A Total Watershed Workflow for Assessing and Monitoring Post-Wildfire Impacts on Reservoir Water Quality

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Abstract

The US Army Engineer Research and Development Center (ERDC) Post-Wildfire Water Quality and Ecology team has initiated a study on watershed impacts to reservoir water quality following wildfire and other land disturbances. Wildfires and other rapid land use changes have the potential to impact downstream water quantity and quality for many years following disturbance events. Modeling tools are needed to develop guidance for water quantity and quality management for decision makers to maintain authorized reservoir uses and sensitive habitats during fire recovery. This paper will describe a workflow applied to examine water quality perturbations at Detroit Lake, Willamette National Forest, observed following the 2020 Beachie Creek and Lionshead fires which impacted nearly 50% of the contributing area to the lake. Initial analysis focuses on watershed water temperature, which is especially important since the streams studied are historically home to spring-run Chinook salmon. The workflow includes statistical analysis of historical data collected on major tributaries to the lake which show that although there are long term trends in the system, wildfires introduce statistically significant changes in discharge and water temperature. Additional post-fire field observations on previously ungauged and unmonitored tributaries are strategically paired with geospatial information to identify vulnerable sub-watersheds. Finally, ongoing monitoring will be incorporated to predict recovery timelines and improve the capability of watershed modeling products to capture the impacts of intensive land use change on water quantity and quality. The ultimate goal of this work is to enable efficient post-fire response and the selection of priority restoration efforts.

Introduction

The Need for Water Quality Data Post-Fire

When wildfires occur, it is important to collect the water quality data from these events. A study by Smith (2011) examined several wildfire events occurring in different areas and in different years. In most cases, the years following the first year after the fire did not have data available. This can limit the knowledge gained from these events and the analyses that can be applied to the data. Additionally, the study pointed out that these fires, even the ones that occur in forested areas can impact the nearby urban water supply. Approximately 2/3s of US's water supply comes from forested areas. Benefits of water from the forested areas are longer residence time which reduces contaminates in the water. The water flows as runoff into streams and reservoirs which eventually connect to water treatment facilities for water supply use. It would be beneficial to understand how the wildfires can impact water from these areas, especially in the

Pacific Northwest (PNW), where water supply from forested reservoirs is quite common (Smith et al., 2011).

Introduction to Detroit Lake and Fires

In August 2020, there were two wildfires that occurred at the same time around Detroit Lake, OR (Figure 1). These fires, Beachie Creek and Lionshead led to the destruction of several structures impacting the water in Detroit Lake. Detroit Lake is a drinking reservoir and home to some important species. Before, during, and after these fires, water quality and water flow data were recorded by USGS and NOAA stations. Also as shown in Table 1, the gauging areas had different amounts of burned area, allowing for comparisons of different levels of burn severity. Making Detroit Lake a perfect study area for testing a workflow targeted at understanding the impacts of the fire on the area.

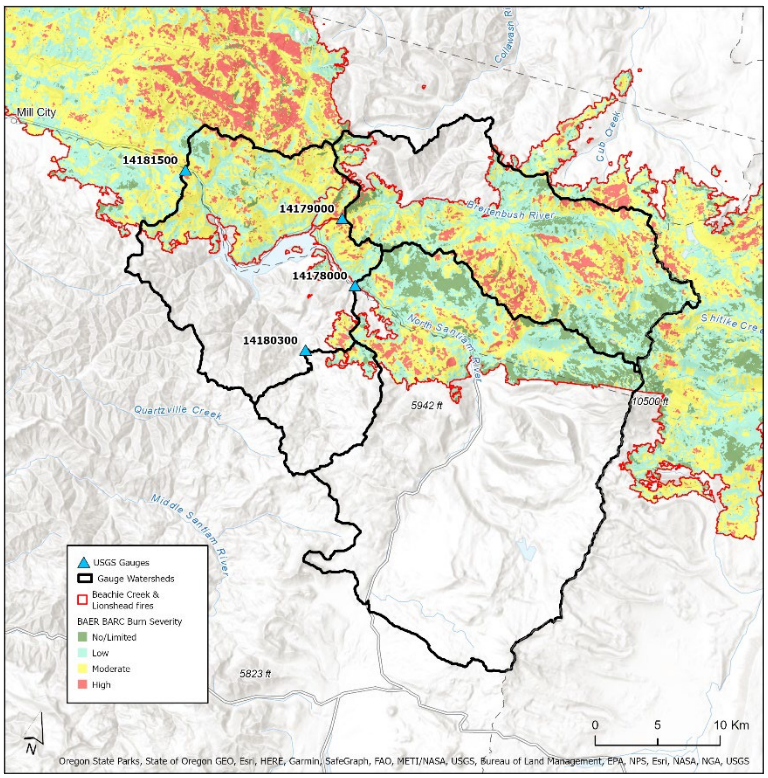

Figure 1. Burn Severity Maps for Beachie Creek and Lionshead fires with the locations of the USGS gauges used for this study and their respective watersheds

Table 1. Burn severity percentages and burned/unburned areas for four watersheds investigated during this study[Soil Burn Severity (SBS)]

Watershed	14178000	14179000	14180300	14181500
Low SBS	10.1%	30.1%	4.7%	15.9%
Moderate SBS	7.3%	30.1%	1.4%	16.3%
High SBS	1.7%	9.4%	0.3%	3.8%

Burned %	19.1%	69.6%	6.3%	36.0%
Unburned %	80.9%	30.4%	93.7%	64.0%
Burned Area (km^2)	106	189	4	421
Unburned Area (km^2)	451	82	62	749
Total Area (km^2)	5578	272	66	1170

Detroit Lake Study

Post-fire Impacts on Detroit Lake Watersheds

Fire induced changes to terrestrial ecosystems initiate dynamic evolution of clear water, sediment, and debris flow regimes. Post-fire discharges show increased volume and intensity of runoff due to variety of factors. The most obvious is a significant reduction in living vegetation (trees, shrubs, grasses, etc) and conversion of organic material on the forest floor from a carbon rich sponge to mineral soil with limited hydrologic holding capacity. These effects may last decades as successional regrowth works to establish a new equilibrium. Alongside disturbances to the biologic system, soils experience spatial and temporally heterogeneous impacts depending upon the parent geology, land use, climate, and historic vegetation and fire to name a few. From the initiation of the fire, vegetation and soils change and evolve, producing dynamic flow states until the watershed finds a new state of equilibrium.

