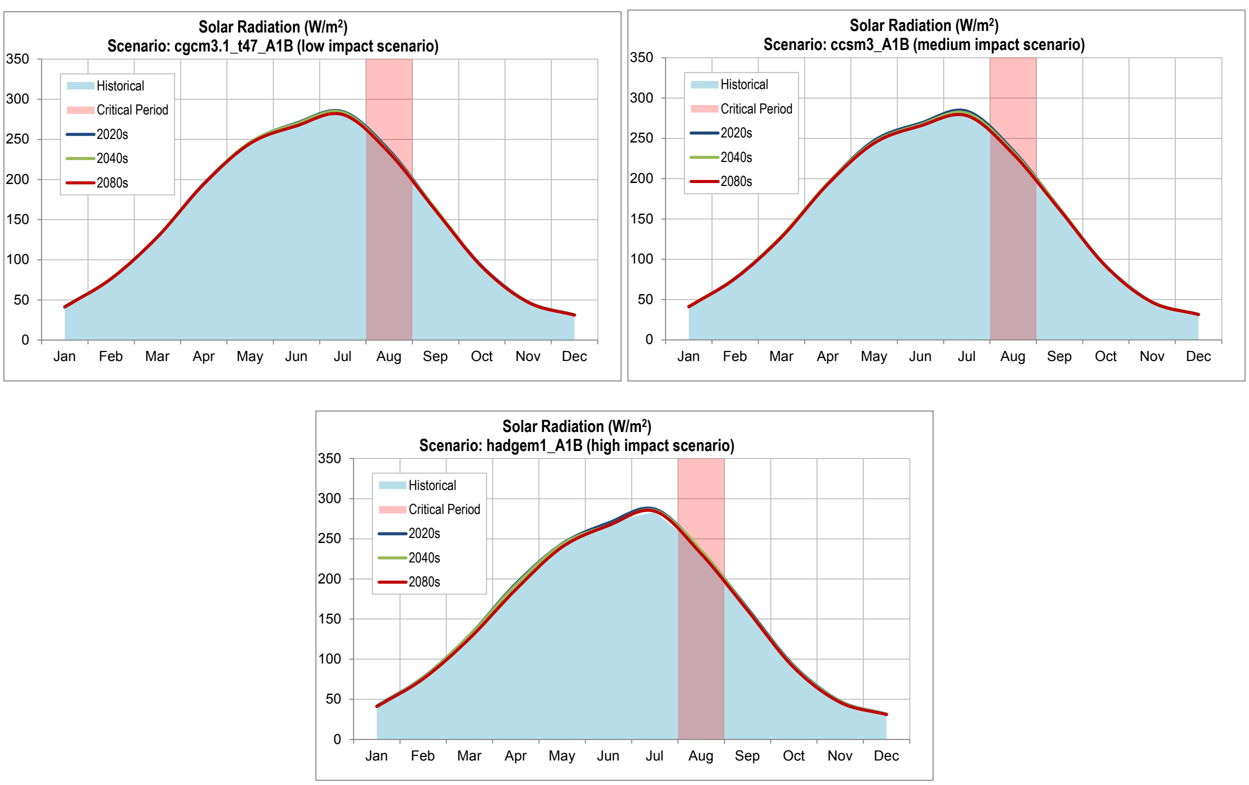


Figure 3-9. Climate Model Projections of 2080s Average Vapor Pressure Deficit in the SFNR Watershed at the Headwaters (left) and Outlet (right)

3.2.4 Solar Radiation

Figure 3-10 summarizes projected incident solar radiation from the VIC model output. As with humidity, the VIC pre-processor calculates solar radiation based on an empirical relationship to temperature. Little change is forecast, although small decreases in summer solar radiation are predicted as a result of increased cloud cover.



Note: Results shown are medians across all the CIG grid cells intersected by the SFNR watershed.

Figure 3-10. Climate Model Projections of Monthly Solar Radiation in the SFNR Watershed for Low-, Medium-, and High-Impact Scenarios

3.3 VIC HYDROLOGIC MODEL

CIG estimated hydrologic response to climate scenarios using the VIC model (Gao et al., 2009; Liang et al., 1994; Liang et al., 1996). The VIC model is a macro-scale hydrologic model that simulates watershed hydrology using estimates of vegetation, soil properties, topography, and daily weather variations. The VIC application for the state of Washington (Elsner et al., 2010) uses the Penman-Monteith energy balance approach to estimate potential evapotranspiration and then estimates surface and subsurface runoff rates at the daily time scale for model grid cells (1/16th degree spatial scale or about 26.7 km^2). Results can be routed and aggregated to a desired streamflow location or spatial scale.

For the Washington State application, VIC was calibrated and validated to runoff in the Columbia and Yakima rivers on streamflow at specific gage locations, and gridded temperature and precipitation data adjusted for orographic effects using the PRISM climatology (Daly et al., 2002). The model is not calibrated to individual small watersheds such as the SFNR.

The VIC output matches observed summer flows well in the SFNR, but does not seem to provide a particularly close fit to observed winter flows as seen by comparison to the Wickersham gage in Figure 3-11. Notably, VIC appears to not fully represent the role of snow in supporting May–June runoff. (VIC does predict a transient regime for higher elevations in the SFNR under historical conditions, but apparently weights the total watershed runoff too much toward rain-dominated conditions, as can be seen below in Figure 3-14 and Figure 3-15.) Similar results are found for comparison to different 30-year periods within the gage record. Comparisons of daily time series (e.g., Figure 3-12) show that VIC does a reasonable job of tracking daily variations in runoff and reproducing critical summer flows in the SFNR, but tends to over predict large winter runoff events. Wu et al. (2012) report similar results for validation tests of VIC at 12 PNW gages and obtained median daily and monthly Nash-Sutcliffe coefficients (Nash and Sutcliffe, 1970) of 0.56 and 0.70, respectively, and median daily correlation coefficient of 0.90 across the 12 sites. For these reasons it is best to use the VIC results to compute seasonal relative change factors for future climate rather than applying the model output directly in the temperature model.

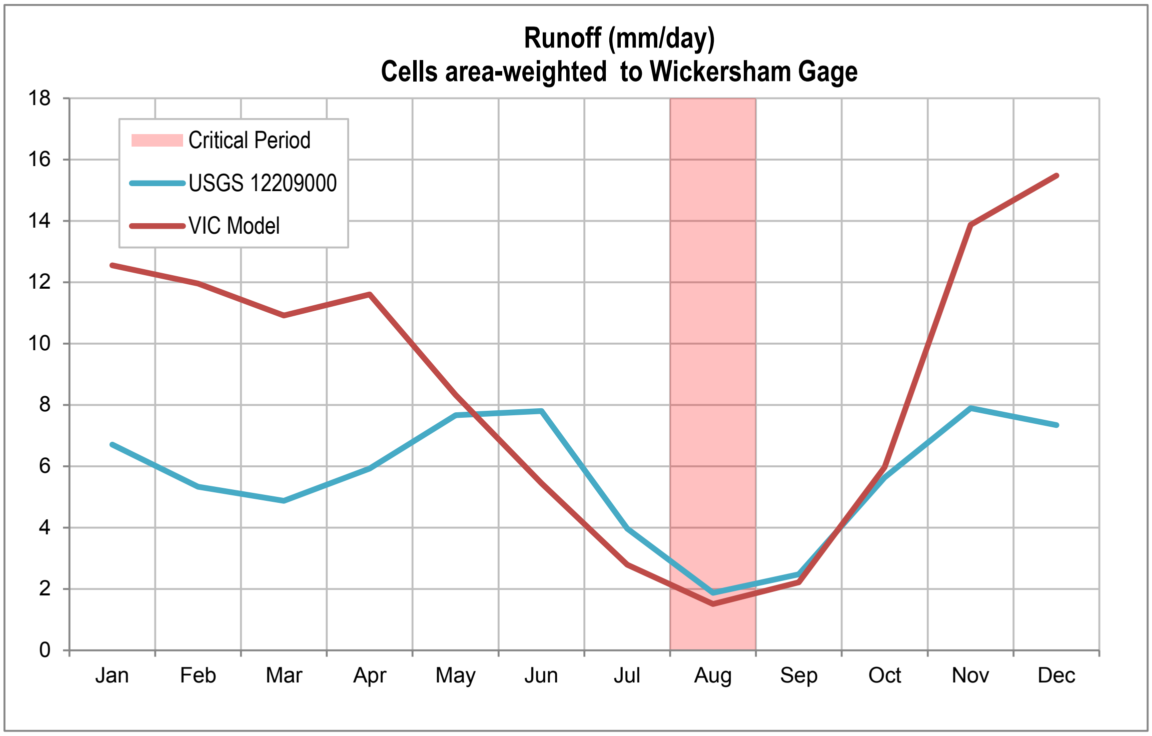


Figure 3-11. Comparison of Monthly Average VIC Model Flows to USGS Gaged Flows for the South Fork Nooksack River at Wickersham (12209000) for 1934–2006

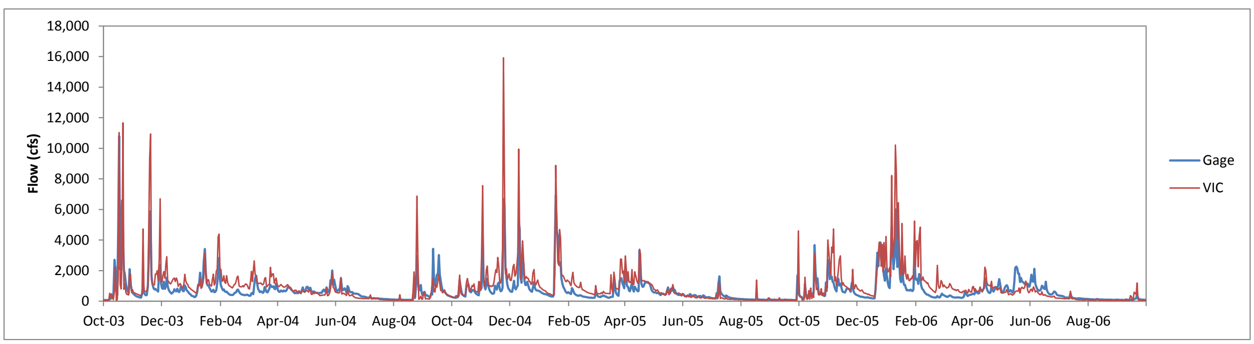


Figure 3-12. Time Series Comparison of Daily Average VIC Model Flows to USGS Gaged Flows for the South Fork Nooksack River at Wickersham (12209000) for 2003–2006

Over the entire state of Washington, the VIC applications suggest that future climate will result in a significant decrease in April 1 snow water equivalent storage, with accompanying shifts from snow-dominant to transient and from transient to rain-dominant regimes (Elsner et al., 2010; Mantua et al., 2010). Annual runoff across the state is projected to increase by 0–2 percent by the 2020s, 2–3 percent by the 2040s, and 4–6 percent in the 2080s, primarily due to projected increases in winter precipitation. In contrast, warm season (April–September) flow is projected to decrease by 33–43 percent by the 2080s.

3.3.1 Water Yield

As was shown above, the VIC model does a reasonable job of estimating summer low flows that are critical for temperature impacts in the SFNR, but does not provide a particularly accurate fit to historical winter-spring hydrology in the watershed. VIC's ability to predict responses of SFNR hydrology to significant changes in future climate is untested. More generally, the VIC model code has been widely applied and the theoretical construct of the model shown to provide a satisfactory representation of the water balance. We therefore assume that VIC simulations under projected future climate conditions provide at least a reasonable representation of the *relative* change that can be expected in watershed response. Thus, change factors, based on comparison of VIC output for a future scenario and historical conditions, applied to the observed historical flow series provide a reasonable estimate of the flow regime that can be expected under future climate conditions.

In general, VIC simulations of future watershed responses to all three GCMs project an increase in winter flows coupled with a decline in summer flows (Figure 3-13). The pattern varies considerably by elevation. At the headwaters, VIC correctly predicts the historical transient regime with the important role of snow in delaying runoff. This regime is predicted to change drastically, with a shift to a rain-dominated regime consistent with regional results (e.g., Mantua et al., 2010; Wu et al., 2012). On the other hand, predicted changes in hydrology at low elevations are generally small (Figure 3-14).

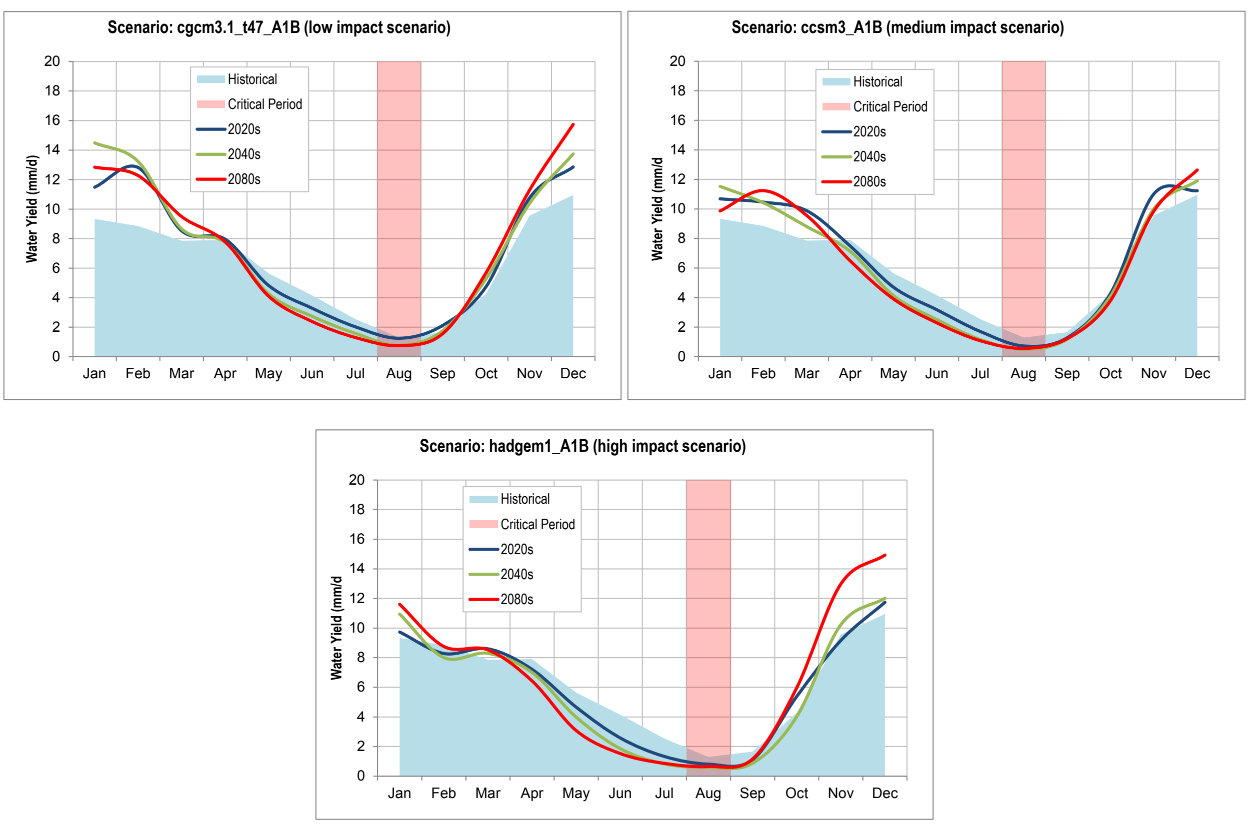


Figure 3-13. Monthly Average Water Yield in the SFNR Watershed Predicted by the VIC Model for Low-, Medium-, and High-Impact Climate Scenarios

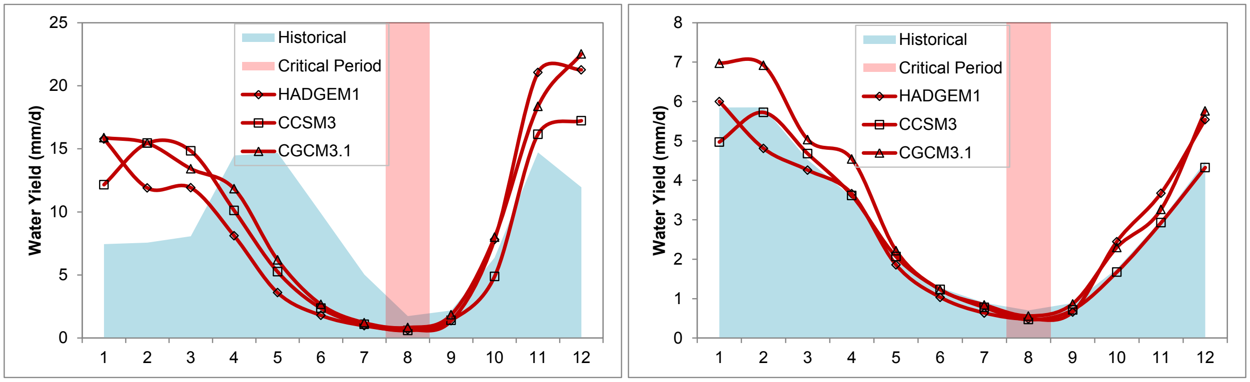


Figure 3-14. 2080s Average Water Yield in the SFNR Watershed Predicted by the VIC Model for Headwaters (left) and Outlet (right) Grid Cells

3.3.2 Baseflow

Thermal processes in streams are strongly dependent on the ratio of the surface area exposed to the atmosphere to the volume and thermal mass of the stream (Wu et al., 2012). As a result, stream temperature is often observed to co-vary with streamflow (Gu and Li, 2002). Summer baseflow is therefore important in determining the water temperature extremes in the SFNR, with lower baseflow resulting in increased heat gain during summer critical conditions.

The baseflow component of runoff emphasizes strong elevation differences within the SFNR. Under historical conditions, baseflow at high elevations represents a transient regime, with winter snow supporting spring and summer baseflow, with a peak in April and May, while the lower elevations have rain-dominated regime with peak baseflow in February. By the 2080s the model predicts little change in summer baseflow at low elevations; however, the baseflow pattern at high elevations shifts from a transient to a rain-dominated regime (Figure 3-15), showing this transition more clearly than the total flow plots presented above. This results in increased winter baseflow, but strong decreases in baseflow generated in the upper part of the watershed during the spring and summer.

