Yakima River Scoping Study to Assess Temperature and Dissolved Oxygen Levels to Inform Water Management Options

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Cover Photo: Sockeye Salmon spawning in the headwaters of the Cle Elum River in the Yakima Basin. (Yakima Nation – Tom Ring).

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The purpose of this scoping study was to understand the data, tools and models currently available that describe Yakima river water quality, specifically temperature and dissolved oxygen. The Yakima River is a tributary of the Columbia River in Washington State and is the only migratory pathway for Yakima Basin juvenile salmonids migrating downstream to the ocean and adults returning to their natal streams to spawn. High water temperature and low dissolved oxygen levels in the lower Yakima River create migration barriers and become lethal for migrating salmon. The objective of this project is to help advise water managers when flow management options can be used to change water quality conditions and benefit salmonid migration. This scoping study gathered existing data and water quality models, reviewed previous and concurrent work being conducted in the basin and developed project partnerships to support the writing of a full research/conducting proposal for fiscal year 2022. The conducting proposal will create a predictive tool on how and when strategic flow releases at the upstream dams or other water management options might improve water temperature and dissolved oxygen levels in the lower Yakima River to allow adult salmon to migrate upstream and enhance juvenile salmon downstream migration survival.

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Acronyms and Abbreviations

Basin	Yakima River Basin
cfs	cubic feet per second
DO	dissolved oxygen
DPM	Deep Percolation Model
Ecology	Washington State Department of Ecology
EIM	Environmental Information Management
FLIR	forward-looking infrared
KID	Kennewick Irrigation District
NAWQA	National Water-Quality Assessment
NWIS	National Water Information System
PRMS	Precipitation-Runoff Modeling System
Reclamation	Bureau of Reclamation
RM	river mile
SOAC	Yakima System Operations Advisory Committee
SWAT	Soil Water Assessment Tool
TMDL	total maximum daily load
°C	degrees Celsius

Contents

Executive Summary

The purpose of this scoping study was to understand the data, tools and models currently available that describe Yakima River water quality, specifically temperature and dissolved oxygen. The Yakima River is a tributary of the Columbia River in Washington State and is the only migratory pathway for Yakima Basin juvenile salmonids migrating downstream to the ocean and adults returning to their natal streams to spawn. High water temperature and low dissolved oxygen levels in the lower Yakima River create migration barriers and become lethal for migrating salmon. The objective of this project was outline a conducting proposal and study that would help advise water managers when flow management options could be used to change water quality conditions and enhance juvenile migration survival and elicit an adult upstream migration response. The focus of this study is to improve water temperatures and dissolved oxygen levels to help adult Sockeye and summer Chinook salmon migrate up the lower Yakima River to higher quality upstream habitat and to enhance juvenile downstream survival for Sockeye, Coho, and Chinook salmon and Mid-Columbia Steelhead (listed as threatened under the Endangered Species Act). This scoping study gathered existing data and water quality models, reviewed previous and concurrent work being conducted in the basin and developed project partnerships and collaborations to support the writing of a full research/conducting proposal for fiscal year 2022. The conducting proposal outlines the development of predictive tool for water managers to determine how and when strategic flow releases at the upstream dams or other water management options might improve water temperature and dissolved oxygen levels in the lower Yakima River to benefit migrating salmonids. To this end, this report contains the peer-reviewed literature review in the main body and the final conducting proposal submitted to the Science and Technology Program FY21 call in the Appendix.

1 Introduction

The Yakima River Basin (Basin), located entirely in the state of Washington, drains an area of approximately 6,155 square miles (Figure 1). Within this heavily irrigated basin lies the Yakima River, which flows 214 miles (approximately 344 km) from the outlet of Keechelus Lake in the Cascades, to its mouth downstream from Horn Rapids Dam near Richland. The river then joins the Columbia River which flows west into the ocean. The Yakima River can be divided into three primary reaches (Morace et al., 1999). The upper reach, which drains the Kittitas Valley has a high gradient and contains approximately 74 miles of river from the foot of Keechelus Dam to just upstream of Umtanum. The middle reach drains the Mid Valley into 33 miles of river from Umtanum to Union Gap. The lower reach drains the lower valley which contains most of the irrigated agriculture in the Basin and runs 107 miles from Union Gap to the mouth of Yakima River. There are multiple dams located in the Yakima River Basin, many of which are owned and operated by the U.S. Bureau of Reclamation (Reclamation). Three Reclamation-owned reservoirs include the Keechelus Reservoir, the Kachess Reservoir and the Cle Elum Reservoir, all located at the northern end of the Yakima Valley. Two additional reservoirs are located on the Naches Branch of the Yakima: Bumping Lake and Rimrock Lake. Reclamation also owns the Roza Diversion Dam, located 10 miles north of Yakima and the Easton Diversion Dam located below the confluence of the Kachess and Yakima Rivers.