GAP/LANDFIRE National Terrestrial Ecosystems Land Cover (NTE LC) data was queried to identify vegetation and land cover changes within the study watersheds. The NTE LC dataset contains 584 unique classes to provide sufficient granularity for computation and comparison of land cover impacted by fire. NTE LC implements the U.S. National Vegetation Classification System (NVCS) composed of a hierarchy of classification levels from broad landscape wide classes to fine scale regional ecological systems.

The largest land cover type impacted by the 2020 fires around Detroit Lake falls within the Vancouverian Lowland and Montane Forest Macrogroup under the Cool Temperate Forest and Woodland Formation which is contained within the Forest and Woodland Class (Figure 2). This macrogroup is the second largest land cover type in Oregon with almost 12% coverage with a composition of temperate and boreal forest, and woodland dominated by deciduous and needle-leaved trees. Douglas Fir, Western Hemlock, and Silver Fir compose more than 50% of the 2020 burned forest type (Table 2). The largest land cover macrogroup in Oregon, approaching 25%, is Tall Sagebrush Steppe and Sagebrush under the Desert and Semi-Desert Class. (https://www1.usgs.gov/csas/nvcs/unitDetails/872761)

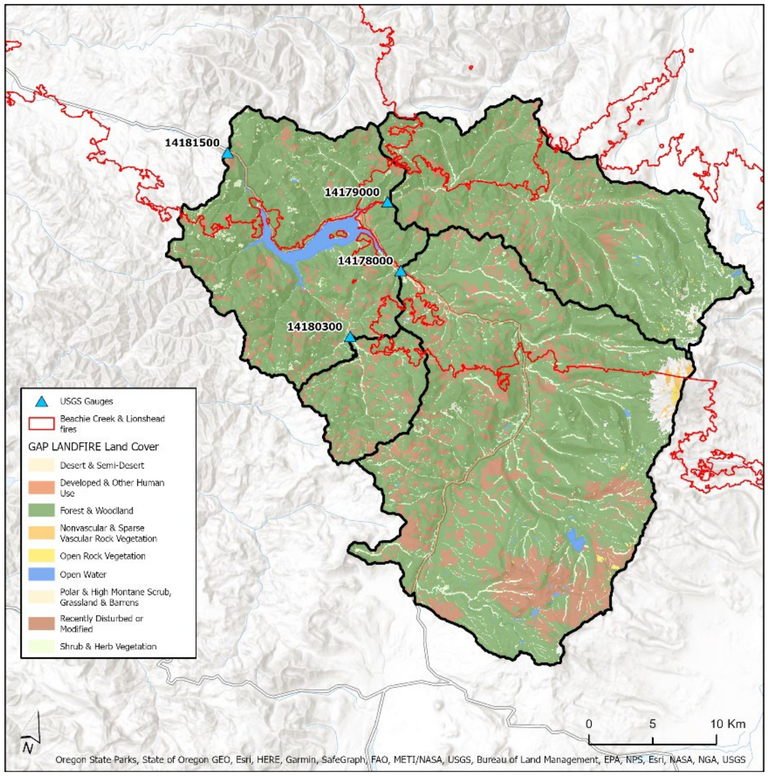

Figure 2. GAP/LANDFIRE National Terrestrial Ecosystems Land Cover Map of the Detroit Lake watersheds

Table 2. Land Cover values with highest percent burn for the four Detroit Lake watersheds

LC Value	Percent of Burn	National Terrestrial Ecosystems Land Cover Ecological System
14178000		
171	33.9%	North Pacific Maritime Dry-Mesic Douglas-fir-Western Hemlock Forest
172	21.6%	North Pacific Maritime Mesic-Wet Douglas-fir-Western Hemlock Forest
167	15.9%	North Pacific Dry-Mesic Silver Fir-Western Hemlock-Douglas-fir Forest
14179000		
171	27.2%	North Pacific Maritime Dry-Mesic Douglas-fir-Western Hemlock Forest
167	21.6%	North Pacific Dry-Mesic Silver Fir-Western Hemlock-Douglas-fir Forest
172	16.0%	North Pacific Maritime Mesic-Wet Douglas-fir-Western Hemlock Forest
14180300		
171	62.5%	North Pacific Maritime Dry-Mesic Douglas-fir-Western Hemlock Forest
172	25.6%	North Pacific Maritime Mesic-Wet Douglas-fir-Western Hemlock Forest
14181500		
171	36.3%	North Pacific Maritime Dry-Mesic Douglas-fir-Western Hemlock Forest
172	18.5%	North Pacific Maritime Mesic-Wet Douglas-fir-Western Hemlock Forest

167	16.8%	North Pacific Dry-Mesic Silver Fir-Western Hemlock-Douglas-fir Forest

In addition to the immediate impact to forests and overland ecosystems, wetlands are heavily impacted directly and indirectly by fire. The U.S. Fish and Wildlife Service maintains the National Wetlands Inventory used by scientists, land managers, and policy makers to identify ecologically sensitive regions. Figure 3 illustrates the density of recognized wetlands in the Detroit Lake watershed. Table 3 shows the total area burned of each type of wetland surveyed in the National Wetlands Inventory and the percent of each wetland in relation to the full watershed. Wetlands have an outsized impact on water quality for the percentage of landscape they occupy (Hemond and Benoit, 1988). Wetlands act as intermediate retention areas for sediments moving downstream and, because of the high level of biogeochemical functioning within wetlands, they are also key transformation sites for nutrients, metals, and contaminants.