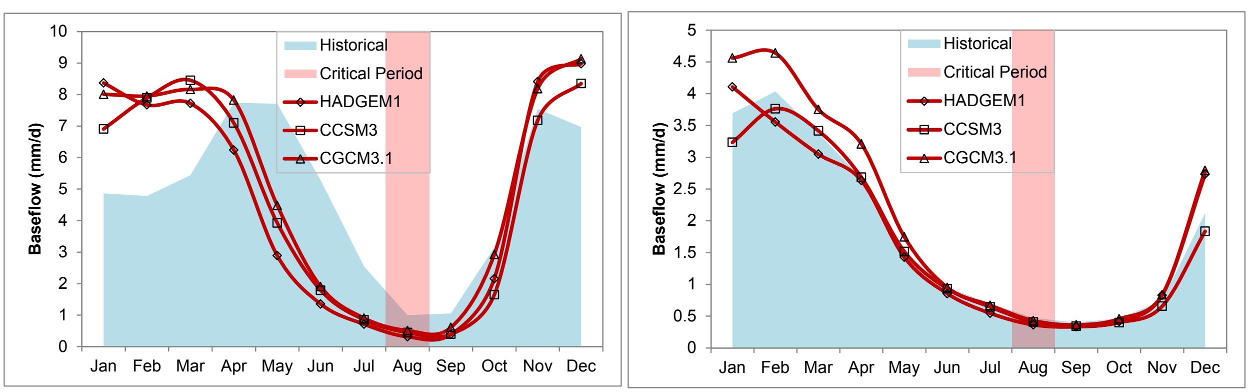


Figure 3-15. 2080s Average Baseflow Discharge Rate in the SFNR Watershed Predicted by the VIC Model for Headwaters (left) and Outlet (right) Grid Cells

4 Future Climate Boundary Conditions

The draft TMDL analysis was developed using a steady-state QUAL2Kw model (Ecology, 2003a) application to critical conditions within the SFNR. For the purposes of this assessment, and to assist with current and future salmon recovery planning, each of the critical conditions inputs is reevaluated under estimated future climate conditions. This section describes how each of the boundary conditions in the draft TMDL model was modified for the future climate scenarios.

4.1 MAINSTEM AND TRIBUTARY FLOW BOUNDARY CONDITIONS

The QUAL2Kw model represents the mainstem SFNR up to the confluence with Wanlick Creek and consists of 58 segments (see Figure 2-5 above). The model requires flow boundary conditions for the headwater reach and for each of the 37 tributary inflows, as well as for the direct ground water inputs to the mainstem (see Table 4-1).

The critical conditions run for the draft TMDL is based on 7Q10 flow, representing a critical low-flow condition combined with air temperatures of a similar recurrence (the 90^{th} percentile 7-day annual maximum). Some model simulations were also conducted using the 7Q2 flow combined with the median summer maximum temperature to represent the temperature stress on salmon populations during an average or “typical” year. Flow boundary conditions under future climates are based on an estimate of the effect of climate on flow during low-flow periods. To do this, the climate change application incorporates predicted changes in summer baseflow from assessments conducted by CIG with the VIC hydrologic model. VIC simulations suggest that total annual streamflow volume could increase slightly throughout much of the PNW in the 2040s and 2080s (Elsner et al., 2010). However, summer flows are projected to decrease across most of the region, with a mean decrease of more than 30 percent by the 2080s (Wu et al. 2012).

While the VIC model predictions of the water balance differ from historic gage records for the SFNR, the fit is generally good for the critical late summer period. Therefore, mapping and extrapolation of CIG estimates to the QUAL2Kw domain is necessary. Specifically, the CIG output is applied using a change method in which the TMDL 7Q10 flow at the model headwaters and for all tributary and diffuse inflows is modified by the ratio of CIG estimates of low flows under historic and future climate conditions.

Table 4-1. SFNR Tributary Catchments Included in the QUAL2Kw Model

Index	Name	Drainage Area (km^2)	Mean Elevation (m)	Confluence Distance from Headwaters (km)	Forested Area (%)
1	Wanlick	25.183	645.310	0	81.93%
2	SFN Headwaters	53.933	815.590	0	69.80%
3	Unnamed Trib 22	5.019	598.566	2.1	68.66%
4	Unnamed Trib 21	3.261	629.726	2.7	50.36%
5	Unnamed Trib 20	1.691	1036.890	2.8	74.27%
6	Unnamed Trib 19	5.474	552.084	4.4	76.36%
7	Unnamed Trib 18	2.353	691.332	6.4	89.78%
8	Unnamed Trib 17	1.937	624.672	8.1	80.78%
9	Unnamed Trib 16	1.290	596.201	10.5	57.97%
10	McGinnes	2.817	460.355	11.1	63.36%
11	Howard	20.013	429.725	11.7	67.57%
12	Unnamed Trib 15	1.359	503.633	13.9	91.63%
13	Unnamed Trib 14	1.980	512.113	16.9	84.10%
14	Canyon	3.671	452.229	19	80.44%
15	Unnamed Trib 12	2.028	418.746	21.2	61.99%
16	Unnamed Trib 11	1.472	464.442	22.9	52.14%
17	Unnamed Trib 10	2.133	443.301	24.6	77.52%
18	Plumbago	17.835	262.050	25.1	62.19%
19	Fobes	5.781	219.222	27.1	65.45%
20	Unnamed Trib 8	5.905	232.520	29	64.05%
21	Cavanaugh	24.147	389.141	30.8	76.64%
22	Unnamed Trib 7	2.071	280.670	31.2	76.91%
23	Edfro	7.622	278.374	32.9	73.48%
24	Skookum	57.677	259.506	34.5	66.91%
25	Unnamed Trib 6	4.163	235.014	38.1	73.76%
26	Pond	3.731	155.147	39.6	79.38%
27	Unnamed Trib 5	1.109	101.906	40.9	19.81%
28	Hutchinson	46.037	175.113	41.1	66.76%
29	Unnamed Trib 4	8.998	148.683	43.5	47.09%
30	Jones	7.130	225.005	44.5	57.45%
31	McCarty	6.232	164.868	46.8	57.37%
32	Standard	3.802	230.584	48.3	78.76%
33	Hard Scrabble Falls	2.686	240.694	50.4	71.93%
34	Sygitowicz	6.666	171.917	51.6	77.48%
35	Unnamed Trib 2	5.933	175.004	52.7	56.94%
36	Black Slough	26.003	124.464	54.2	51.06%
37	Unnamed Trib 1	4.777	137.119	55.3	80.70%

Note: Tributaries are un-nested and each discharges directly to the SFNR mainstem.

The VIC model historical conditions run is based on meteorology from January 1, 1915, to December 31, 2006, with current land use (from the 2006 digitization). The VIC model output includes the following climate variables:

- Precipitation
- Average, minimum, and maximum air temperature
- Solar radiation
- Relative humidity
- Vapor pressure deficit
- Evapotranspiration
- Potential evapotranspiration
- Runoff (surface flow depth per unit area)
- Baseflow (subsurface flow depth per unit area)
- Soil moisture
- Snow depth
- Snow water equivalent

The VIC output (for each 92-year time series associated with the distribution statistics of a 30-year time horizon, as shown in Table 3-1) was converted to unit-area 7-day flows, and the 7-day flows analyzed to determine the empirical 7-day flow with 2- and 10-year recurrence intervals. The same procedure was followed for each of the future climate scenarios and the ratio between future climate and historic conditions for 7Q10 flows was calculated for each VIC grid cell (and area-weighted if necessary) to estimate a ratio for each tributary watershed. These ratios were applied to the boundary inflow to yield the climate-modified inflow estimate for the critical condition. The flows are thus adjusted using a multiplicative change factor approach in which a multiplicative factor of 1 results in no change and values less than 1 result in future 7Q10 estimates that are less than historic estimates. The 7Q10 flow change factors are summarized graphically in Figure 4-1. The least change is associated with the low-impact GCM, which predicts relatively wetter summer conditions.

The resulting ratios for tributary flow vary strongly by elevation, with greater reductions at higher elevations (which have the highest water yield under historic conditions) and larger fractional reductions for the 7Q2 flow than for the 7Q10 flow. For example, in the 2080s under the high (HADGEM1) scenario, the predicted 7Q2 at the eastern ridgeline of the watershed is only 26 percent of the existing 7Q2 flow, while the baseflow of tributaries near the mouth of the SFNR remains at 90 percent of their existing 7Q2 flow. This reflects a shift away from snow-dominated runoff at high elevations and is broadly consistent with the VIC model output for the mainstem Nooksack River reported by Mantua et al. (2010), who found that 7Q2 flow there was predicted to be between 85 and 95 percent of existing 7Q2 flows through the 2040s and between 75 and 85 percent of existing flows by the 2080s. For the 7Q10 flows, the corresponding ratios are 53 and 94 percent.

Flows for direct ground water inputs are analyzed in the same manner as the tributary flows, except that the multiplicative change factors are based on VIC output for subsurface flow only. For the portion of the lower Nooksack that is a losing stream under low-flow conditions the rates of water loss (which sum to about 6 percent of the total flow) are left unchanged.

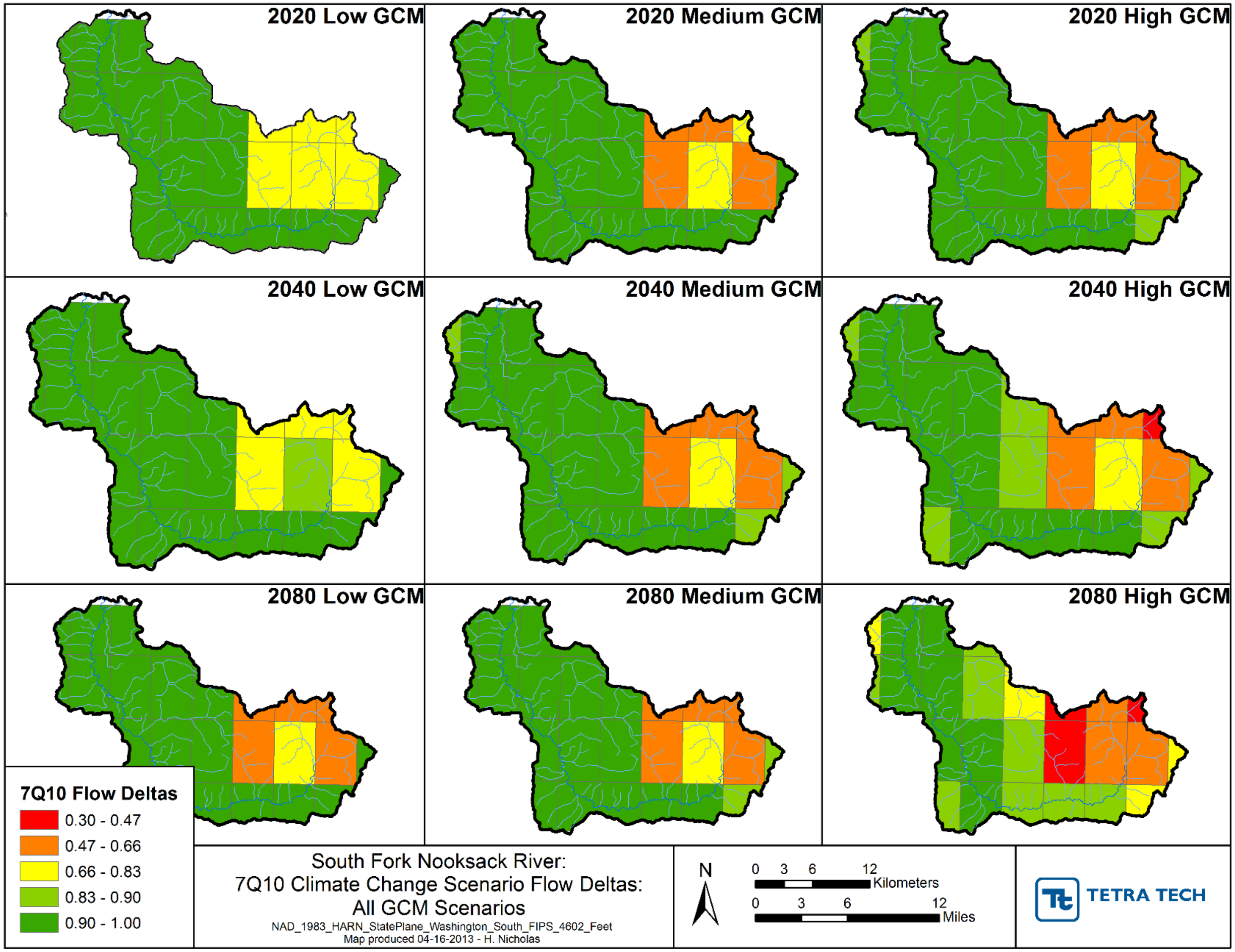


Figure 4-1. 7Q10 Flow Multiplicative Change Factors (Unitless) for Tributary Flow from VIC Model for Low-, Medium-, and High-Impact Scenarios (Columns) and 2020s, 2040s, and 2080s Time Horizons (Rows)

Figure 4-1 shows the spatial distribution of changes in tributary inflows. Total flow within the SFNR is calculated by the QUAL2Kw model as the integrated result of all headwater and tributary inflows. The 2080s predictions for 7Q10 low-flow conditions within the SFNR are compared to the historic 7Q10 flows by river mile in Figure 4-2. The absolute decrease in 7Q10 flows is greatest at the mouth (River Mile 0); however, the relative decrease is greatest at the headwaters (31 percent) and steadily shrinks to an approximately 20 percent decline near the mouth, reflecting the smaller change in tributary inflows at lower elevations.

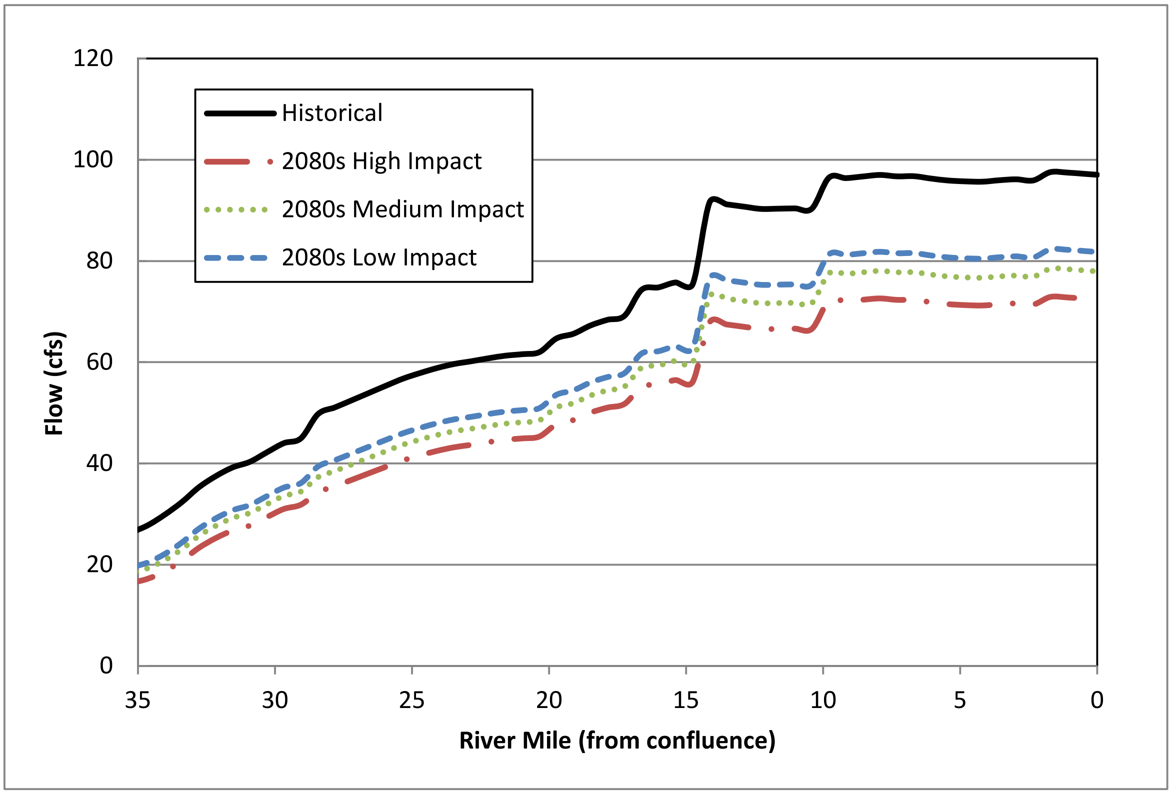


Figure 4-2. Simulated 7Q10 Flows by River Mile under Historic and 2080s Climate in the SFNR

4.2 MAINSTEM AND TRIBUTARY WATER TEMPERATURE BOUNDARY CONDITIONS

The QUAL2Kw model application provides a process-based simulation of the energy balance and temperature conditions in the mainstem SFNR; however, it requires specification of water temperatures for all influent boundary conditions. The tributary inflows influence resulting water temperatures in the SFNR, although active heat exchange across the air-water interface damps out the influence on downstream water (Mohseni and Stefan, 1999). The modeling scenarios assume tributary temperatures associated with the summer low-flow calibration run, which had tributary temperatures that might be slightly lower than 7Q10 flow conditions. Sensitivity analyses to temperature forcing in the tributaries is presented below in Section 5.3.

QUAL2Kw inputs headwater temperatures as a diurnal (24-hour) time series, developed from monitored data, while tributary temperatures are characterized by a daily mean and range. For future climate conditions the diurnal pattern or shape of the curve between the daily maximum and daily minimum temperature is assumed to remain unchanged; however, the daily maximum and daily minimum temperature could change. These changes are represented by an additive delta approach. That is, an absolute estimated change (as °C) is applied to both the maximum and minimum tributary water temperature.

The CIG climate analysis provides daily minimum and maximum air temperature; however, the VIC model does not predict stream water temperature. Therefore, an approach was developed in which the water temperature deltas were assessed using a regression approach that uses the VIC model output as explanatory variables. The Research Plan anticipated that the best approach would be to develop predictive multiple linear regressions based on VIC model output for daily minimum and maximum air temperature and daily surface and subsurface flow. However, subsequent testing showed that this approach did not yield acceptable results. Therefore, additional nonlinear approaches were developed and tested based on peer-reviewed literature for the prediction of stream temperature from landscape and climate variables (e.g., Flint and Flint, 2011; Isaak et al., 2010; Mohseni et al., 1998). The tributary temperature prediction method (the combined regression method described in Section 4.2.2) is able to predict observed stream temperature from climate variables, but does not use the VIC flow output as a predictor of water temperature.