In addition to dividing up Yakima River by reaches, the Yakima River Basin is also divided up into three subbasins: (1) upper Yakima Basin, (2) lower Yakima Basin, and (3) Naches River Basin. These subbasins represent a unique combination of landscapes and climates that have differing effects on water quality and biological communities. The upper Yakima River Basin contains the three northern Reclamation reservoirs and starts off in the steeper headwaters above the reservoirs before draining down into the lower, flatter areas around Umtanum. The Naches River Basin is a large contributor of streamflow to the Yakima with steeper, more mountainous reaches than the other two basins. The Naches River Basin is perennial with peak runoff occurring during snowmelt and has less urbanization than the other two basins. The lower Yakima River Basin is separated from the upper Basin by a natural break in Ahtanum Ridge called Union Gap. The lower basin is dominated by irrigated agriculture and contains more urban areas than the other two basins. The Yakima Nation is also located in the southwest portion of the lower Yakima River Basin. The lower Yakima River Basin is the warmest and driest part of the larger basin and is used primarily as a corridor for migrating fish. All three subbasins are heavily regulated and where approximately 60% of this mean annual streamflow is diverted for irrigation, drinking water and power generation (Cuffney et al., 1990).

Historically, salmon migrated from the ocean up the Columbia and then Yakima River to spawn; however, with the construction of multiple dams along the Yakima, salmon populations have been substantially diminished or extirpated in the Yakima Basin over the past 100 years. For example, anadromous fish runs have declined from more than 500,000 adults annually during the 1880's to less than 4,000 adults during the 1980's (Bonneville Power Administration, 1988). In addition to the construction of dams, changes in water quality, primarily water temperature and dissolved oxygen, has altered the thermal regime of Yakima River making it difficult for migratory fish to survive and spawn. Some migratory salmon, such as spring chinook (Oncorhynchus tshawytscha) and coho (*Oncorhynchus kisutch*) have adapted to migrate outside the hottest months of the summer. Other salmon species, such as summer chinook and sockeye (*Oncorhynchus nerka)* have less flexible migration patterns and rely on migration during the hot and dry summer months. For instance, adult sockeye salmon pass McNary Dam during June-August each year and then spawn in the upper Yakima River Basin during September-November (Matala et al., 2019). In the middle of summer, water temperatures in the lower Yakima River have been shown to surpass 24°C, preventing the migration of these salmon species. This phenomenon is known as a 'thermal block' where migration is blocked when river temperatures reach 18-24°C depending on the river (ex. Appel et al., 2011; Macdonald et al., 2000).

Not only has agriculture and urban areas impacted salmonid habitats but projected climate change in the Yakima River Basin is anticipated to affect river temperatures and thus fish habitat. Hatten et al. (2014) linked a watershed model, a river operations model, a two-dimensional hydrodynamic model and two climate change scenarios to project how an increase in temperature might impact salmonid habitats on the Yakima River. Results indicated that 75% of the 28 different discharge-habitat responses exhibited a decrease in habitat quantity under scenarios with 1-2°C increase in mean air temperature. Given the current temperature regimes within the Yakima River and the projected increase in future air temperatures and thus reservoir and river temperatures, it is imperative to understand how different water management practices might alleviate thermal blocks and benefit salmonid migration.