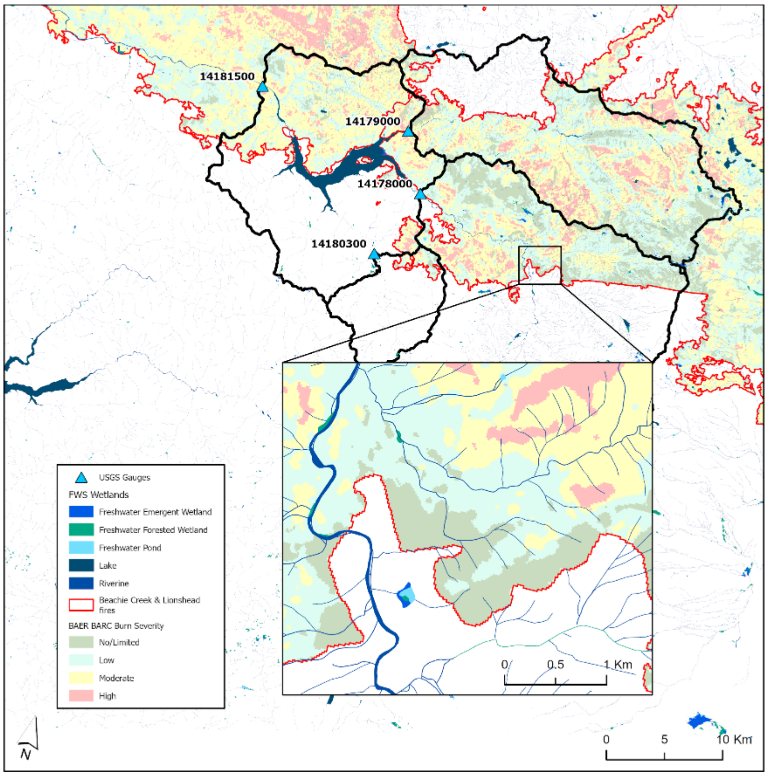

Figure 3. US Fish and Wildlife National Wetlands Map of the Detroit Lake watersheds. Detail showing density of wetlands within the burn perimeter

Table 3. US Fish and Wildlife National Wetlands Inventory types directly impacted by the 2021 fires

Watershed	FWS Wetlands Inventory Type	Area (m^2)	Percent of total watershed
14178000	Freshwater Emergent Wetland	308172	1.6%
	Freshwater Forested/Shrub Wetland	405620	2.1%
	Freshwater Pond	134785	0.7%
	Lake	251	0.0%
	Riverine	2756283	14.1%
14179000	Freshwater Forested/Shrub Wetland	704371	7.4%

	Freshwater Pond	430901	4.5%
	Lake	389970	4.1%
	Riverine	6019178	63.0%
14180300	Freshwater Emergent Wetland	1025	0.2%
	Freshwater Forested/Shrub Wetland	3104	0.5%
	Riverine	17120	3.0%
14181500	Freshwater Emergent Wetland	2121364	2.2%
	Freshwater Forested/Shrub Wetland	4364128	4.6%
	Freshwater Pond	2028066	2.1%
	Lake	17529044	18.5%
	Riverine	21415144	22.6%

Statistical Analysis of Environmental Time Series

Water quality and climatic data from USGS (2016) and NOAA (Vose et al., 2014) were analyzed using the R statistical software (v4.2.1). In order to analyze the data, observations recorded at a subdaily frequency were consolidated to a single value per day of year (1-366). This ensured that the same number of values were used for pre- and post-fire data years and gave a way for the pre- and post- fire data to be paired for comparison. In most cases 20 years of pre-fire data were used, thus consolidation was also necessary to reduce the size of the input dataset. Water temperature is used as an example constituent because of its significance for fish habitat in the Willamette basin, but the analysis developed could be performed for any constituents of concern.

Three sets of analysis were performed on water temperature time series:
1) Mean difference tests between pre- and post-fire observations at a single gauge site to see if the post-fire (2020-2022) data was different from the pre-fire period (1999-2020).
2) Scatterplots of historical pre-fire observations to compare observations in different parts of the Detroit Lake system.
3) Historical box plots of pre-fire observations at various time scales overlain with post-fire observations to identify when in the year deviations from pre-fire norms are occurring.