4.2.1 Fitting Data

The major obstacle to the regression approach proposed in the Research Plan is that good spatial coverage of temperature monitoring data from the SFNR tributaries is not contemporaneous with the VIC historical run, which covers 1915–2006. In contrast, the tributary stream temperature monitoring data used for the TMDL model was collected in July and August of 2007 through 2012 (Table 4-2). Most of the earlier temperature data in the system are from the mainstem only.

Table 4-2. SFNR Tributary Stream Temperature Monitoring Data

Tributary Name	Station Name (Years Monitored)
Wanlick Creek	SF0210 (2007), Wanlick10 (2010)
Plumbago Creek	411 (2010, 2012)
Deer Creek (tributary to Plumbago Creek)	SF0135 (2007), 412 (2010, 2012)
Cavanaugh Creek	SFT016 (2007), 410 (2010, 2012)
Edfro Creek	SFT015 (2007), 409 (2010, 2012)
Skookum Creek	SF0130 (2007), 413 (2010, 2012), USGS Station12209490 (2009-2010)
Hutchinson Creek	408 (2010, 2012), Ecology Station 01C070 (2003-2011)
Upper Tributary to Hutchinson Creek	604 (2012)
Second Upper Tributary to Hutchinson Creek	605 (2012)
McCarty Creek	SF0033 (2007)
Jones Creek	608 (2012)
Upper Tributary to Jones Creek	609 (2012)
Hard Scrabble Falls Creek	610 (2012)
Sygitowicz Creek	611 (2012)
Black Slough Creek	407 (2012)
Upper Tributary to Black Slough Creek	601 (2012)
Tinling Creek (tributary to Black Slough Creek)	602 (2012)
Upper Tributary to Tinling Creek (tributary to Black Slough Creek)	603 (2012)

Note: Monitoring by Nooksack Indian Tribe, unless otherwise indicated.

Given the lack of temporal overlap, it was not possible to predict daily variations in stream temperature from contemporaneous VIC output. Instead, the focus was shifted to a more generalized representation of critical period stream temperatures from which appropriate deltas could be calculated. Specifically, the revised analysis focused on the 7-DADMax and the corresponding maximum of the 7-day average minimum temperature in the monitoring series. Using the 7-day average is consistent with the temporal basis of the temperature water quality criterion and also dampens the effects of any individual anomalous observations. Examination of the changes in both the daily minimum and daily maximum of the critical temperature conditions is needed to define the proper diurnal cycle.

4.2.2 Regression Analysis

A variety of approaches were evaluated for predicting the observed 7-day average critical temperatures. Multiple linear regression has been highly successful in predicting thermal regime in mountain streams. For example, Isaak et al. (2010) developed multiple regression models of both mean stream temperature and maximum weekly maximum temperature (MWMT) using a large data set for the Boise River watershed. Isaak et al. (2010) developed models both with and without spatial covariance structures based on the degree of flow connection between different sites. The predictor variables in Isaak's final models are elevation, solar radiation, mean flow, and either mean or maximum weekly maximum air temperature. The models with spatial covariance structure yield R^2 values of 0.857 and 0.925 for the MWMT and mean stream temperature models, respectively; however, the nonspatial models yielded much lower R^2 values of 0.543 and 0.679.

We constructed similar models for the SFNR, but using VIC-predicted climate conditions rather than observations for the tributaries and without defining a spatial correlation structure as all the SFNR tributary sites are on individual small tributaries to a single mainstem and are thus not flow connected with one another. The resulting models obtained adjusted multiple R^2 values ranging from 0.575 to 0.649, which is consistent with the quality of fit obtained by Isaak et al. (2010) for the nonspatial models — despite the fact that we were constrained to use noncontemporaneous data—but still relatively weak as a predictive tool. We then examined regression models of the type developed by Flint and Flint (2008, 2011) to predict daily average temperature in the Klamath River basin of northern California that incorporate a nonlinear day-of-year (DOY) function and modified the approach to predict 7-day averages of maximum and minimum stream temperature. Stepwise regression fits to individual tributary data sets were promising, with R^2 values often around 0.8, but a good fit was not obtained to the entire data set simultaneously.

We also fit nonlinear logistic models of the type developed by Mohseni et al. (1998) to predict weekly stream temperatures observed in 2007–2012 using average air temperature from paired weeks in the 2000–2006 VIC model output. Mantua et al. (2009, 2010) fit models of this form to stations throughout the PNW including the mainstem Nooksack River at North Cedarville and Nooksack River above Middle Fork. Our results for many individual streams yielded multiple adjusted R^2 values around 0.75; however, there was significant variability in parameter values between individual sites, and fit was poor for Wanlick Creek, near the headwaters, and Hardscrabble Creek. Further, the Mohseni models require minimum and maximum temperature parameters and it is unclear if these parameters would be stable and appropriate for application under future climates. This model form, therefore, was deemed suboptimal for prediction under changed climate. However, the application did suggest the potential utility of using data from matched calendar weeks from different years.

Based on the various approaches discussed above, a nonlinear regression approach was undertaken that combines the Flint approach with findings of the general stepwise regression to predict the entire set of 7-day average minimum temperature and 7-day average maximum temperature (all observations) based on the Flint variables plus three potential additional terms for elevation (ELV, meters), drainage area (DRN, km^2), and fraction of area forested (FOR) in the following nonlinear form:

$$T_S = a + b(Rn) + c(VDD) + d(Tmean) + e(DA) + f(DA^2) + g(ELV) + h(FOR) + i(DRN).$$

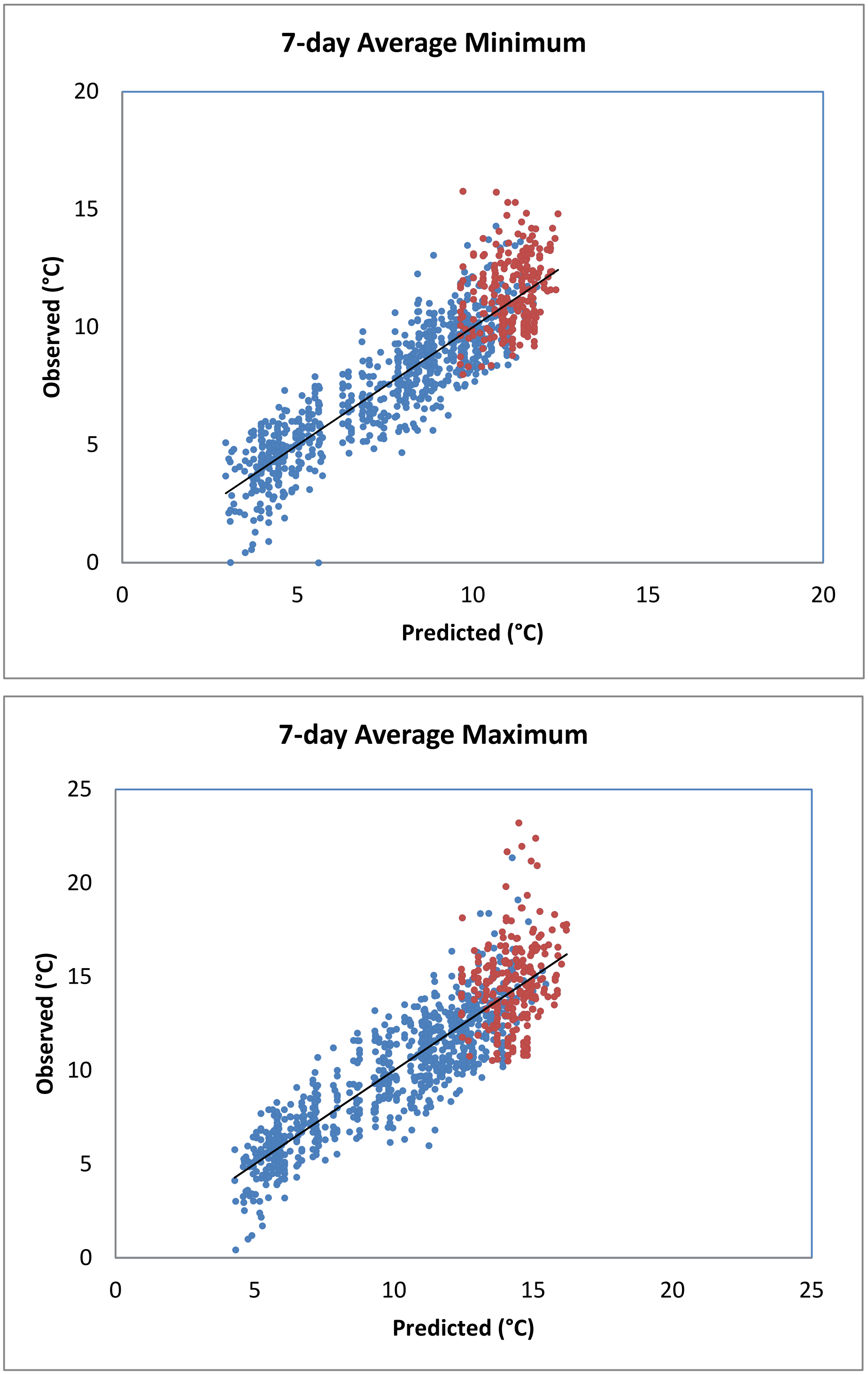
Here, T_S is the predicted stream water temperature in Celsius, Rn is the solar radiation (W/m^2), VDD is the vapor density deficit (Pa), $Tmean$ is the average air temperature, ELV is elevation (m), FOR is the fraction of area forested, and DRN is the drainage area (km^2). DA is a day-of-year (DOY) function that includes an internal fitting parameter, *t*:

$$DA = sin\left(\left({}^{DOY}/_{365}\right) * 360 + t\right)$$

Both forward and backward stepwise regressions converged on the same model equation in which all but one parameter in the equation for the average maximum temperature were significant. The model fit is shown in Figure 4-3; the coefficients and statistics are summarized in Table 4-3 and attain adjusted multiple R^2 values across all sites of 0.77 for the 7-DADMax and 0.80 for the corresponding maximum of the 7-day average minimum temperature. In general, the model is unbiased but somewhat imprecise due to the necessity of fitting noncontemporaneous stream water temperature and air temperature data. For the summer period of July 15–August 26 the average errors are -0.32 °C and -0.37 °C for the minimum and maximum, respectively, while the average absolute errors are 1.20 °C and 1.80 °C. The noise in the model fit is likely due to site-specific conditions in individual tributaries. The five largest under predictions of summer 7-day average maximum temperature all occur at station 410 on Cavanaugh Creek, while the 23 largest over predictions are all at Ecology station 01C070 on Hutchinson Creek.

The equations presented in Table 4-3 are used to calculate maximum 7-day average minima and maxima for each tributary during the model critical period under existing and future climates. These in turn are used to calculate additive deltas with which to modify the daily maximum and daily minimum temperatures specified in the TMDL model. (Using the delta method helps to minimize the potential impacts of bias in predictions for individual stations in the regression model.) Finally, the hourly temperatures are fit to the existing shape between the maximum and minimum over the course of the day. Note that this approach preserves a difference between the future runs without TMDL implementation and runs with SPV for the TMDL. The TMDL implementation runs, in addition to system potential shade, assume that under current conditions the tributary and headwater temperatures are at water quality criteria if the current 7-DADMax is greater than the applicable criterion. Thus, the system potential runs and the runs with current shade apply the same additive deltas to tributary temperatures, but the system potential run applies the deltas to a lower baseline in tributaries that currently exceed temperature criteria.

Table 4-4 and Figure 4-4 show examples of the predicted daily maximum tributary water temperatures for TMDL critical (7Q10) conditions for the 2080s, along with the current conditions daily maximum temperature used for the 7Q10 TMDL run.



Note: Data from Nooksack Indian Tribe stations are from June–October. The Ecology and USGS stations have year-round data. Results from July 15–August 26 are highlighted in red.

Figure 4-3. Prediction of 7-day Average Minimum and Maximum Water Temperature

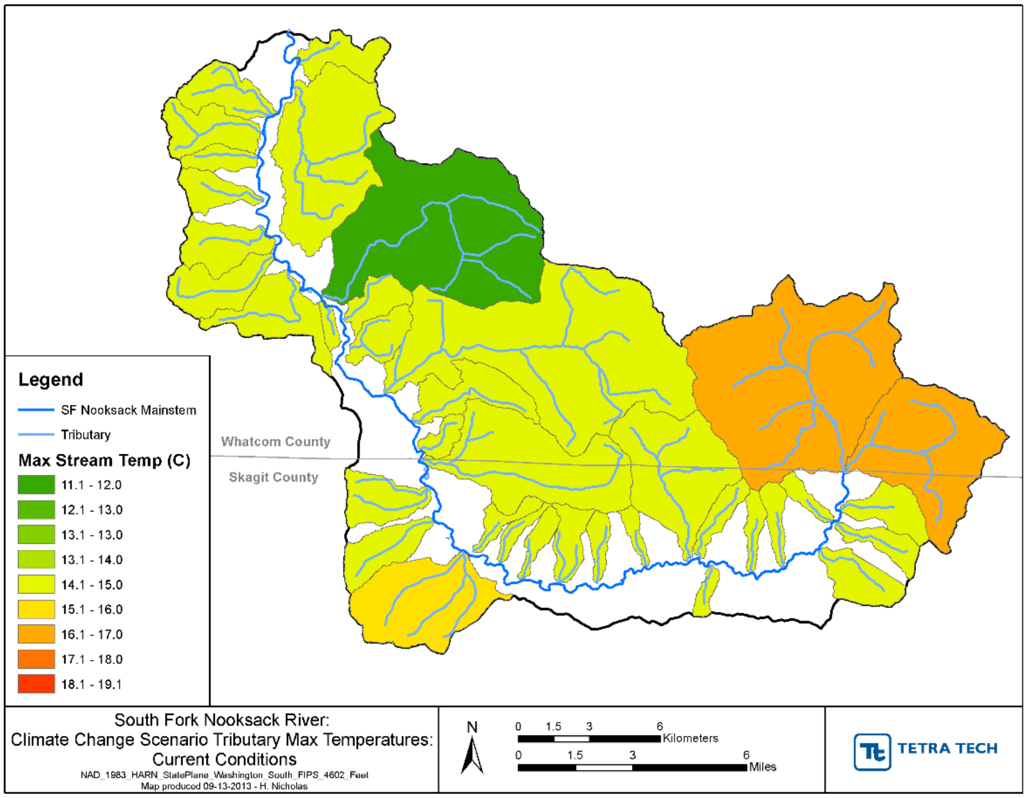
Table 4-3. Coefficients of Water Temperature Prediction Model

Coefficient	7-day Average Minimum Temperature (°C)	7-day Average Maximum Temperature (°C)
a (constant)	1.509	1.249
b (Rn: Solar Radiation, W/m^2)	-0.010	-0.006
c (VDD: Vapor Density Deficit, Pa)	266.622	432.452
d (Tmean: Average Air Temp, °C)	0.519	0.518
e (DA: Day of Year function)	-0.128	0.000
f (DA^2)	-0.666	0.575
g (ELV: Elevation, m)	0.000	0.001
h (FOR: Forested Fraction)	3.066	4.491
i (DRN: Drainage Area, km^2)	-0.010	-0.027
t (Day of year parameter, degrees)	1.000	-0.607
Summary Statistics		
Count	1052	1052
Multiple R	0.896	0.879
Adjusted Multiple R^2	0.801	0.772
Standard Error of Estimate	1.290	1.761
F-ratio	605.9	509.0
P value	< 0.001	<0.001
Average Error (7/15–8/26)	-0.31	-0.34
Average Absolute Error (7/15–8/26)	1.24	1.81

Table 4-4. Average of Projected Daily Maximum Tributary Temperatures (°C)

	Existing Vegetation			System Potential Vegetation		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
Baseline	14.45	14.45	14.45	13.21	13.21	13.21
2020s	15.47	15.86	15.62	14.23	14.62	14.39
2040s	15.87	16.14	15.90	14.63	14.90	14.66
2080s	16.13	16.60	16.64	14.89	15.36	15.40

Note: Average of the projected diel maximum for all tributaries is shown.



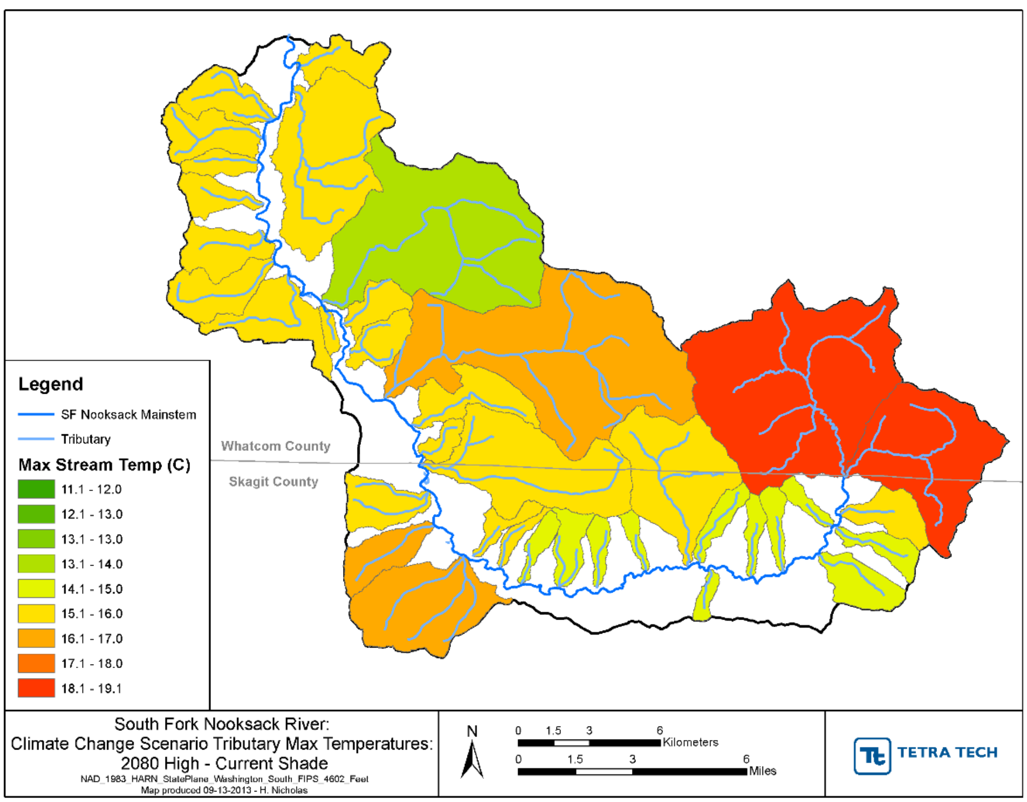


Figure 4-4. Predicted Maximum Hourly Tributary Temperatures under 7Q10 Flow Conditions for TMDL Scenario (top) and 2080s High-Impact Climate Scenarios with Current Shade (bottom)

4.3 METEOROLOGICAL FORCING

The QUAL2Kw model requires direct input of several meteorological variables, by reach, as described below.