In 2001, a literature review and synthesis on ecological studies in the Yakima River Basin concluded that there were five major challenges for migrating salmonids in the lower Yakima River (Snyder & Stanford, 2001):

1. Negative interactions between fish species show competition between exotic and native species can lead to declining native populations. In addition, hatchery-reared fish can also have a negative impact on wild populations.
2. The current magnitude and timing of the flow regime is drastically different from the natural flow regime historically observed in the Yakima River Basin.
3. The water quality impairment related to urbanization, irrigation activities and altered flow regimes is detrimental to fish health. High levels of pesticides have been found in fish, and although evidence of toxicity to fish populations has not been found, there are strong indirect effects on productivity through food web influences.
4. The alteration of natural streamflow temperatures has inhibited passage of migratory fish in the lower Yakima below Prosser. Temperatures have been impacted in part by less connectivity with groundwater aquifers that contribute cooler flows to the river, differences in flowrates due to diversions and reservoir releases and climate change.
5. Reduction in habitat heterogeneity and flood plain connectivity reduces ecosystem resilience which can impact all levels of biodiversity.

While all of these factors likely contribute to the decline in migratory fish passage in the Yakima River, this literature review will focus on how the altered flow regime and increasing temperatures observed in the Yakima River are impacting fish migration.

The main objective of this project is to develop a tool water managers can use to determine when a timed release of cool reservoir water or other operational actions will decrease water temperatures and improve D.O. levels in the lower 100 miles of the Yakima River enhancing salmonid migration.

This study is largely driven by efforts to reestablish summer runs of sockeye and summer chinook but can also address concerns that further warming could limit the more flexible migration patterns of spring chinook salmon, steelhead trout and coho salmon. In order to accomplish these objectives, it will be necessary to better understand the driving mechanisms associated with temperature and DO changes in the Yakima River. Those mechanisms could include weather variables, reservoir releases and different water management operations.