Mean difference tests at Detroit Lake and Green Peter Lake: August 16, 2020 was used as the first date of the post-fire period. A Shapiro test determined that none of the time series data follow a normal distribution during the pre-fire or post-fire period. This led to use of the Wilcoxon test (which is similar to a t-test but does not require normally distributed data) for identifying differences in the means of comparison data sets (Xia, 2020). The Wilcoxon signed rank test, with a 95% confidence interval test, was performed for each of the six observation points at Detroit Lake and Green Peter Lake (Table 4) with two goals; first to determine if the pre-fire data and post-fire data were statistically similar, and secondly to determine if Green Peter Lake, which had not experienced significant burns in 2020, could serve as a control compared to Detroit Lake. Thus, a rejection of the null hypothesis is a determination that the pre- and post-fire data are statistically different while a failure to reject the null hypothesis indicates that the pre- and post-fire data cannot be statistically separated. Results from the Wilcoxon test show that for all four sites tested at Detroit Lake there was a significant change in temperature. In contrast, the null hypothesis cannot be rejected at Green Peter Lake making it a suitable control. The results from the analysis are shown in Table 4, where a p-value less than 0.05 means to reject the null hypothesis. Wilcoxon p-value results for comparison of pre- and post- fire water temperature

Table 4. Wilcoxon p-value results for comparison of pre- and post-fire water temperatures

Gauge	Lake System	Location	p-value	Reject/Fail to Reject the Null
14178000	Detroit	North Santiam River	<2.2e-16	Reject
14179000		Breitenbush Creek	<2.2e-16	Reject
14180300		Blowout Creek	2.78e-06	Reject
14181500		North Santiam River at Niagara	0.0001696	Reject
14185800	Green Peter	Middle Santiam River	0.498	Fail
14186200		Middle Santiam River Below Green Peter Lake	0.6832	Fail

Scatterplots of pre-fire observations: To better understand the relationship between typical temperatures in different parts of the system, scatterplots of date paired pre- fire observations were made with temperature data color coded by season. Figure 4 shows the water temperature scatterplot for two tributaries to Detroit Lake, Breitenbush Creek and the North Santiam River. Both sources drain from the east of the reservoir with Breitenbush creek north of the North Santiam River. Figure 4 shows that summer and winter temperatures at the two gauges are very similar. Breitenbush Creek warms 1-2 degrees Celsius higher than the North Santiam in the spring while the North Santiam remains slightly warmer in the fall. Both gauges show more variability in fall temperatures than other times of the year. Scatterplots between other tributary pairs show similar patterns with only 1-2 degree differences between date paired observations.

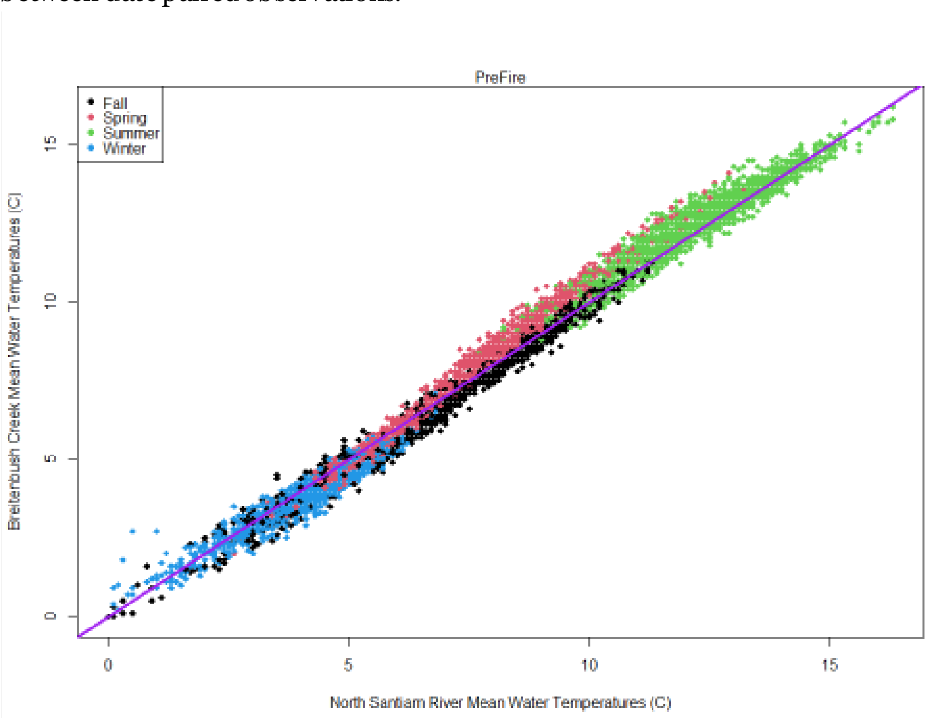

Figure 4. Pre-fire water temperatures observed at two tributaries to Detroit Lake, Y-Breitenbush Creek compared to X-North Santiam River

In contrast, date paired water temperatures above and below Detroit Lake can be as much as 10 degrees Celsius different (Figure 5). The temperature difference is greatest in the fall when water temperatures observed in the North Santiam River at Niagara, below the reservoir, are significantly higher than in any of the tributaries. This reflects the accumulation of heat within the reservoir brought by warm tributary waters during spring and summer and the selective management of releases to provide cooler waters to the North Santiam below the dam during summer. Like the tributaries, the river below the dam shows the greatest variability in temperatures during fall.