4.3.1 Air Temperature

Air temperature under future climate is represented through an additive delta approach. Monthly average VIC model output for the historical run (1915–2006) was subtracted from the VIC model output for the climate scenario runs (2020s, 2040s, 2080s) to determine the difference in minimum and maximum air temperatures at each grid cell for the month represented in the TMDL runs. The delta change values for each climate scenario were added to the baseline condition to calculate a new daily maximum and daily minimum air temperature for each model segment. Weighted interpolation between the old and new maximum and minimum temperatures was used to calculate new air temperature based on the baseline condition on an hourly basis for each reach. Table 4-5 shows averages of the air temperature delta values for August critical conditions. Note that the changes in August temperature are greater in the medium-impact scenario than in the high-impact scenario for the 2020s and 2040s, even though the average annual change in temperature is greater in the high-impact scenario.

Table 4-5. Average Additive Deltas for August Air Temperature and Dew Point (°C)

Scenario	Low Impact		Medium Impact		High Impact	
	Air Temperature	Dew Point	Air Temperature	Dew Point	Air Temperature	Dew Point
2020s	1.35	0.69	2.71	1.71	2.04	0.98
2040s	2.32	2.02	3.96	2.49	3.67	1.41
2080s	3.13	2.75	4.76	4.16	6.69	3.76

Note: Results shown are average of change in maximum and minimum August temperatures averaged across all VIC grid cells intersecting the SFNR mainstem.

4.3.2 Dew Point Temperature

The VIC model does not directly output dew point temperature, but does provide relative humidity (RH) and air temperature (T, °C). From these, dew point temperature (T_d) is readily calculated via the Magnus-Tetens formula (Barenbrug, 1974) as:

$$T_d = \frac{b \cdot \alpha(T, RH)}{a - \alpha(T, RH)}, \text{ with}$$

$$\alpha(T, RH) = \frac{a \cdot T}{b + T} + \ln(RH), \; a = 17.27, \text{ and } b = 237.7\ °\text{C}.$$

We used RH rather than vapor pressure deficit to calculate T_d to maintain consistency with the approach used in the TMDL. After calculating dew point temperatures, the same additive delta method is applied as was used for air temperature. This involves establishing a delta-modified maximum and minimum daily dew point temperature with weighted interpolation between the minimum and maximum. Table 4-5 above shows average delta values. In all cases, the increase in dew point is smaller than the increase in air temperature.

4.3.3 Cloud Cover

The TMDL application assumes zero cloud cover (clear sky) as a critical condition. No adjustments are made to this assumption under future climates.

4.3.4 Wind

Wind speed influences conductive and convective heat exchanges at the water surface. Although wind is liable to change under future climate conditions, downscaled analysis of this variable is not available from CIG. Wind stress, therefore, is kept constant at TMDL conditions for all climate change scenarios. Hourly wind speeds for the critical condition runs range from 0 to 1.73 meters per second.

4.4 Other Boundary Conditions

4.4.1 Ground Water Inflow Temperatures

The QUAL2Kw model includes direct ground water discharge to the SFNR and the temperature of this discharge has an important effect on the heat balance in the river. Under future climate conditions, the ground water inflow temperature is modified using an additive delta. To derive the delta it is assumed that ground water temperatures are ultimately proportional to annual average air temperatures with the superposition of an annual cycle that results in ground water temperatures that are a few degrees warmer than the annual average air temperature during the late summer critical period. Therefore, the delta in the annual average air temperature is used to modify the ground water inflow temperature.

Because the annual average air temperature deltas have a very small range between VIC grid cells, the median delta was chosen from each climate scenario condition to be applied to all ground water inputs (Table 4-6).

Table 4-6. Additive Deltas on Average Annual Air Temperature (°C)

Scenario	Low Impact	Medium Impact	High Impact
2020s	0.977	1.212	1.464
2040s	1.630	2.154	2.878
2080s	2.472	2.948	5.193

4.4.2 Physical Boundary Conditions

Physical boundary conditions are generally assumed to be unchanged under future climates. This simplifying assumption introduces uncertainties into the prediction.

Riparian Shade: The QUAL2Kw core model uses estimates of existing shade on the mainstem of the river based on observations (e.g., LiDAR, aerial imagery) and the Shade model. The TMDL application also evaluates the natural condition of full potential shade ("system potential" conditions). Even though there is a likelihood that riparian vegetation composition (e.g., diversity and abundance) could be altered as a result of climate change, we do not have the tools to predict these changes and thus do not evaluate climate-induced changes in riparian shade outside the range of conditions to be evaluated for the TMDL.

Channel Structure: The channel structure is set to existing conditions for all model setups, including climate change scenarios. It is acknowledged that alterations in climate, such as increased winter high-flow events, could alter channel geometry. For example, powerful high-flow events could result in a widening of the channel with lessened shade and increased solar input. We do not, however, have the tools to predict these changes and thus do not evaluate potential climate-induced changes in channel structure.

Hyporheic Exchange: In rivers with coarse (sand, gravel, cobble) bed sediments, a portion of the flow (hyporheic flow) occurs within the bed sediment. Heat flux between the water and sediment during hyporheic flow can help stabilize stream water temperatures and provide cooling during summer months. Changes to flow and temperature under future climates could alter the effectiveness of hyporheic exchange in maintaining stable water temperatures.

The user inputs to QUAL2Kw that control the effect of hyporheic exchange on water temperature are the thermal conductivity, thermal diffusivity, the effective thickness of the sediment layer, and the bulk hyporheic exchange flow. These parameters are determined primarily through calibration. The primary uncertainty for addressing climate impacts through hyporheic flow in the QUAL2Kw model is that the bulk hyporheic exchange flow is a user-specified input. The fraction of hyporheic flow adopted for the TMDL model is not altered for the future climate model runs, resulting in specification of a linear change in hyporheic flow as total flow in the reach changes. Therefore, no additional changes to boundary conditions are needed to evaluate how the effects of hyporheic exchange could change under future climates.

5 Temperature Model Results

The QUAL2Kw model of TMDL critical conditions was reapplied with future climate forcings as described in Section 4. We report the resulting maximum water temperature predictions for the 2020s, 2040s, and 2080s under low-, medium-, and high-impact climate scenarios. Note that because QUAL2Kw is a steady-state model (with diel variability) the daily maximum water temperature predicted by the model under critical conditions, as defined below, is assumed to be equivalent to the 7-DADMax temperature defined in the water quality standards.

5.1 Critical Conditions Scenario

The SFNR temperature TMDL scenarios are based on a steady-state analysis of critical conditions, which combine high air temperatures with low flows, leading to increased heating. Specifically, the following assumptions were used to estimate critical conditions:

- 7Q10 flows are assumed. The 7-day average low flow that occurs, on average, once every 10 years.
- Headwater and tributary temperatures are at water quality criteria (or observed current temperature if cooler). This is applied for scenarios with SPV (not current vegetation).
- Air temperature, dew point, and relative humidity are at critical conditions (90th percentile air temperature defined as the 90th percentile of the series of the annual maxima of 7-day average air temperatures for each week of record, and corresponding atmospheric moisture content), modified to account for a microclimate effect associated with SPV. As specified by Ecology, the microclimate effect is simulated by a drop in temperature of 2 °C at every hour of the day.
- Direct ground water discharge rates based on 1990s seepage study and a method synthesized from Curran and Olsen (2009) as incorporated into the model calibration to conditions of August 2, 2007, and adjusted to 7Q10 flows.
- Temperature of direct ground water discharge initially based on annual average air temperature and adjusted during model calibration.
- Cloudless sky, consistent with maximum temperature impact in later summer.

As discussed in Section 2.1, modeling scenarios were developed to estimate natural conditions by assuming SPV. Modeling scenarios were also developed assuming current shade, recognizing that attaining SPV can take decades. Runs that included current shade omitted the microclimate effect associated with SPV, and also omitted the decreased headwater and tributary temperatures.

5.2 Climate Change Scenarios

Ecology and EPA requested 18 future climate simulations. These runs (identified as Scenarios 9 through 26 in the draft TMDL document) address 2020s, 2040s, and 2080s climate for the high-impact, medium-impact, and low-impact climate scenarios, with current or system potential shade. We constructed each scenario by perturbing the results (Scenario 5 or Scenario 3) by the climate deltas or change factors discussed in Section 4. The future scenarios, along with the two comparable current climate TMDL runs, are summarized in Table 5-1, along with the resulting maximum predicted stream temperatures. Results are discussed in more detail below.

Table 5-1. Critical Period Maximum Water Temperature Results Summary

Scenario (Scenario numbers are as given in the draft TMDL document.)	Maximum Stream Temperature (°C) (averaged across reaches)		
	All Reaches	Headwaters to Reach 28[1]	Reach 28[1] to Outlet
Critical Condition TMDL Runs			
3 (Current climate and shade, 7Q10)	21.04	20.15	21.84
5 (Current climate, system potential, 7Q10)	18.73	17.78	19.60
2020 GCM Comparisons			
9 (2020 High, current shade)	23.40	22.75	23.98
12 (2020 High, system potential)	21.02	20.26	21.71
10 (2020 Medium, current shade)	23.65	22.94	24.30
13 (2020 Medium, system potential)	21.30	20.48	22.05
11 (2020 Low, current shade)	22.78	22.10	23.39
14 (2020 Low, system potential)	20.42	19.64	21.13
2040 GCM Comparisons			
15 (2040 High, current shade)	24.61	24.07	25.10
18 (2040 High, system potential)	22.15	21.45	22.78
16 (2040 Medium, current shade)	24.68	24.04	25.26
19 (2040 Medium, system potential)	22.31	21.54	23.02
17 (2040 Low ,current shade)	23.55	22.84	24.19
20 (2040 Low, system potential)	21.22	20.39	21.96
2080 GCM Comparisons			
21 (2080 High, current shade)	26.97	26.54	27.36
24 (2080 High, system potential)	24.61	24.00	25.15
22 (2080 Medium, current shade)	25.70	25.07	26.27
25 (2080 Medium, system potential)	23.35	22.56	24.06
23 (2080 Low, current shade)	24.46	23.81	25.04
26 (2080 Low, system potential)	22.10	21.33	22.80

Notes:
[1] From headwaters to 27.5 km downstream, the water quality criterion is 12 °C 7-DADMax; below this point it is 16 °C.

The increases in maximum water temperatures shown in Table 5-1 arise from the combination of increased air temperature, increased ground water and tributary water temperatures (both of which are in turn dependent on air temperature, among other factors), and decreased flows. For the 2080s the median ratio of the change in maximum water temperature to change in maximum air temperature is 0.96.

Table 5-1 reports the simulated daily maximum temperature under critical conditions because it is the surrogate for 7-DADMax temperature, which is the focus of the TMDL. Projected changes in daily average temperature for the August critical day (Table 5-2) are smaller than changes in the daily maximum temperature. The results are generally consistent with the findings of Wu et al. (2012), who projected mean summer temperature changes for transient systems in the PNW of up to 3.97 °C for the 2040s and up to 5.71 °C for the 2080s.

Table 5-2. Critical Period Daily Average Water Temperature Results Summary

Scenario (Scenario numbers are as given in the draft TMDL document.)	Average Water Temperature (°C)	Change Relative to Scenario 3 or Scenario 5 Baseline (°C)*	Ratio to Average Air Temperature Change
Critical Condition TMDL Runs			
3 (Current climate and shade, 7Q10)	17.21		
5 (Current climate, system potential, 7Q10)	15.35		
2020 GCM Comparisons			
9 (2020 High, current shade)	19.12	1.90	0.93
12 (2020 High, system potential)	17.22	1.87	0.92
10 (2020 Medium, current shade)	19.41	2.20	0.81
13 (2020 Medium, system potential)	17.54	2.19	0.81
11 (2020 Low, current shade)	18.62	1.40	1.04
14 (2020 Low, system potential)	16.73	1.38	1.02
2040 GCM Comparisons			
15 (2040 High, current shade)	20.16	2.95	0.80
18 (2040 High, system potential)	18.22	2.87	0.78
16 (2040 Medium, current shade)	20.32	3.11	0.79
19 (2040 Medium, system potential)	18.44	3.09	0.78
17 (2040 Low, current shade)	19.40	2.18	0.94
20 (2040 Low, system potential)	17.53	2.18	0.94
2080 GCM Comparisons			
21 (2080 High, current shade)	22.33	5.11	0.76
24 (2080 High, system potential)	20.46	5.11	0.76
22 (2080 Medium, current shade)	21.28	4.07	0.86
25 (2080 Medium, system potential)	19.41	4.06	0.85
23 (2080 Low, current shade)	20.15	2.94	1.07
26 (2080 Low, system potential)	18.28	2.93	1.07

*Note that the Baseline Scenario for all "current shade" runs is Scenario 3, and the Baseline Scenario for all "system potential" runs is Scenario 5.

The ratios of change in daily average water temperature to change in air temperature for the 2080s (0.76–0.94, median 0.85) are somewhat greater than the typical ratio of changes in summer average water temperature to change in air temperature of 0.67 reported by Isaak et al. (2011). However, the researchers also note that "Comparison of trends in annual temperature extremes…suggested more rapid warming of the year's highest and lowest weekly temperatures." Specifically, they report an increase in 7-day average maximum water temperature of about 0.28 °C per decade corresponding to air temperature increases of 0.36 °C (as an average across seven unregulated sites), for a ratio of 0.78. The somewhat higher ratios predicted for the SFNR are likely due to the additional impact of large reductions in 7Q10 flows projected for the higher elevation portions of the SFNR watershed as the climate pattern shifts from transient snow to rain-dominated conditions. Cristea and Burges (2009) applied the QUAL2Kw model to predict future water temperatures in the Wenatchee River watershed. Their Table 3, reporting effects of future climate with current shade at 7Q10 flows, shows a ratio of predicted increase in daily average water temperature to change in July–August air temperature of 0.52 to 0.62 in the mainstem Wenatchee (which is influenced by Lake Wenatchee at the headwaters) and 0.61 to 0.83 in Nason Creek; however, their results also show ratios of change in maximum water temperature to change in air temperature from 0.87 to 1.1 in Nason

Creek (median 1.0). The larger ratio in Nason Creek, consistent with the results presented here for the SFNR, appears to be due to the strong influence of reduced 7Q10 flows.

5.2.1 Climate Change Scenarios: System Potential Shade

The critical conditions scenario (Scenario 5) represents the 7Q10 critical low-flow condition and accompanying 7-day average maximum air temperature with SPV and associated microclimate climate effects (see Section 2.2). Climate change scenarios focus on examining the effects of future climate on the TMDL critical conditions run both with and without SPV and the accompanying microclimate effect. Figures compare longitudinal profiles of maximum stream temperature to the numeric water quality criteria (the criteria applicable in August) and the comparable system potential modeling run (Scenario 5). In addition, approximate thresholds for salmonid lethality are provided based on WAC 173-201A-200(1)(c)(vii)(A) (the natural conditions provision for water quality standards) and an Ecology study (Hicks, 2002) that evaluated lethal temperatures for cold water fish. The approximate lethality thresholds from these studies are 23 °C, the within-day temperature maximum threshold, and 22 °C, a critical temperature for the 7-DADMax. It should be noted that these are summary values and reported lethal temperatures differ among salmon species as well as by life stage. (See Richter and Kolmes (2005) for a review of data.) Given that the steady-state critical conditions run is intended to represent the 7-DADMax temperature, comparison to the 22 °C threshold is most relevant for evaluating risk.

The two comparison levels (22 °C and 23 °C) are estimates of temperatures at which 50 percent of individuals in a sample are at risk of dying in laboratory studies (for the given exposure period). These are presented for comparison purposes only and are not necessarily predictive of outcomes in natural systems. First, the QUAL2Kw model simulates reach-average temperatures and does not account for the possible presence of small-scale cold water refuges that can provide shelter during high-temperature events. Second, while extensive research has been undertaken, the temperature tolerance levels of salmonids are complex and depend on the rate of temperature change and the temperatures at which fish have been previously acclimatized. Many of the laboratory tests on which lethal temperatures are based used constant temperature exposures and did not replicate the diel variability of temperatures found in nature. In addition, salmonid populations in streams with warmer waters can show adaptive capacity (or *phenotypic plasticity*) that increases their ability to survive warmer temperatures (Beechie et al., 2006; Waples et al., 2004). Nonetheless, it is clear that water temperatures in excess of 22 °C are sub-optimal for salmonid survival and impose significant stress on salmonid populations. Increased water temperatures, especially 7-DADMax temperatures that exceed this level, are likely to diminish the health of fish populations, so management measures to minimize the occurrence of such conditions are essential.

The TMDL simulation (Scenario 5), even with SPV, exceeds the numeric temperature criteria throughout the river and approaches the temperature levels identified as potentially lethal for 1-day and 7-day exposures (22 °C and 23 °C, respectively) in the downstream reaches. Figure 5-1, Figure 5-2, and Figure 5-3 show the projected temperature profiles for system potential shade conditions in the 2020s, 2040s, and 2080s, respectively. In the 2020s the QUAL2Kw model projects an increase in the instantaneous maximum water temperature of approximately 2 °C (relative to the TMDL scenario with existing climate conditions plus system potential shade) under all scenarios (note that the medium-impact scenario produces slightly higher water temperature projections in 2020 than the high-impact scenario), while a 3–4 degree increase is predicted for the 2040s. By the 2080s the different climate scenarios begin to diverge further, but all show a strong projected increase in stream water temperature across the length of the river. Figure 5-4 compares the maximum temperature profiles under critical conditions for existing climate (without system potential shade) and 2020, 2040, and 2080 climate (with system potential shade). The addition of system potential shade results in little change through 2020, but a gradual increase in temperature in all reaches in later decades.