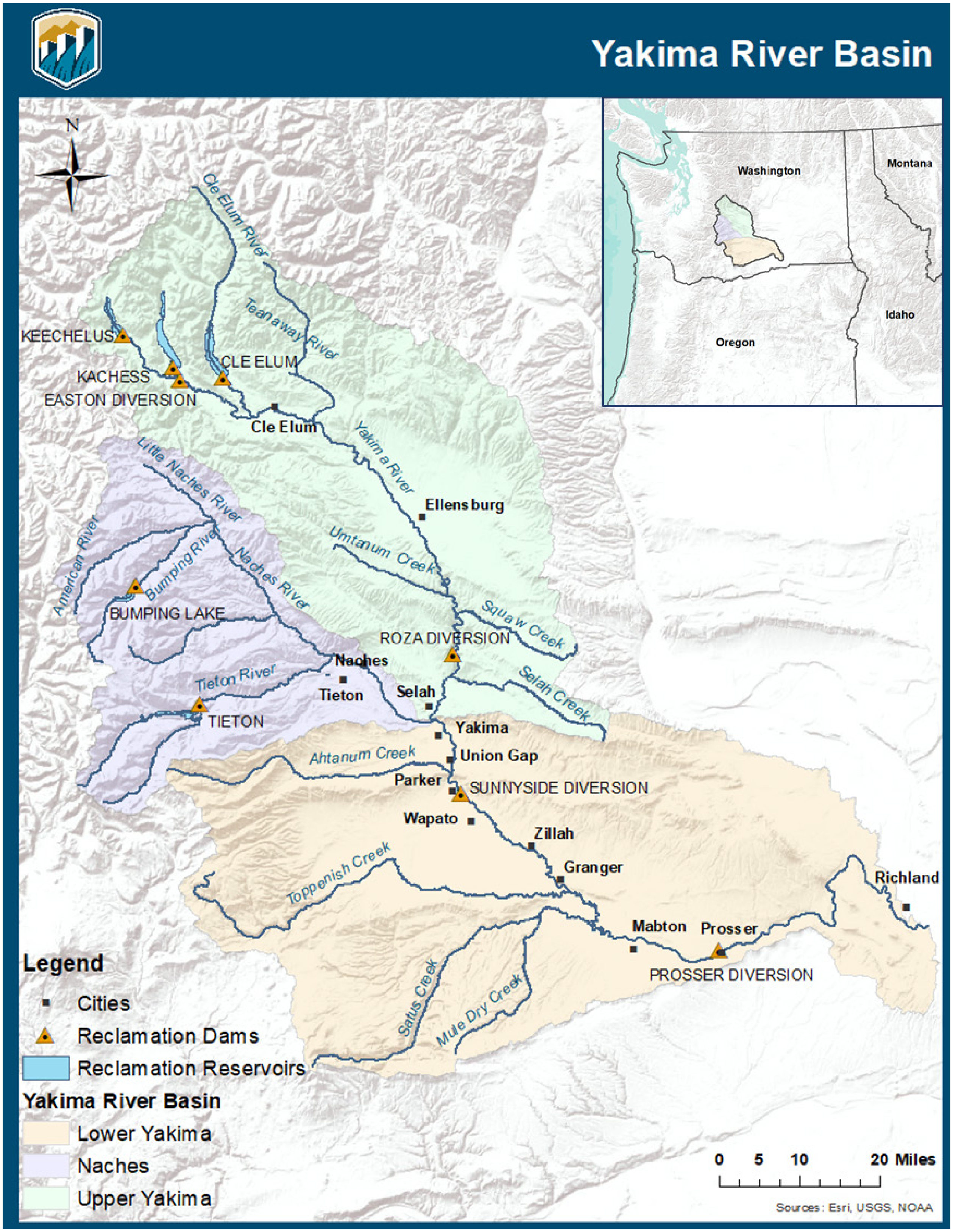

Figure 1. Map of the Yakima River Basin.

1.1 Water Management Operations

Yakima River water management operations are complex, as the basin divides its water among instream flows for aquatic functions, irrigation districts and municipal and domestic water supply. It is possible that different water management operations at different times of the year might have a beneficial impact on downstream water quality. These operations could include pulsed flows from upstream reservoirs or changing the magnitude and timing of certain diversions. There are three upstream reservoirs owned by Reclamation and two reservoirs located in the Naches arm of the Yakima River Basin that could be used for these timed, pulsed releases to improve water quality on the Yakima River.

1. Cle Elum Reservoir: Cle Elum Reservoir is the largest of the three upstream reservoirs with a storage capacity around 436,900 acre-feet. Cle Elum experiences strong stratification from July to September (Reclamation & Ecology, 2014) thus preserving the cool, deeper waters. The outlet works are located at an elevation of 2,110 feet (full pool is 2,240 ft), well below the thermocline and therefore release colder water downstream. Outflow water temperatures ranged from approximately 6- 19.5°C in 2004-2005. During a later 2014 sampling campaign in June, July and August, the average outflow water temperature was 10.7°C (Reclamation & Ecology, 2014). The reservoir has a warm surface layer with increasing DO concentrations with depth. This typically occurs in reservoirs with large algal populations that build up density in the middle layers of the reservoir and produce oxygen. As of 2015, there were no water quality models developed of this reservoir. Water travels from Cle Elum Reservoir approximately 70 miles downstream along fairly low gradients until it reaches the lower Yakima River.
2. Keechelus Reservoir: Keechelus Reservoir stratifies in the summer with a high surface temperature of around 21.6°C and bottom temperatures around 4°C. Keechelus Reservoir has about a third the storage capacity of Cle Elum Reservoir but with a fair amount of dead storage not accessible due to the height of the reservoir outlet. The outlet is located approximately 92 feet below full pool elevation. There is a CE-QUAL-W2 model of this reservoir further discussed below in Section 4.2.
3. Kachess Reservoir: The Kachess Reservoir is the least likely to impact downstream water temperatures as its outflow goes directly into lake Easton, two miles downstream of Kachess Reservoir. Kachess Reservoir has a similar temperature profile as Keechelus Reservoir, with a strong thermocline present in summer with a maximum surface temperature of around 22°C and bottom temperatures of 4°C. The thermocline is normally around 32-40ft in depth. Unfortunately, even though the reservoir is quite deep, the outlet is located in at an elevation of around 2,192 feet, which is only 72 feet below the full pool elevation and does not pull the coldest waters from the reservoir. Sampling has shown that waters below the thermocline remain under 12°C which is approximately where the outlet pulls water from assuming full pool. There is a CE-QUAL-W2 model of this reservoir further discussed below.
4. Bumping Reservoir: Bumping Lake reservoir is located on the Bumping River in the Naches branch of the Yakima River Basin. It was constructed to provide storage for irrigation water and flood control storage. It is a narrow reservoir with an averaged width of 0.47 miles and a length of 4.3 miles. The outlet works of Bumping Reservoir is located approximately 37 feet below the reservoir spillway and thus removes the warmer,

oxygenated waters from the reservoir. A bathymetric survey of this lake was completed in 1990. There are no known water quality models of Bumping Reservoir.