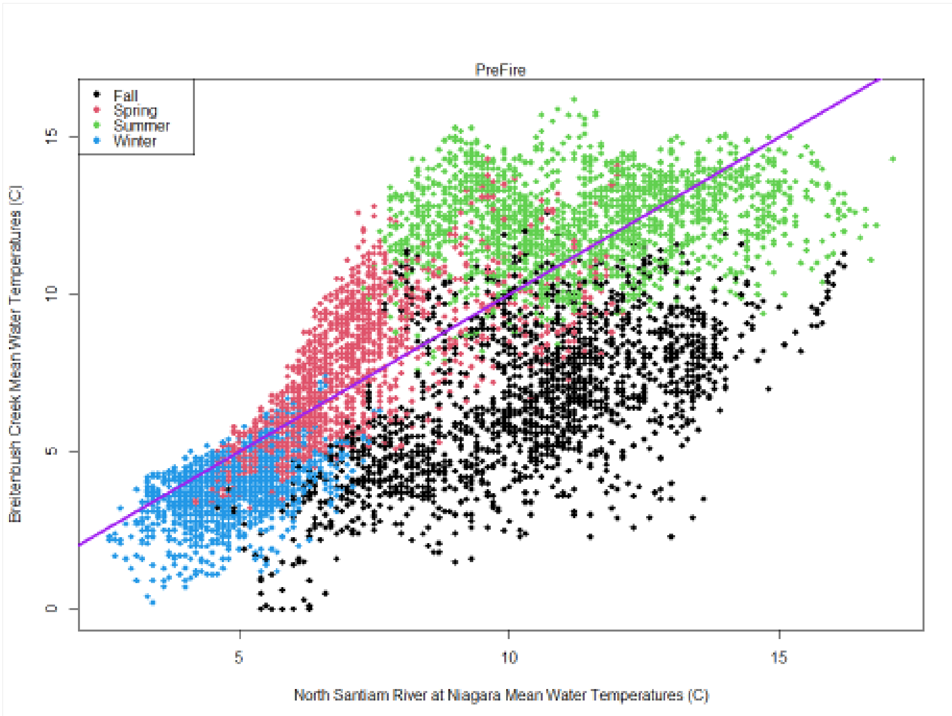

Figure 5. Pre-fire water temperatures observed at tributaries to Detroit Lake compared to the river below the lake, Y -Breitenbush Creek compared to X-North Santiam River at Niagara, a gauge site below Detroit Lake

Pre-fire and Post-fire comparisons: The Wilcoxon test determined that there was a pre- to post- fire mean temperature difference at each of the four gauges near Detroit Lake, however this test cannot give any information about the mechanism of change. Because there are only two years of post-fire water quality data, a custom box plot was designed to superimpose individual post-fire observations on top of pre-fire observations summarized in a box and whisker plot. The box and whisker plot can be made at several averaging intervals from daily to seasonal. Figures 6 and 7 show the custom box plots for weekly water temperature data at Breitenbush Creek and the North Santiam River at Niagara respectively. Each blue box represents a week of the year (week one is January 1-7) and spans the 25th to the 75th percentile of the pre-fire water temperatures with the median value indicated by the solid black line. Error bars (whiskers) are marked at the 95th confidence interval and outliers are indicated with blue dots. The orange triangles are the individual (non-averaged) post-fire water temperature measurements. This format allows us to assess when and in which direction temperatures have deviated from long term norms in the post-fire period.