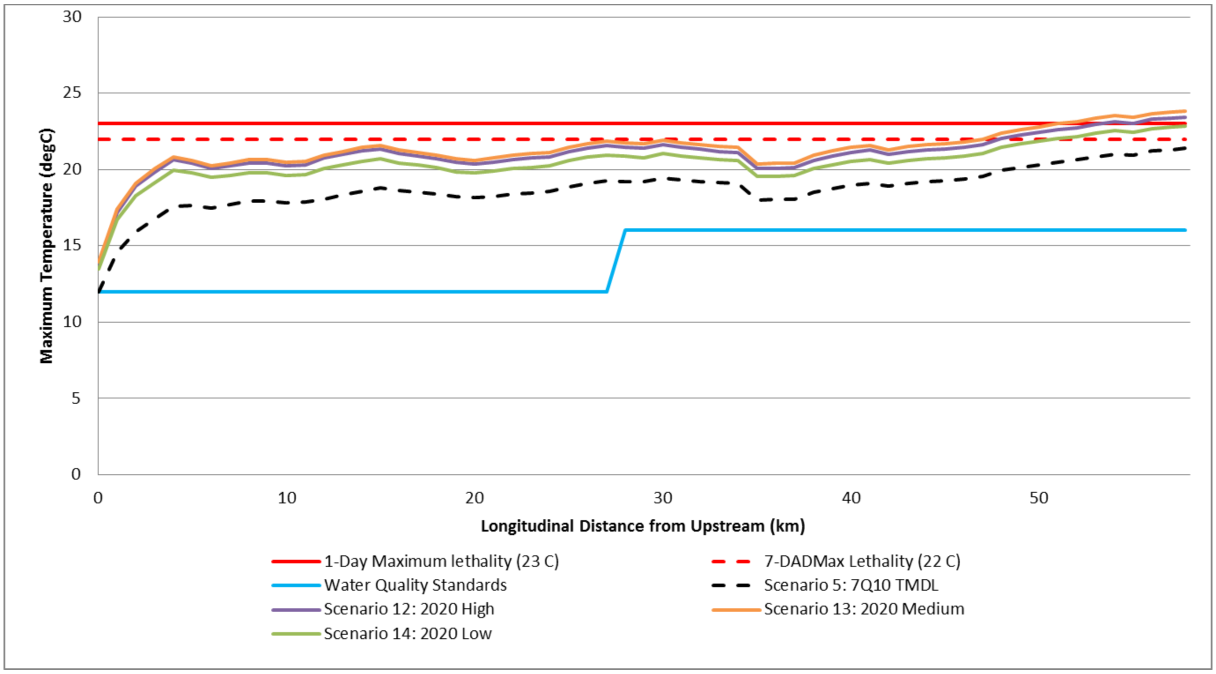


Figure 5-1. Maximum Stream Temperature by Reach for Scenario 5 (7Q10 flows, 90th Percentile Meteorology, System Potential Shade, and Tributaries/Headwaters at Water Quality Criteria) and Scenarios 12, 13, and 14 (2020 High GCM, 2020 Medium GCM, 2020 Low GCM)

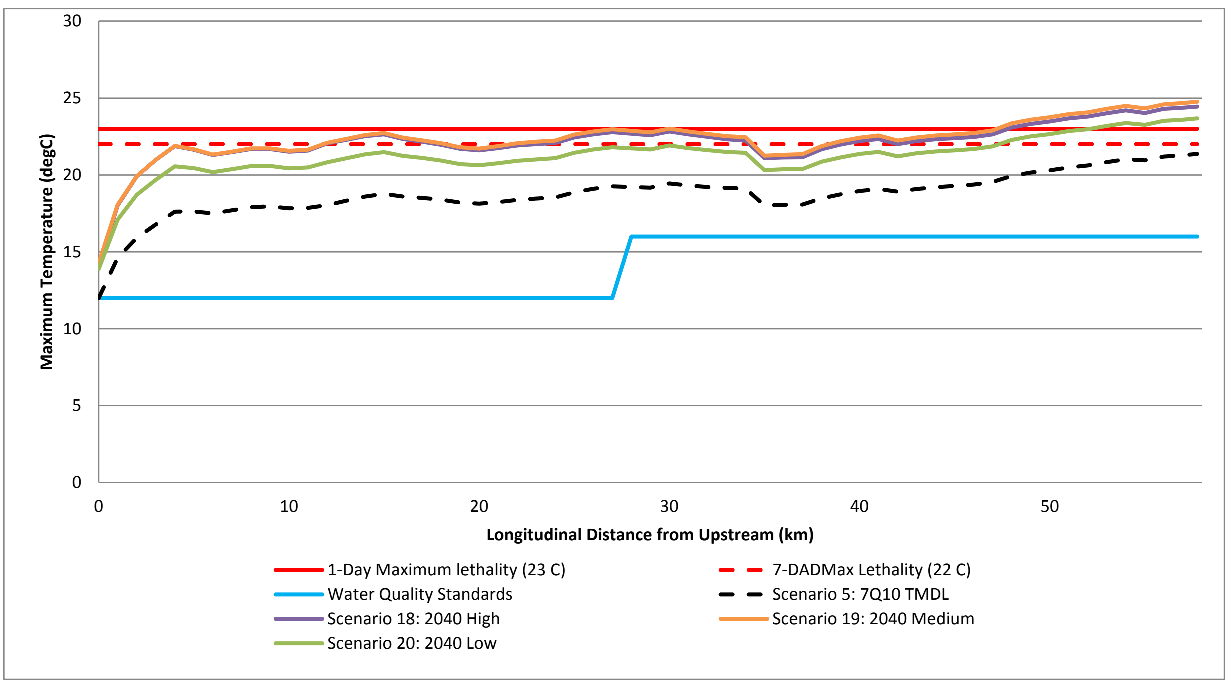


Figure 5-2. Maximum Stream Temperature by Reach for Scenario 5 (7Q10 flows, 90th Percentile Meteorology, System Potential Shade, and Tributaries/Headwaters at Water Quality Criteria) and Scenarios 18, 19, and 20 (2040 High GCM, 2040 Medium GCM, 2040 Low GCM)

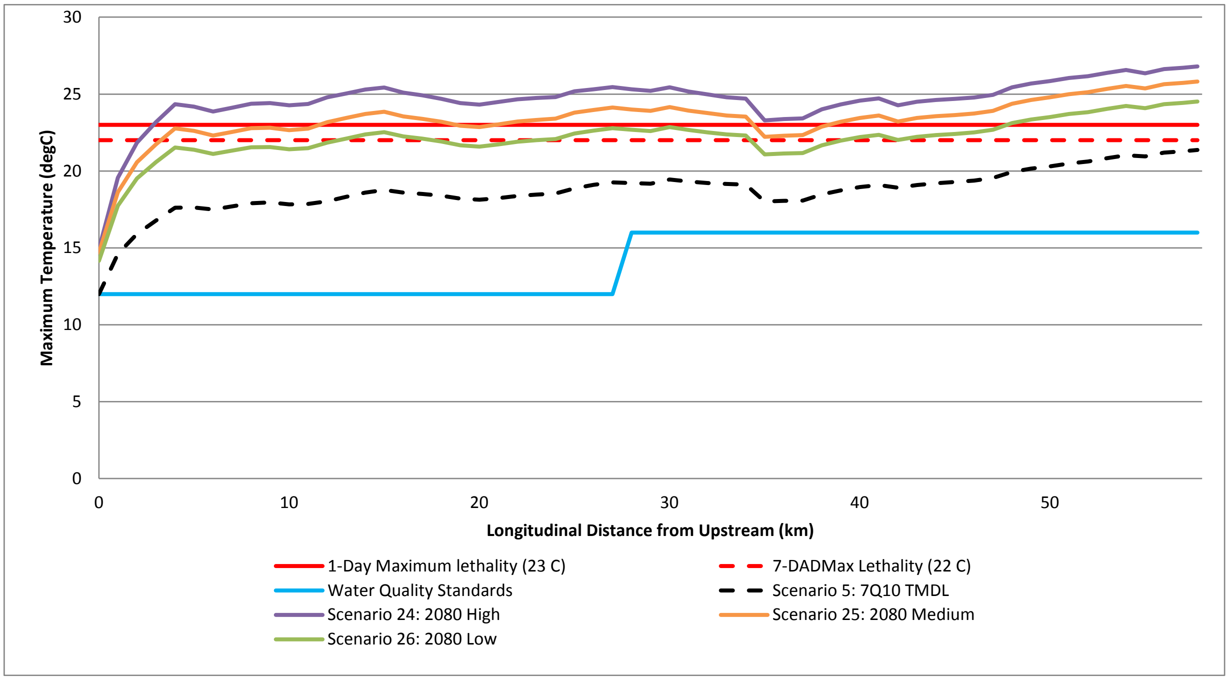


Figure 5-3. Maximum Stream Temperature by Reach for Scenario 5 (7Q10 flows, 90th Percentile Meteorology, System Potential Shade, and Tributaries/Headwaters at Water Quality Criteria) and Scenarios 24, 25, and 26 (2080 High GCM, 2080 Medium GCM, 2080 Low GCM)

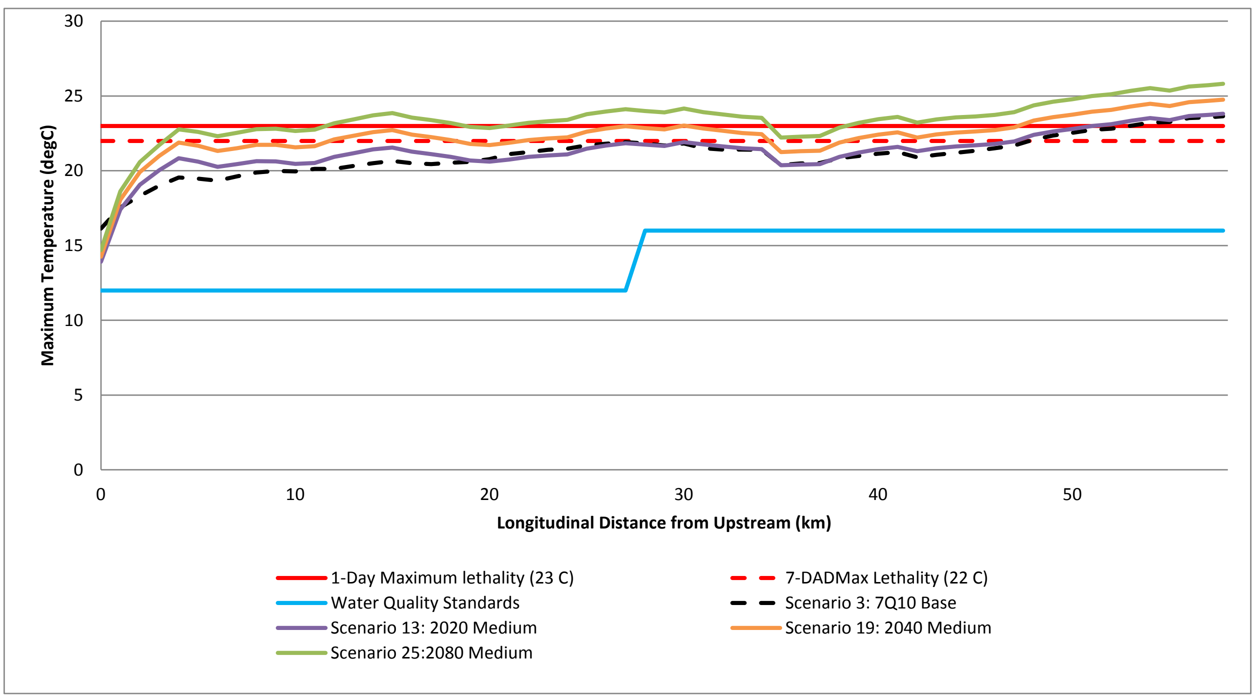


Figure 5-4. Comparison of Maximum Temperature Profiles at 7Q10 Flow and 90th Percentile Meteorology for Existing TMDL Conditions and Medium GCM Scenarios for 2020, 2040, and 2080 (with System Potential Shade)

5.2.2 Climate Change Scenarios: Current Shade

We also estimated the impact of climate change on Scenario 3 (as described in Section 2.2), which also uses 7Q10 flow but has a baseline condition of current shade, no microclimate effect, and existing tributary temperatures on which each climate scenario is overlain. Longitudinal profile results are shown in Figure 5-5, Figure 5-6, and Figure 5-7 for the 2020s, 2040s, and 2080s, respectively. Not surprisingly, predicted water temperatures are noticeably warmer than under the SPV scenarios, and they are projected to exceed the 1-day maximum lethality threshold of 23 °C over much of the river, even by the 2020s. This is of practical concern because it could take considerably longer than a decade to achieve SPV. However, it should be recalled that TMDLs are based on extreme critical conditions, and more typical conditions will not be as adverse, as shown in Section 5.4. In addition, the QUAL2Kw model is predicting reach-average conditions and the presence of micro-scale cooler refuges could reduce lethality.

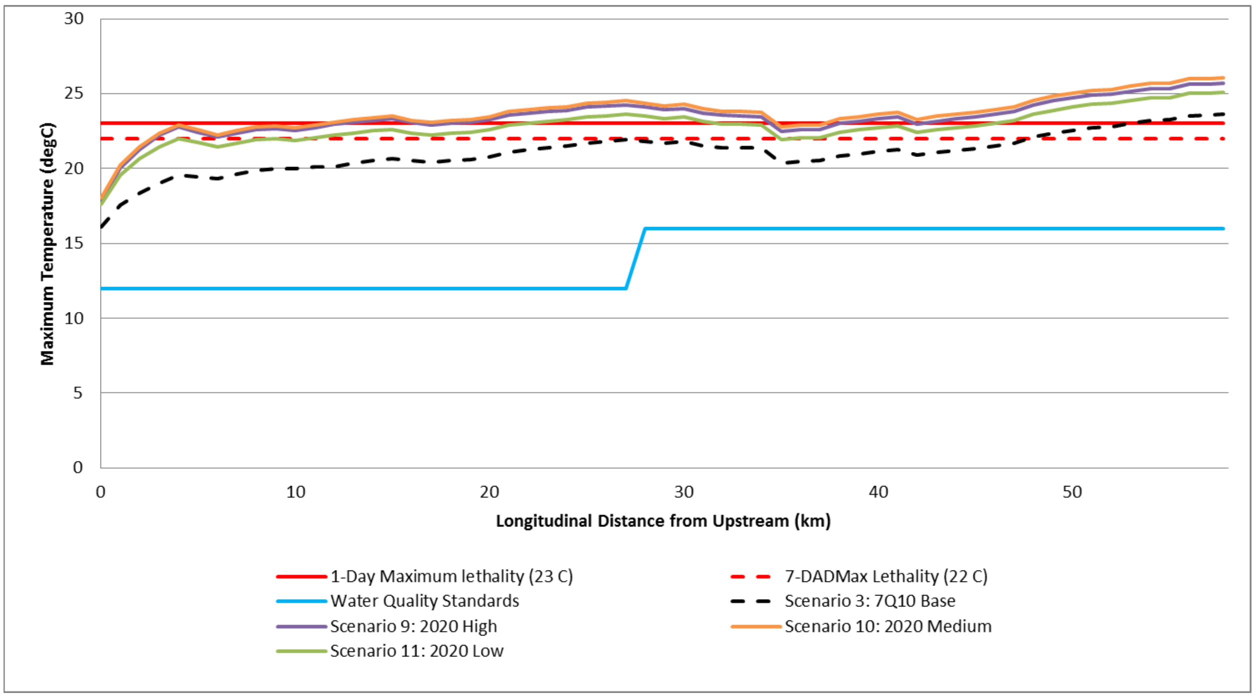


Figure 5-5. Maximum Stream Temperature by Reach for Scenario 3 (7Q10 flows, 90th Percentile Meteorology, Current Shade) and Scenarios 9, 10, and 11 (2020 High GCM, 2020 Medium GCM, 2020 Low GCM)

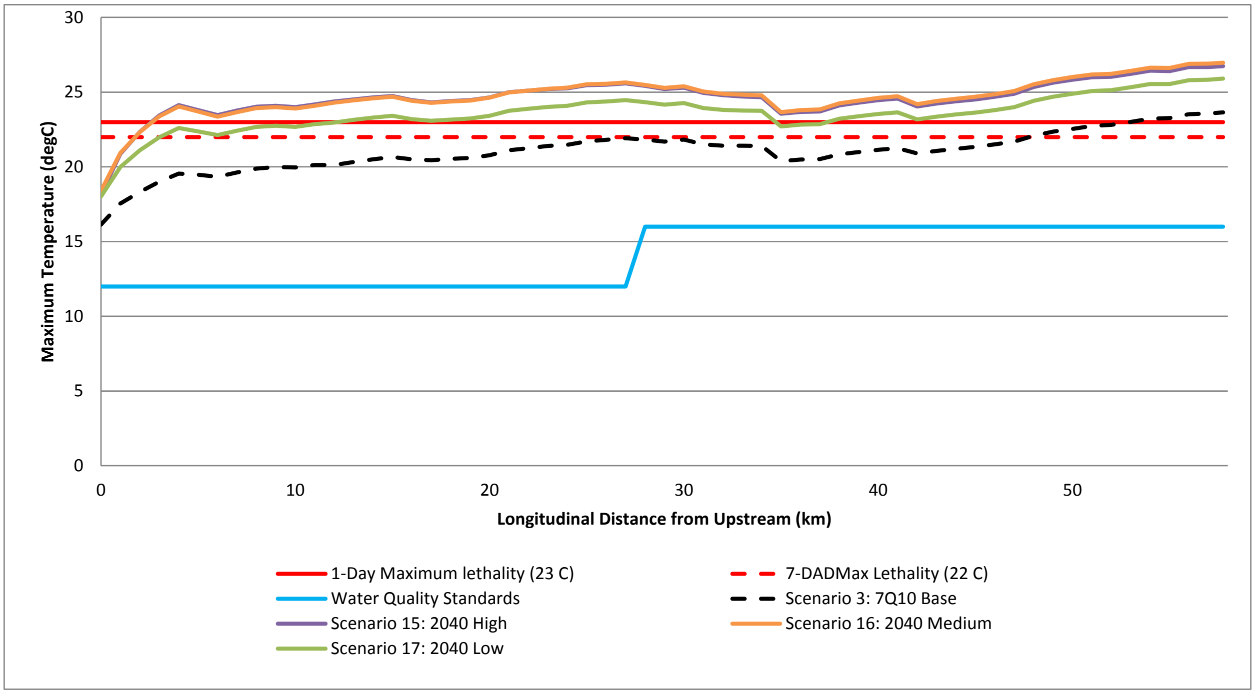


Figure 5-6. Maximum Stream Temperature by Reach for Scenario 3 (7Q10 flows, 90th Percentile Meteorology, Current Shade) and Scenarios 15, 16, and 17 (2040 High GCM, 2040 Medium GCM, 2040 Low GCM)

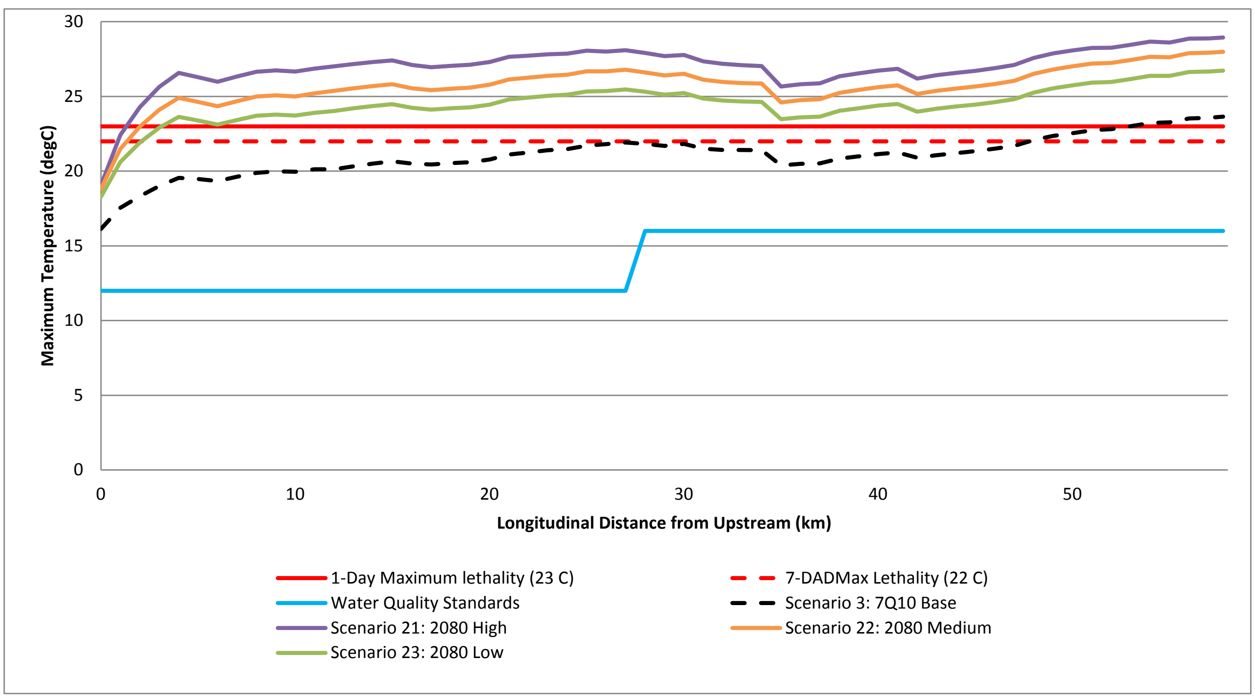
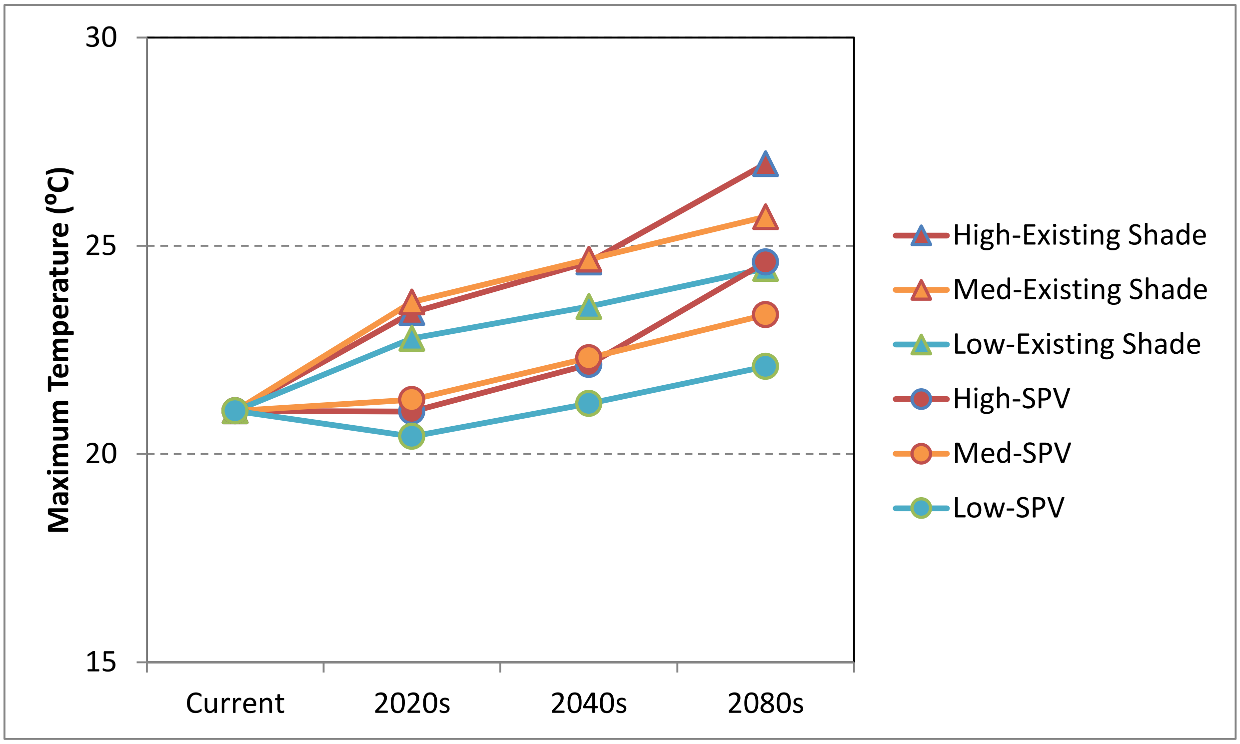


Figure 5-7. Maximum Stream Temperature by Reach for Scenario 3 (7Q10 flows, 90th Percentile Meteorology, Current Shade) and Scenarios 21, 22, and 23 (2080 High GCM, 2080 Medium GCM, 2080 Low GCM)

5.2.3 Analysis of Results

Comparison between scenarios is facilitated by displaying average 7Q10 water temperatures throughout the modeled reaches of the river on the same plot.

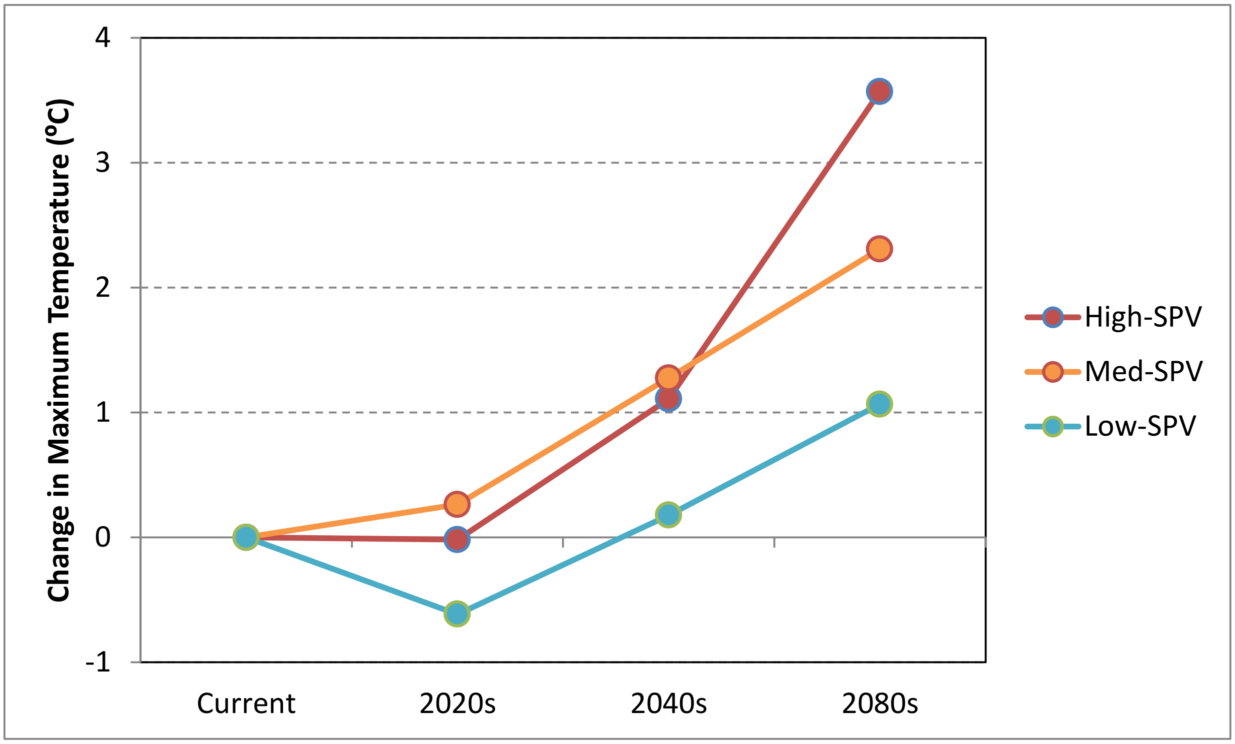
Figure 5-8 summarizes all 18 climate scenarios and the expected steady increase in water temperature over time. It also shows that SPV reduces average water temperature by about 2 °C. This is sufficient to mitigate water temperature increases in the 2020s, but not for later periods.



Note: Results shown are the average of the maximum water temperatures from all model segments. High, Med, and Low refer to the high-impact, medium-impact, and low-impact future climate scenarios. SPV = System Potential Vegetation.

Figure 5-8. Spatially Averaged Maximum Water Temperature in the South Fork Nooksack River Mainstem at Critical Conditions for Existing TMDL Conditions and Future Climate with Existing and System Potential Vegetation Shade

Figure 5-9 further explores the time trends in projections with SPV, confirming that the additional shade is able to buffer the temperature effects due to climate change through the 2020s, but that a steady increase in water temperature is predicted to occur in future decades even with SPV. This figure also shows that the ranking of climate scenarios as high, medium, and low impact is appropriate for the 2080s, but that in the 2020s the impacts are slightly greater under the "medium" scenario.



Note: Results shown are the average of the maximum water temperatures from all model segments. High, Med, and Low refer to the high-impact, medium-impact, and low-impact future climate scenarios. SPV = System Potential Vegetation.

Figure 5-9. Change in Spatially Averaged Maximum Water Temperature in the South Fork Nooksack River Mainstem at Critical Conditions for Future Climate with System Potential Vegetation Compared to Existing TMDL Conditions and Vegetation

The spatial distribution of the results is summarized graphically in the following figures. Figure 5-10 shows the results for existing climate, with and without system potential shade. In these figures each modeled stream segment is shaded according to the ratio of the predicted daily maximum water temperature under critical 7Q10 flow conditions to the lethality threshold. The left side of the river (facing downstream) is colored according to the ratio to the 1-day lethality threshold of 23 °C. The right side is colored according to the ratio to the 7-day lethality threshold of 22 °C. A ratio of 1 is shown in yellow. The green to blue range represents conditions below the target, while the orange to red range represents conditions above the target temperature. Figure 5-11 shows the spatial distribution for the 2040s and 2080s climate scenarios, with system potential shade.

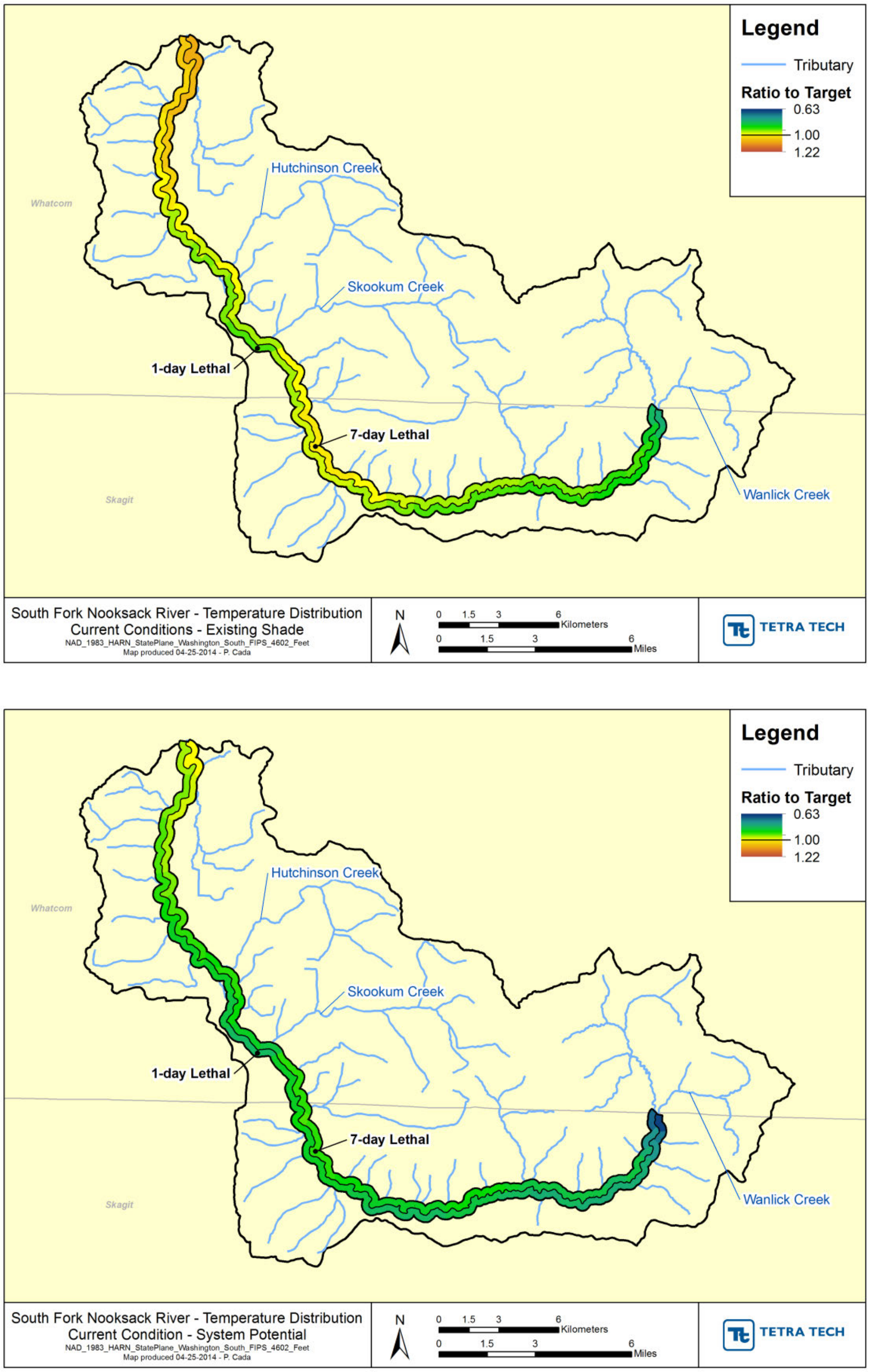
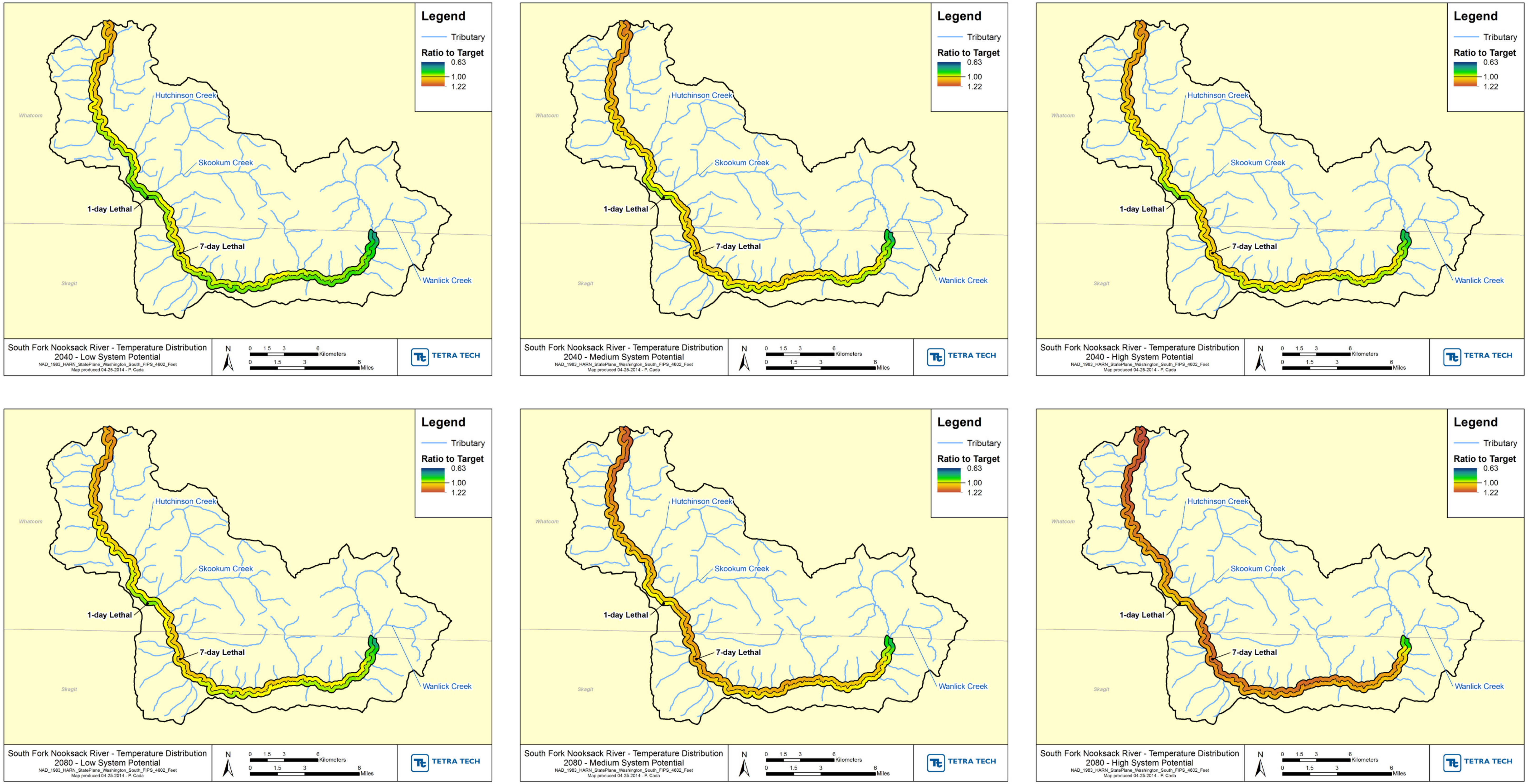


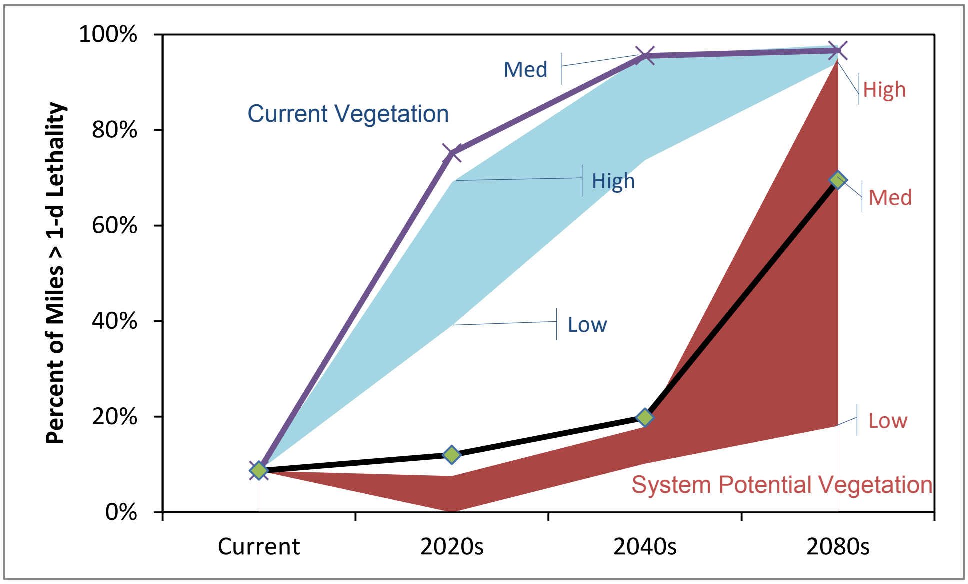
Figure 5-10. Spatial Distribution of Ratio to Lethal Temperatures at Critical Conditions, Existing Climate with Existing (top) and System Potential Shade (bottom)



Note order of images: 2040 low-, medium-, and high-impact scenarios along the top; 2080 low-, medium-, and high-impact scenarios along the bottom.