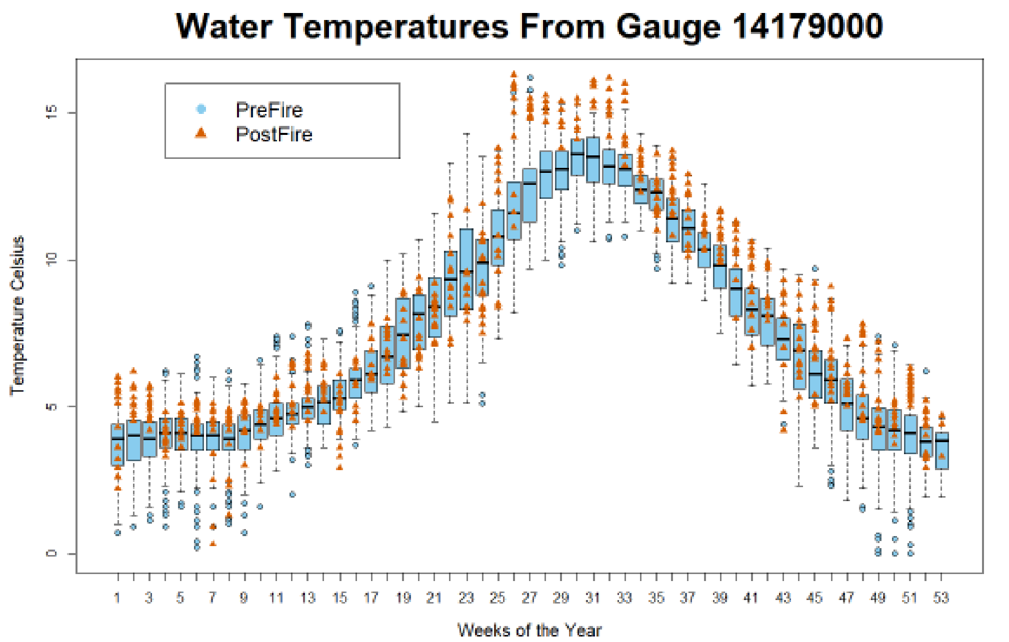

Figure 6. Pre-fire norms and post-fire observations at Breitenbush Creek

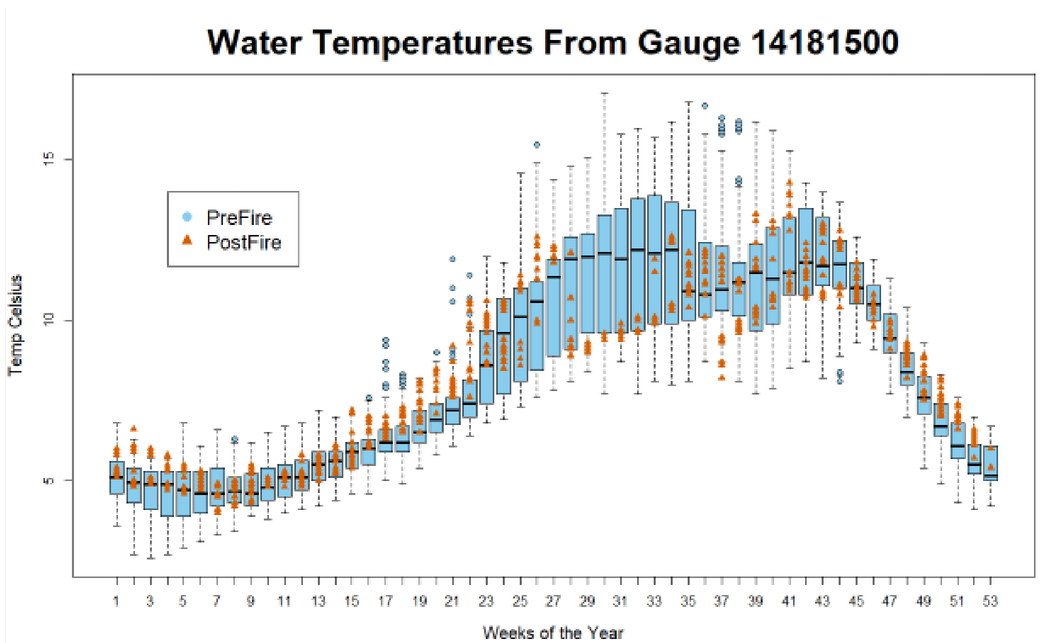

Figure 7. Pre-fire norms and post-fire observations at the North Santiam River at Niagara

Post-fire temperatures at Breitenbush gauge have tended to be warmer than the pre-fire norms for most of the year with far more points falling above the 75th percentile than below the 25th percentile. Two periods of the year may be experiencing temperature changes, weeks 15-21 and weeks 27-53. During weeks 15-21, which occur in spring, the post-fire temperatures skew slightly colder than average, including week 15 when the coldest water temperature for that week was recorded during the post-fire period. During the peak of summer, weeks 27-33, all observed post-fire values exceeded the historical 75th percentile and several weeks experienced their highest temperatures of record. Air temperatures in both 2021 and 2022 peaked in week 26 but while air temperature cooled after the heat waves, the tributaries stayed warmer than normal. For every week of the remainder of the calendar year more temperatures fall above the pre-fire median than below it and there are additional weeks reaching all time maximum water temperatures. Thus, in the two years following the fire, the summer and fall periods have experienced warmer than historical tributary water temperatures while springs have been slightly cooler than normal. The other tributaries show similar thermal patterns.

Figure 7 shows a custom box plot for water temperatures observed in the North Santiam River at Niagara, below Detroit Lake and Big Cliff Dam. Here the water temperatures show different patterns from the tributaries due to the retention of water in the reservoir and the selective release of reservoir water to the river. During weeks 1-15 temperatures overlay the boxes for the historical norms. Weeks 16-21, as spring transitions to summer, are warmer than pre-fire. In contrast to the tributaries, the peak of summer temperatures are significantly colder, likely due to selective withdrawal of deep lake waters. Thus, for the two summers following the fires, water is entering Detroit Lake around 15 degrees Celsius while it is being exported downstream around 8 degrees Celsius. Temperatures return to pre-fire norms around week 33 and stay in typical ranges until week 46 when they shift to warmer than the historic median for the rest of winter. The one exception is week 37 which experienced its coldest temperature for that week ever in the post-fire period.

Green Peter Lake is located approximately 10 miles southwest of Detroit Lake with shared watershed divides in the Willamette National Forest. The contributing area of Green Peter Lake has not experienced significant fire in the last 10 years; there is no difference in the water temperature means for the period after the fires of 2020 (Table 4), so it is a reasonable control site allowing the differentiation of larger regional trends in water temperatures and other parameters versus fire induced changes at Detroit Lake. Water temperatures in the tributary to Green Peter Lake (Figure 8) are warmer than the Detroit Lake tributary (Figure 6) but both follow a similar annual trend. Both lakes experienced unusually high air temperatures in summer 2021. However, comparing the 2021-2022 water temperatures in the Breitenbush upstream of Detroit Lake for weeks 27-33 versus the temperatures at the Middle Santiam above Green Peter Lake for the same period it can be seen that the warm excursions above the normal range were greater at Detroit Lake. In addition, after air temperature peaks in week 26 for the 2021-2022 summers, the water temperatures return to the typical range at the Green Peter Lake tributary while they stay elevated at Breitenbush Creek. Although there were some unusually warm and cold individual observation in the unburned Green Peter Lake tributary, fall temperatures spanned both warmer and colder than the long-term median, in contrast to the highly burned Detroit Lake tributary where they were skewed to the warmer side of the long-term median.