Figure 5-11. Spatial Distribution of Ratio to Lethal Temperatures at Critical Conditions for all Climate Scenarios with System Potential Shade

The results for individual segments are also summarized as percent of stream miles projected to exceed the 1-day average maximum lethality temperature of 23 °C (Figure 5-12). In this figure, the range from the low-impact to high-impact scenario is shown as a colored area, while the medium-impact scenario results are shown as a line (even though the medium scenario exceeds the high scenario for the 2020s). The figure shows that with current shade potentially lethal temperatures could occur in most reaches of the SFNR under critical low flow/high air temperature conditions by the 2020s. SPV could significantly delay such impacts, but the risk of lethal temperatures is projected to increase significantly in the 2080s even with full shade.



Note: The shaded bands represent the range from the climate scenarios selected as minimum and maximum impact in terms of air temperature. The lower, red band represents results with system potential shade, while the upper, blue band represents results with current shade. The lines with markers represent the medium-impact climate scenario (in terms of atmospheric temperature) for both shade scenarios. Current conditions represent existing shade only because restoration of system potential vegetation will take decades to accomplish.

Figure 5-12. Percent of Stream Miles in the South Fork Nooksack River where the Daily Maximum Temperature Exceeds the 1-day Average Maximum Lethality Temperature of 23 °C under Existing TMDL Conditions and Future Climate Critical Conditions

5.3 Sensitivity to Boundary Conditions

Stream water temperature predictions are the net result of the interaction of shade, flow, and various sources of thermal energy. The 7Q10 TMDL model with SPV and medium-impact GCM (Scenario 25) was used to conduct sensitivity analyses relative to direct forcing temperatures in the headwaters and tributaries, in ground water discharge, and in the air, as well as sensitivity to dew point temperature and tributary and headwater flow. The first four, temperature-based variables were each perturbed by ± 1 °C and the results displayed in a tornado diagram (Figure 5-13). Flows were varied by ±5 percent. Responses (as the spatially averaged maximum stream temperature) to perturbations of temperatures in tributary, headwater, and ground water inflow temperatures are relatively small (about 0.25 degree per degree for the first two and 0.18 degree per degree for the ground water inflow temperatures). The magnitude of direct response to air temperature is similar. The greatest response is to dew point temperature (0.32 degrees per degree), showing the importance of evaporative cooling in maintaining stream temperatures. This effect could limit the ability of full SPV to control temperatures because mature riparian canopy will also limit wind and tend to maintain higher water vapor pressure and dew point temperature.

As expected, increasing flow leads to decreases in the maximum stream temperature. The scale of this metric is not directly comparable to the temperature changes, but the response is -0.025 °C per percent increase in headwater tributary flow. As the 2080s scenarios show reductions of more than 50 percent in 7Q10 flows in the upper watershed, the reductions in flow are an important contributor to the predicted increase in maximum temperature, consistent with the findings of Cristea and Burges (2010) for the Wenatchee River watershed.

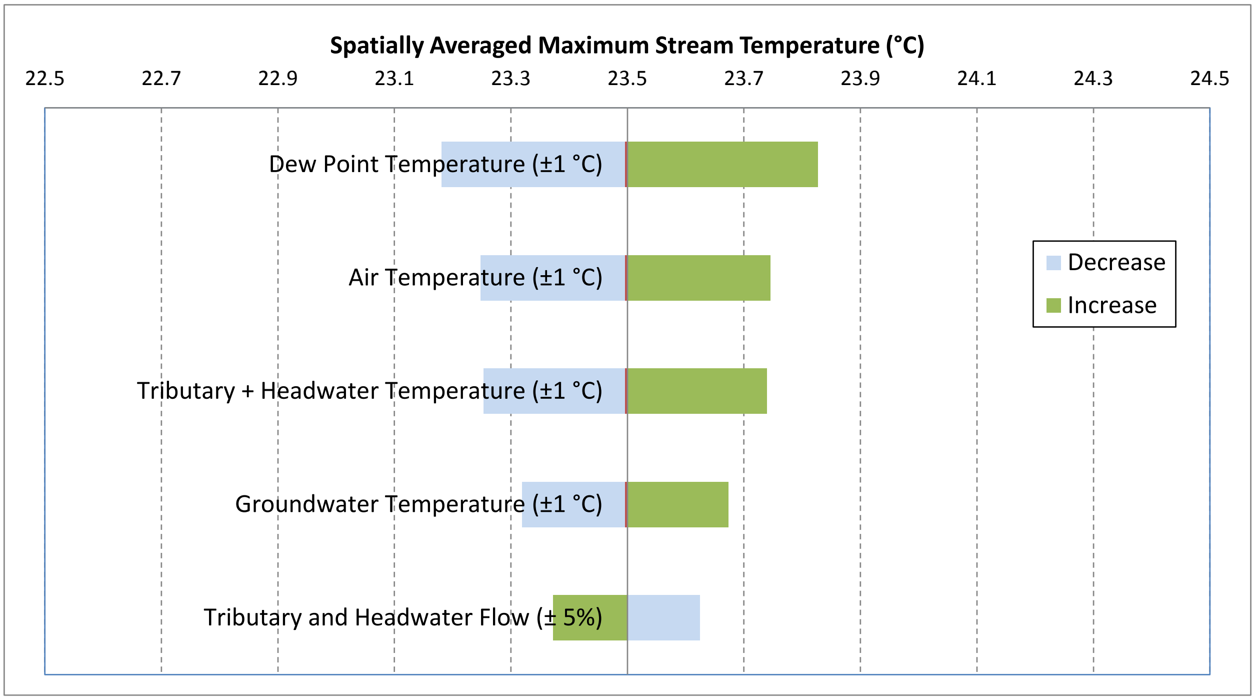


Figure 5-13. Sensitivity of 7Q10 TMDL Model Maximum Water Temperature Predictions to Variations in Boundary Temperature and Flow

5.4 7Q2 Analysis

Analysis of the critical condition 7Q10 flows and 90th percentile meteorology presented in the previous section a high risk of exceeding lethal thresholds for salmon on a reach average (although small, cold water refuges might persist and allow for fish survival). The TMDL analysis of critical conditions, however, purposefully represents relatively extreme worst-case conditions that will not occur every year. Although the future climate models predict significant impacts under these conditions, it should also be recognized that the ability of climate:watershed model pairs to predict rare events at the extreme tails of the annual distribution of flow and air temperature is limited relative to their ability to predict changes in more common events (Tebaldi et al., 2006). Model confidence is generally higher when analyzing less extreme (more frequent recurrence) conditions.

The modeling scenarios undertaken for the TMDL included an average annual condition, based on 7Q2 flows accompanied by the median of the annual series of 7-day average maximum air temperatures and associated predicted water temperature to simulate the maximum stream temperatures that salmon are expected to encounter during a typical year. We also updated this scenario for 2080s climate conditions, using the same techniques described in the previous sections. The estimated 7Q2 flow was updated with the same multiplicative change factor applied to the 7Q10 flow[1].

QUAL2Kw results for 2080s climate coupled with SPV and 7Q2 flows and meteorology are shown in Figure 5-14. The low-impact scenario remains at or below the 7-day lethality temperature, while even the high-impact climate change scenario remains between the 1-day and the 7-day lethality temperature over most of the length of the mainstem SFNR. However, the high-impact scenario does predict temperatures greater than 23 °C for the lower 7 km of the SFNR even under these less extreme, more typical flow conditions. This could present a migration barrier because thermal blockages to migration for salmon are reported to consistently occur in the range of 19–23 °C (Mantua et al., 2010; McCullough et al., 2001; Richter and Kolmes, 2005). Results with current shade (Figure 5-15) are about 2 °C warmer.

Selection of the critical flow has a considerable impact on the results, with maximum projected stream temperatures for 2080 about 2–3 degrees cooler at 7Q2 flows than at 7Q10 flows. (See Figure 5-16 for the medium-impact scenario.) At 7Q2 flows, the 7-DADMax lethality temperature of 22 °C is projected to be exceeded in only the most downstream reaches of the river under this scenario.

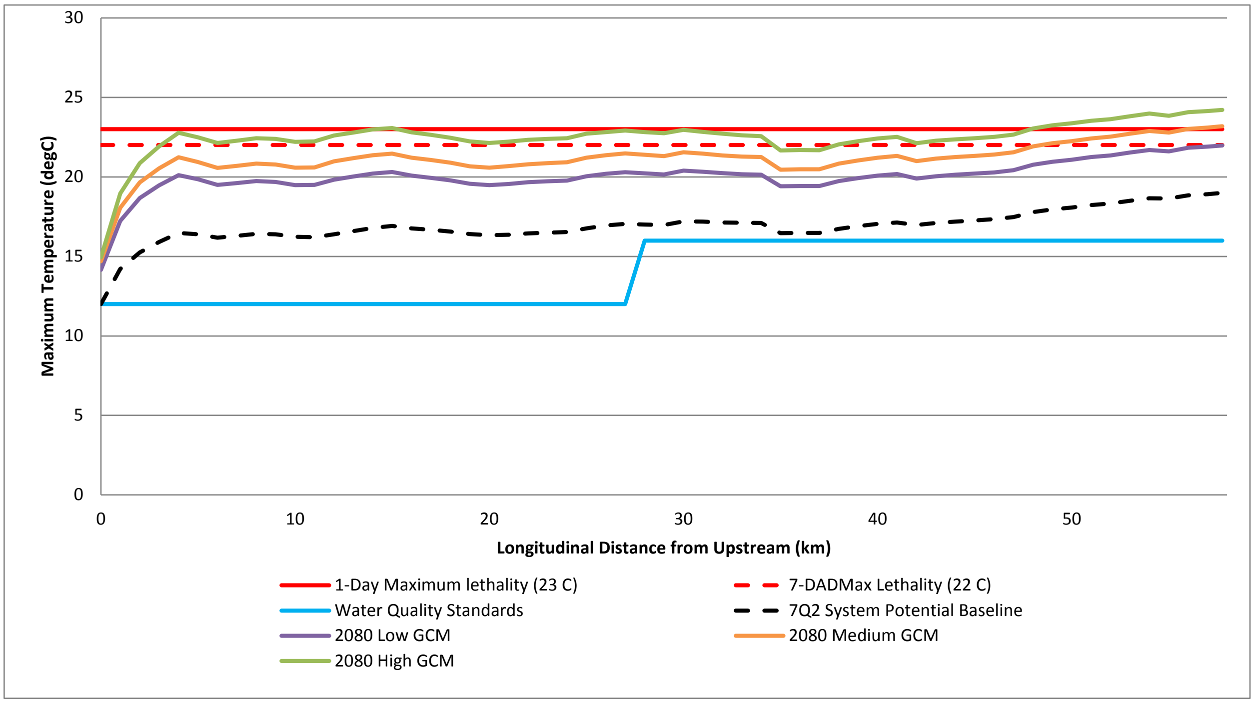


Figure 5-14. Maximum Stream Temperature by Reach for 7Q2 flows, and 50th Percentile Maximum Air Temperature with System Potential Shade for 2080 High GCM, 2080 Medium GCM, and 2080 Low GCM

[1] This is necessary because the VIC model output is not consistent with the observed relationship between 7Q10 flows and 7Q2 flows at the Wickersham gage. VIC predicts a much greater relative difference between 7Q2 and 7Q10 flows under historical climate than is seen in the gaged flow data. VIC also predicts that the difference between 7Q10 and 7Q2 flows will narrow under future climate conditions, implying a greater rate of change in 7Q2 than in 7Q10. As a result, applying the VIC model change factors (calculated for 7Q2 flows) to the observed flows can result in predicted future condition 7Q2 flows that are less than predicted 7Q10 flows. Therefore, the relative change calculated for VIC model 7Q10 flows is used to provide a consistent basis of comparison that agrees with the observed 7Q2:7Q10 relationship and ensures that future 7Q2 remains greater than 7Q10.

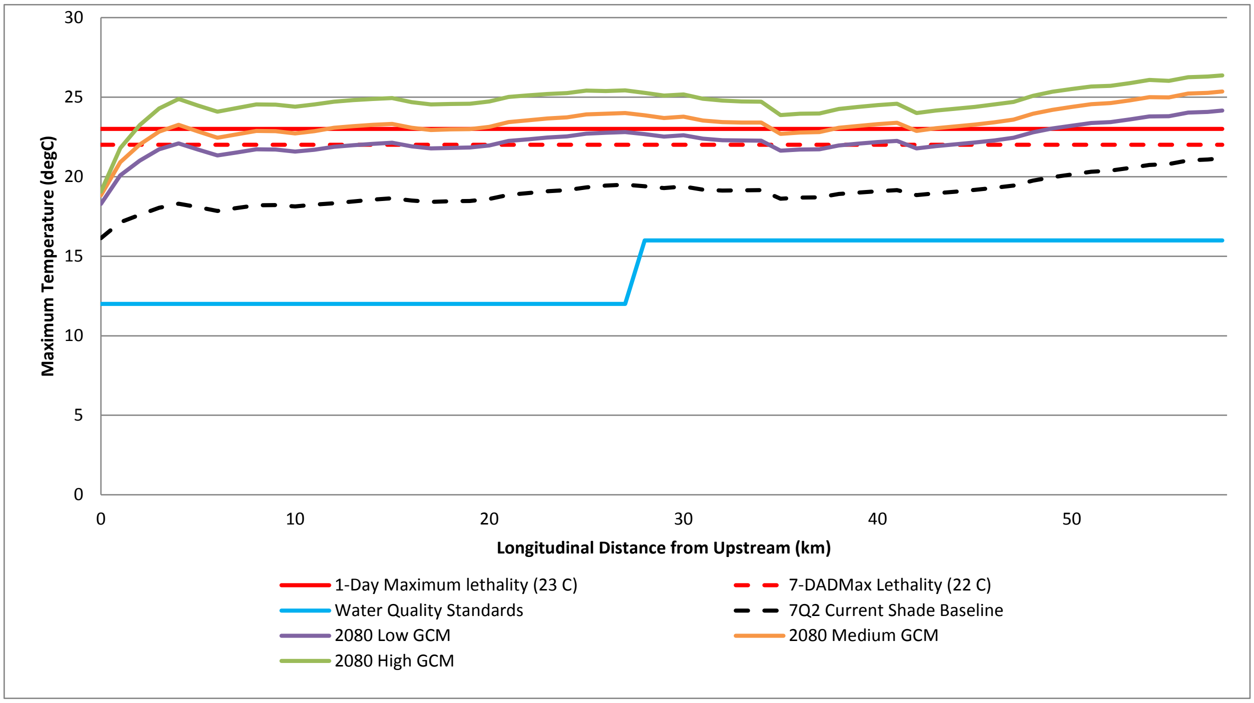


Figure 5-15. Maximum Stream Temperature by Reach for 7Q2 flows, and 50th Percentile Maximum Air Temperature with Current Shade for 2080 High GCM, 2080 Medium GCM, and 2080 Low GCM