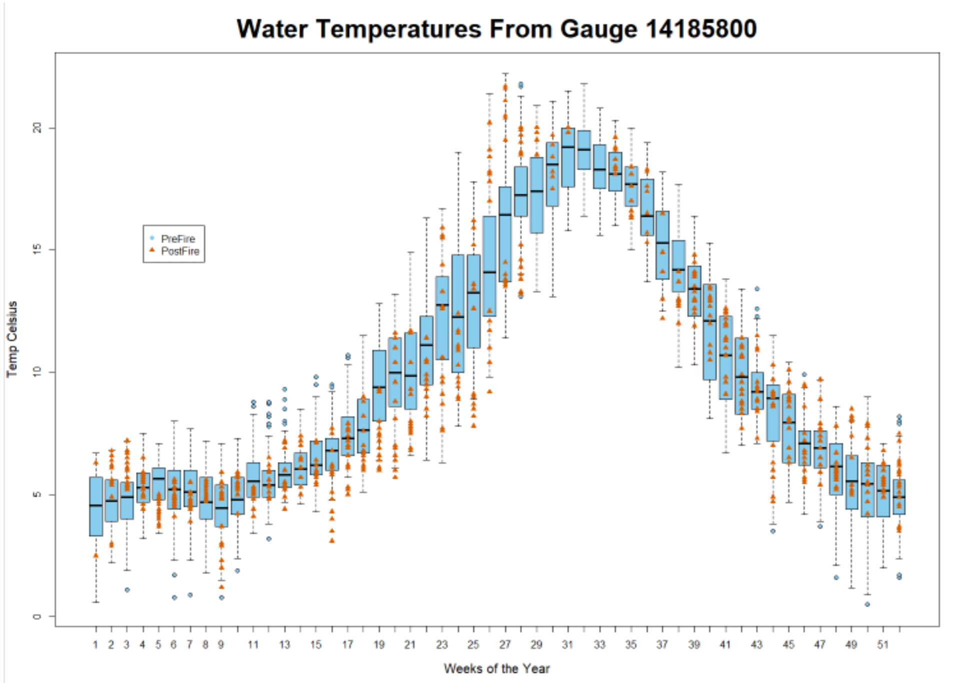

Figure 8. Pre-fire norms and post-fire observations in the Middle Santiam River, tributary to Green Peter Lake

The long-term temperature pattern in the Middle Santiam at Green Peter Lake (Figure 9) indicates a different management practice than at Detroit Lake (Figure 7) with peak temperatures in the river below Green Peter Lake occurring in October. Thus, the rivers downstream of the reservoirs are not as directly comparable as their tributaries. However, it appears that there was an early spring heating event at Green Peter Lake that does not appear at Detroit Lake and unusually high temperatures for a few weeks in October.

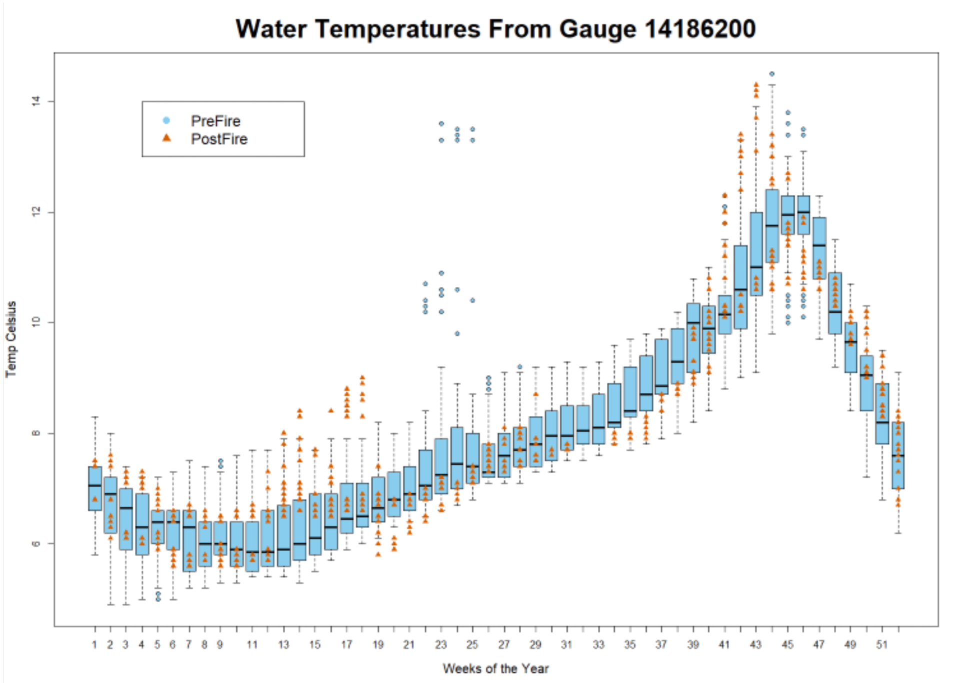

Figure 9. Pre-fire norms and post-fire observations in the Middle Santiam River below Green Peter Lake

Next Steps Discussion/Wrap up

Figure 10 outlines the major components of a generalizable workflow that can be used to guide baseline post-fire assessment of watershed and receiving waterbody water quality. The suggested data sources are readily available and offer wide coverage for the U.S.; the suggested analyses can be performed without any specialized models or software, and in many cases the pre-fire norms can be evaluated even before fire specific data (for example BAER reports) become available. This workflow is not meant to be a one size fits all approach, but rather a starting point that can be expanded to address additional endpoints and concerns with locally derived data and monitoring, modeling, and other specialized studies.