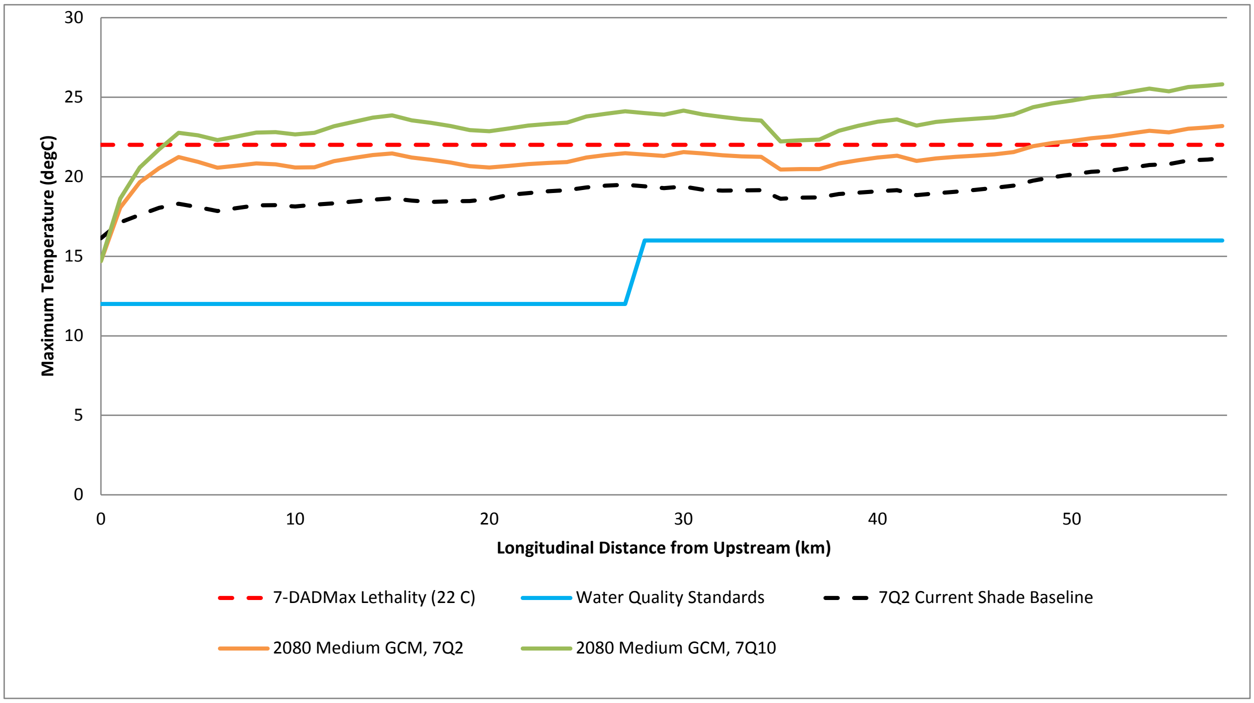


Figure 5-16. Comparison of Maximum Stream Temperature by Reach for 2080s Medium GCM with System Potential Shade at 7Q2 and 7Q10 Flows

5.5 POTENTIAL CHANGES IN EXTREME HIGH FLOWS

The draft temperature TMDL focuses on critical conditions for water temperature, which occur during summer low flow. We have seen that flows might decrease and water temperatures might increase during these critical periods under future climate. However, climate change can also lead to other changes in the hydrology of the SFNR. Most notably, as shown in Section 3.3, higher elevation runoff is expected to shift from a transient regime, with a mix of rain and snow, to a rain-dominant regime, with flows occurring earlier in the year. A possible result in this regime shift is an increase in extreme high flows, which can cause egg scour and loss. Indeed Battin et al. (2007), using the Shiraz salmon population model (Scheuerell et al., 2006) in conjunction with climate change and hydrologic response models, predicted that changes in winter high flows would have a greater negative impact on salmon populations than changes in water temperature in the Snohomish basin (a nearby watershed south of the SFNR basin, also draining to the Puget Sound). Seiler et al. (2003) also demonstrated that flood magnitude was a significant predictor for survival rates for Chinook salmon in Skagit River. Effects of changes in high flows should therefore also be evaluated in salmon recovery planning for the SFNR.

Previous analyses with the VIC model for the PNW indicate that the magnitude and frequency of flooding are likely to increase dramatically in the winter months in currently transient runoff watersheds, with substantial increases in the magnitude of the 20-year flood in Puget Sound drainages by the 2080s (Mantua et al., 2010).

The VIC model is not specifically calibrated for the SFNR and cannot be expected to provide exact estimates of flood magnitude. The model appears to have some weaknesses in its representation of historical spring high flows. However, as in the analysis of boundary conditions, it is appropriate to look at the projected relative changes in high flows to inform the potential magnitude of future changes. To do this we calculated average flow depth (mm/d) for the weighted average of VIC grid cells intersecting the SFNR watershed and extracted the series of annual maxima for historic and future climate conditions. Estimates of peak runoff for various return periods were then calculated using the Gumbel Type I extreme value distribution, as described in Maidment (1993). (The Gumbel distribution is used rather than log Pearson III because the latter distribution requires estimates of skew and the ability of the VIC model to reproduce the skew of the series of annual maxima is untested.)

Results shown in Table 5-3 suggest that the magnitude of floods of various recurrence intervals could increase by amounts ranging from 4 to 39 percent. Interestingly, the low-impact (for temperature) scenario, CGCM3.1, produces some of the largest projected increases in flood magnitude, with a 39 percent increase in the 2-year event and a 35-year projected increase in the 25-year event by the 2080s. In contrast, the medium-impact scenario (CCSM2) produces increases in flood magnitude of 10 to 17 percent, with no acceleration over time. HADGEM1 (the high-impact scenario for temperature) predicts only small changes in flood magnitude through the 2040s, but increases of 26 to 31 percent by the 2080s.

Table 5-3. Projected Percent Change in Magnitude of Floods of Various Recurrence Intervals in the SFNR under Different Climate Change Scenarios

GCM	Recurrence	2020s	2040s	2080s
CGCM3.1	2-year	+23 %	+39 %	+39 %
	10-year	+19 %	+32 %	+35 %
	25-year	+19 %	+30 %	+34 %
CCSM2	2-year	+17 %	+16 %	+15 %
	10-year	+12 %	+12 %	+12 %
	25-year	+10 %	+12 %	+11 %
HADGEM1	2-year	+5 %	+7 %	+31 %
	10-year	+5 %	+5 %	+27 %
	25-year	+5 %	+4 %	+26 %

As an example, the empirical 10-year recurrence daily flow peak at the Wickersham gage, based on 1935–2008 monitoring, is 11,500 cfs. The range of projections for the 10-year flow in the 2080s is from about 12,900 to 15,500 cfs.

The VIC modeling suggests there is a risk of increased magnitude of flood flows, which in turn could affect salmon populations. The work done on channels by flood events is controlled, in part, by the boundary shear stress, which is itself a linear function of slope and flow depth. Hydraulic equations suggest that flow depth in the SFNR changes approximately in relation to the ratio of flows raised to the 0.45 power. Therefore, boundary shear stress may be predicted to increase by up to $1.39^{0.45} = 1.16$ times relative to historic conditions for the 2-year flow under CGCM3.1 projections for the 2080s.

6 Discussion

This paper presents a quantitative assessment of the potential range of impacts of changing climate on the water temperature in the SFNR. Climate models and hydrologic models based on projections of future climate are subject to wide ranges of uncertainty, with different models and scenarios pointing to a range of possible futures. We have confronted these uncertainties by evaluating a range of GCMs (from low to high anticipated impact on air temperature) and by estimating predicted hydrologic responses via a delta change factor method applied to observed and calibrated time series (rather than using model output directly). The resulting analyses should not be treated as forecasts of the future; rather, they are designed to assist managers in defining the potential range of climates to which adaptation might be needed.

The Quantitative Assessment can be thought of as an embedded ecological risk assessment that evaluates climate change vulnerability associated with the SFNR temperature TMDL (Figure 6-1). It is intended to help inform the development of implementation plans for the TMDL that take into account needs for climate change adaptation. Discussions of the implications of the climate change ecological risk assessment to the TMDL process and to restoration and management strategies for the SFNR are provided in the following sections.

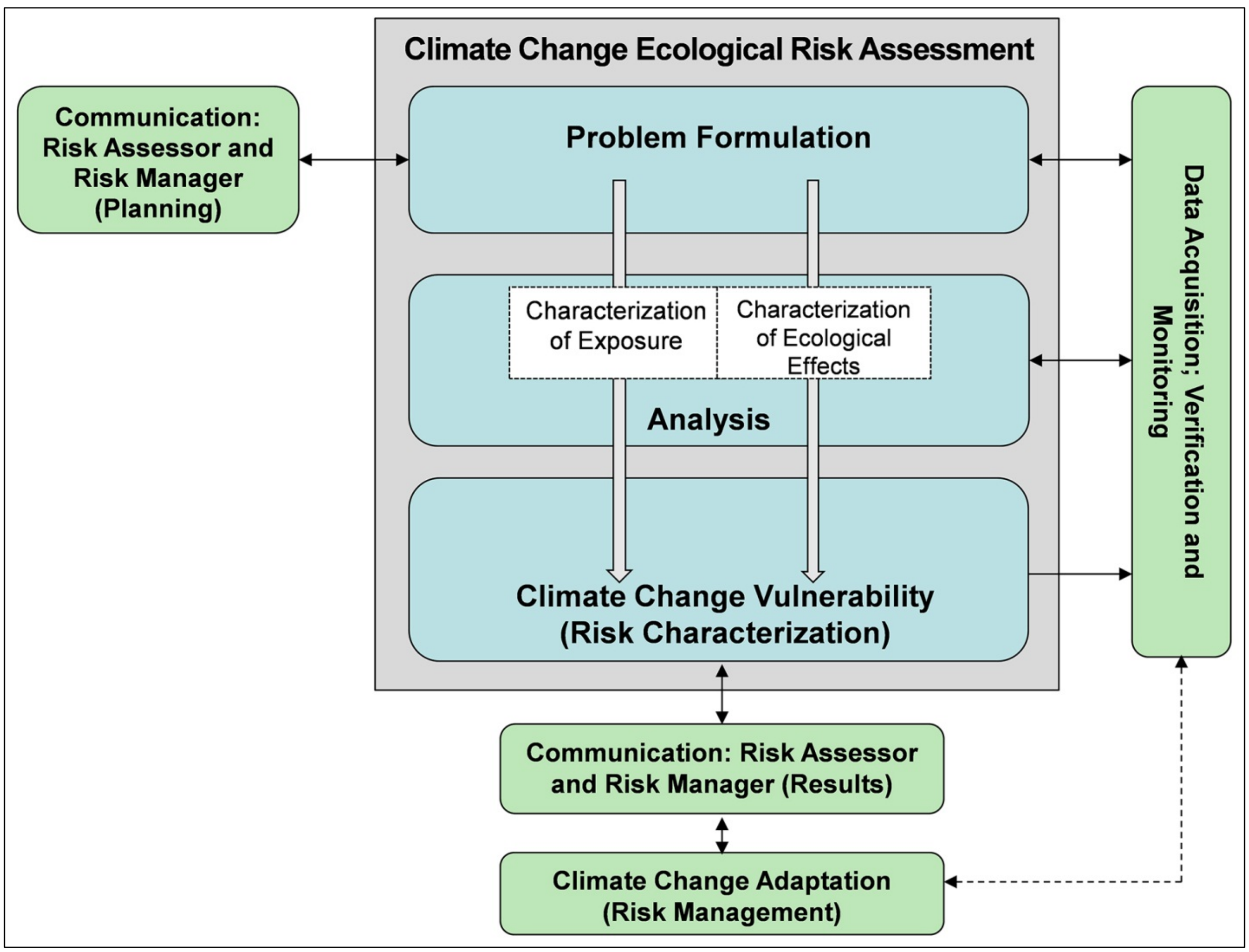


Figure 6-1. Climate Change Ecological Risk Assessment (adapted from USEPA, 1992)

6.1 IMPLICATIONS FOR THE TMDL

The climate change analysis was designed to provide risk managers with an understanding of potential climate change impacts (magnitude and timing) on stream temperature and streamflow. TMDLs have typically been constructed with the assumption of a stationary climate under which historical data on flow and temperature can be assumed to be an adequate guide to future conditions. TMDLs based on assumptions of critical conditions derived from historic climate might not accurately represent risks under potential future climate regimes. TMDLs have by and large not explicitly considered climate change to date. In addition, data for estimating future impacts of climate change have not been readily available to state agencies that develop TMDLs.

The TMDL regulations in 40 CFR require that the TMDL be based on an analysis of loading capacity that is sufficient to attain water quality standards and beneficial uses.

A TMDL is a regulatory tool for addressing specific identified water quality impairments, but TMDL allocations do not necessarily constitute a complete strategy for preserving and enhancing valued resources. The TMDL program’s focus on attaining standards under critical conditions may not address the need for practical management strategies that enhance and protect the resource under less extreme, but more frequently encountered conditions. In general, the TMDL should be viewed not as an end to itself but as one tool within a more holistic resource management strategy (NRC, 2001; Serveiss et al., 2005).

Evaluation of climate change vulnerability could help inform the implementation of the SFNR TMDL. Climate change is time dependent. Managers need first to understand the extent to which designated uses are likely to be attainable at different time horizons and what adaptation strategies should be implemented, on what schedule, to protect those uses. The pace (timing/rate) and priorities of restoration actions for TMDL implementation to ameliorate potential impacts of climate change is a key component of an iterative risk management strategy, as recommended by the National Climate Assessment (Figure 6-2). A key finding of the quantitative analysis for the SFNR is that system potential shade can likely provide substantial resiliency into the future that will help protect beneficial uses, especially if combined with other actions that provide cold water refuges during high-temperature events. To approach the level of protection provided by 100-year SPV (at least 60- to 70-year-old trees) by the 2080s will require planting and protection of all riparian areas along the mainstem SFNR by 2020.

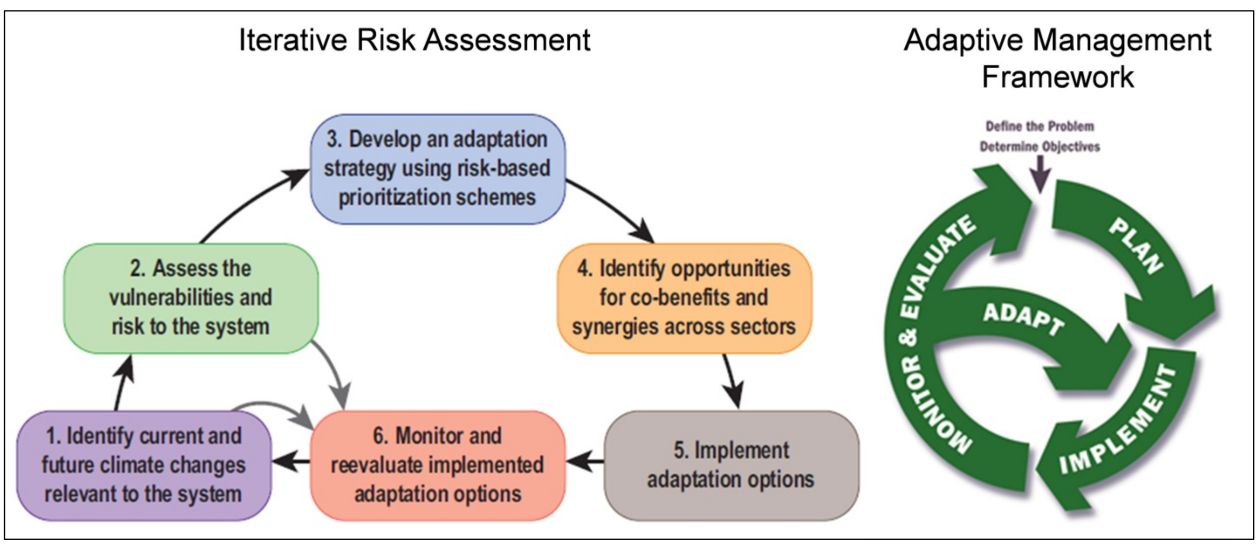


Figure 6-2. Climate Change Adaptation and Iterative Risk Management (Yohe, 2011)

6.2 Implications for Restoration and Management Strategies

The modeling analyses of water temperature maxima associated with projected future climate show that restoring system potential shade will have a strong beneficial impact on the summer temperature regime in the SFNR, while controlling the temperature of tributary inflow also has a small, but important impact. Achieving system potential shade will take time, and consideration must be given to the resilience of restored vegetation under future climate conditions. Although climate change is expected to have a negative impact on forest growth due to increased summer drought, the key risk to planted riparian forests is tree mortality caused by summer drought during early stand establishment (0-10 years after planting). Species selection, seed source, planting density and early stand establishment culturing methods can be evaluated to provide riparian forest vegetation that will be more resilient to increased summer drought effects due to climate change. In addition, potential upland forest management strategies that could help maintain summer flows by delaying the melt of winter snowpack could be evaluated as a climate change adaptation strategy.

The modeling analyses do suggest that climate change will have a significant effect on temperature in the river, and could substantially reduce preferred salmon habitat. However, it must be remembered that the TMDL modeling analysis is purposefully based on an analysis of reasonable worst-case conditions (7Q10 flow combined with 90th percentile annual air temperature maximum) that may occur at a sufficiently low frequency so as to allow recovery or adaptation of the population. Analyses of more typical 7Q2 conditions still suggest significant stress on the salmon population; however, the projected level of risk under 7Q2 flows are not nearly as high as the 7Q10 QUAL2Kw-modeled predictions. Notably, many rivers within the current salmon range, including the Snake and Willamette River basins, have monitored temperatures above published lethal or protective thresholds, yet salmon currently occupy the majority of these rivers (Beechie et al., 2012).

As noted above, the TMDL can be viewed as one component in a holistic strategy for managing and protecting the resource. It can serve and motivate broader scale salmon management strategies that are designed to optimize the resource. Several implications for restoration and management strategies are suggested by the results presented in this report:

Despite the benefits of increased shade, future climate scenarios indicate water temperature regimes that increasingly deviate from preferred habitat for salmon. The model, however, predicts reach-average temperature on an approximately 1-kilometer scale. The impact of occasional high-temperature events is in large part determined by whether the fish can find sufficient cold water refuges that are cooler than the reach average and within their physiological tolerance ranges. Thus, habitat management at a scale smaller than the spatial scale of the model will have an important role in protecting the resource and the implementation plan should combine system potential shade with other options that provide localized cooler habitat. In addition, watershed management that increased stream stability (and thus resulted in a narrowing of the treeless riparian zone) would further increase effective shade on the river and mitigate warming.

Beechie et al. (2012) addressed the question of protecting salmon habitat in the face of anticipated climate change for the 2080s, considering conditions similar to those projected for the SFNR—a decrease in summer low flows, an increase in maximum monthly flows, and stream temperature increases of between 2 ºC and 6 ºC. They concluded that restoring floodplain connectivity, restoring streamflow regimes, and re-aggrading incised channels are most likely to ameliorate streamflow and temperature changes and increase habitat diversity and population resilience.

In sum, restoration of SPV on both the mainstem and tributaries of the SFNR has the potential to mitigate some of the impacts of climate change on water temperature, but only through about 2020. This finding highlights the importance of combining the implementation of system potential shading with other measures that provide cold water refuges during high-temperature events to protect the resource beyond 2020.

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