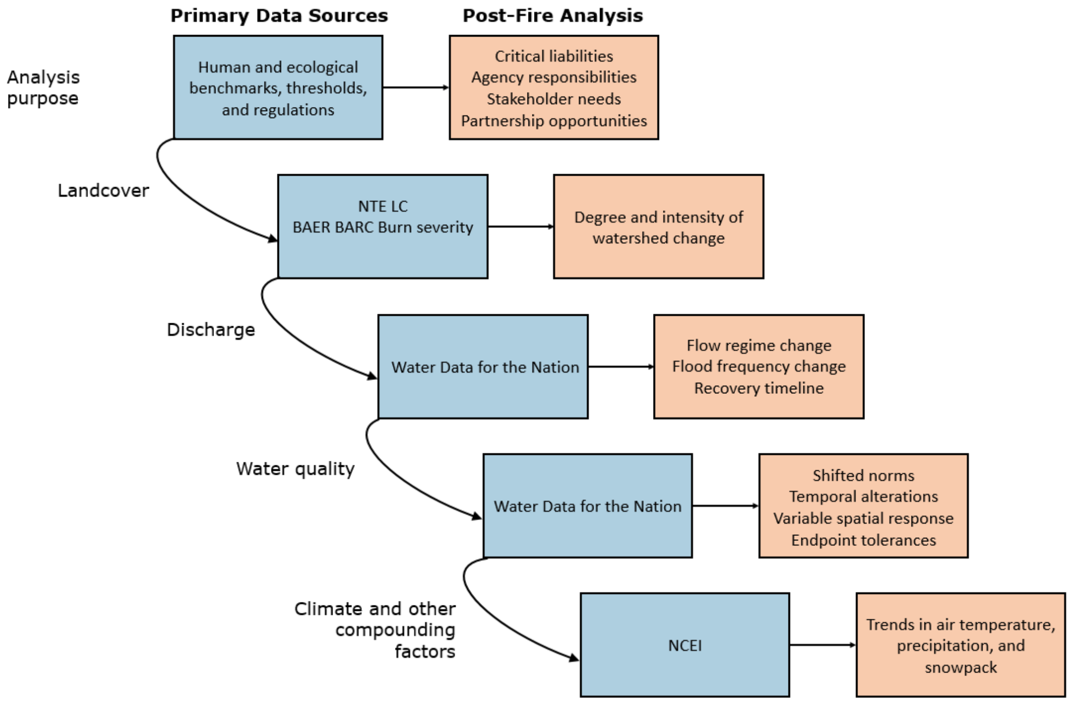

Figure 10. Generalized total watershed workflow for post-fire water quality change assessment

For example, our ongoing study at Detroit Lake includes collection of discharge and water quality measurements at many of the smaller ungauged tributaries to the lake, including both sites that drain into gauged tributaries and directly into the lake. Locations are shown in figure 11 and additional sites are expected to be added as access to burned areas increases. Very few studies have tracked water quality during the regrowth and recovery period following a fire, thus these data will help develop an understanding of how long altered reservoir loading of heat, nutrients, and other water quality constituents may persist.

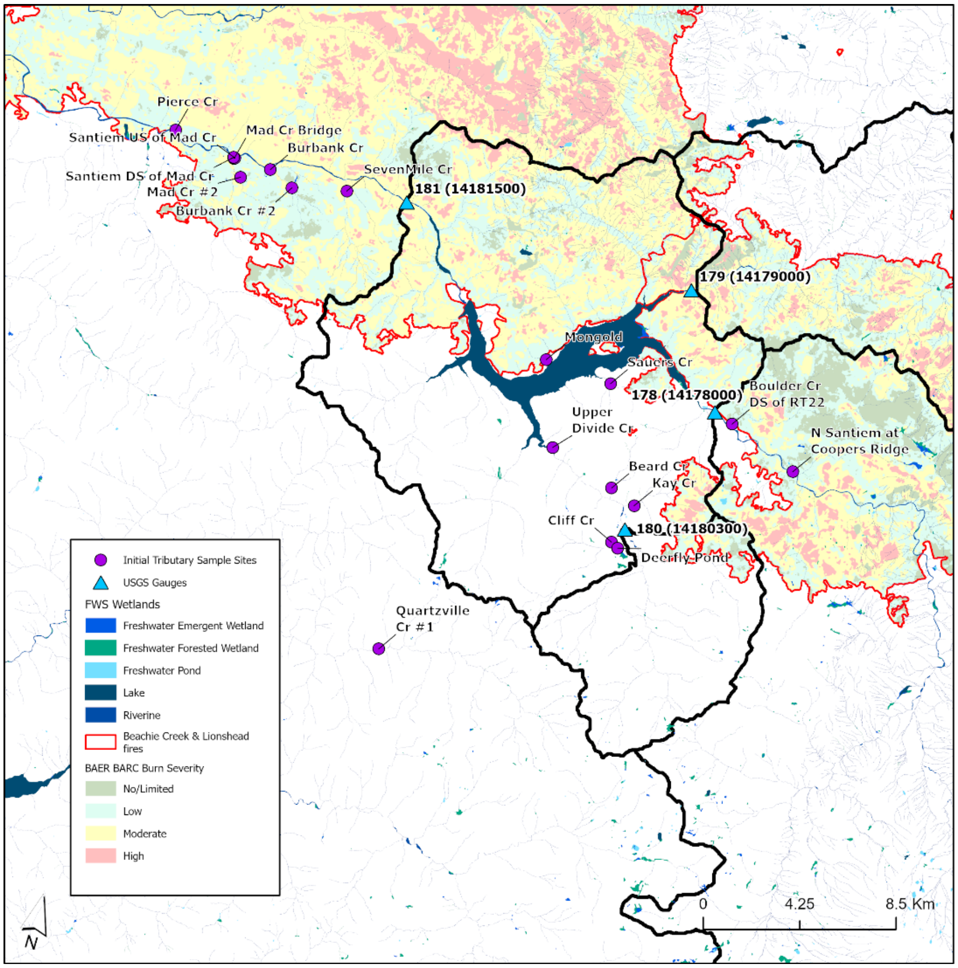

Figure 11. Locations of tributaries sampled in summer 2022

As fires have increased in number, extent, and severity there has been an explosion of engineering approaches to improve the pace and quality of recovery. Water quality is often secondary to other more immediately life-threatening risks such as flooding and debris flows. However, water demand, particularly in the arid West, is creating increased pressures to maintain high quality drinking water and ecological habitat after fire. The workflow presented in Figure 10 offers a quick guide for initiating response and study of post-fire water quality concerns.

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