5. Rimrock Reservoir: Rimrock Reservoir is also located in the Naches branch of the Yakima River Basin along the Tieton River and is impounded by the Tieton Dam. It is another long, narrow reservoir approximately 6 miles in length with a maximum depth of 200 ft. The outlet works are located close to the reservoir bottom, approximately 162 feet from the maximum reservoir water surface. From the Tieton Dam, the water flows approximately 21 miles to the Naches River, which then flows 17.5 miles into the Yakima River just above the city of Yakima (at RM 116). The Tieton and Naches Rivers are also at a higher gradient in areas of higher elevation relief and thus water travel times are faster than water coming out of the three northern Reclamation reservoirs. There are no known water quality models of Rimrock Reservoir.

The Yakima Project provides irrigation water for six irrigation districts along the Yakima River. These five reservoirs provide storage for irrigation water. Therefore, the operations of these reservoirs and water rights will have to be taken into consideration when deciding which reservoir(s) to release water from and when. For instance, Reclamation has changed an annual 'flip-flop' operations scheme in September 2020, where flows out of Cle Elum and Keechelus reservoirs are gradually reduced while flows from the Kachess and Rimrock reservoirs will be increased. Historically, 'flip-flop' occurred in late summer and shifted water demands from the upper Yakima Basin reservoirs to the Naches system reservoirs which disrupted salmonid habitat due to unnaturally high flows in the Tieton and lower Naches rivers.

It will also be important to understand how the Yakima Project impacts flows and water quality on the Yakima River. In general, the Yakima Project reduces winter, spring, and early summer flows from the dams to the mouth of the river. Summer and fall flows tend to be increased from the dams down to the major irrigation diversion point at Parker. However, downstream of Parker up to 75% of the flow is diverted for irrigation purposes which results in significant warming of the river water from Parker to Mabton even though irrigation return flows increase flow rates the farther you go downstream. For instance, it is not uncommon during the middle of summer for flows above Parker to be around 3000-4000 cfs, flows below Parker reduced to around 500 cfs, and flows down at Mabton to be closer to 1200 cfs. Conceptually, the Yakima River water warms up from Parker to below Prosser and reaches a temperature where it is largely equilibrated with the average air temperature with limited dependence on flowrate. A large part of this study will be modeling whether or not pulse flows and other operational changes can alter upstream flows and temperatures enough to improve conditions in this lower reach from Parker to Mabton where water quality is dominated by return flows and air temperature.

In addition to reservoir releases, this project will investigate the impact of other water management options to alter the routing, timing and quality of flows in the lower Yakima River. These other management options could include:

- Diverting cooler water from Parker and above into irrigation canals for delivery back to the river via drains lower in the basin. This diversion assumes that water will remain cooler in the irrigation canals than if left in the river and thus can be used to cool the river at the return locations. This management option would require understanding travel times and temperatures through the canal/drain network and further analysis of canal capacity and operational constraints.

- Reducing diversions at Chandler to protect pulse flows as they move through the bypass reach below Chandler. This could be accomplished by reducing power diversions, using (proposed) electric pumps in place of the water-powered pumps for the Kennewick Irrigation District (KID) water delivery, and/or reducing KID diversions based on the ability of proposed reregulation reservoirs to allow the district to use stored water to supplement temporarily reduced diversions.
- Changing diversion and return flow operations to take advantage of diurnal and weather event related temperature changes. For example, increasing diversions at Parker at night would reduce downstream river flows during the cooling hours of the 24 cycle (resulting in more rapid river cooling) as well as increase the impact of cooler subsurface return flows on overall river temperature. In addition, this would reduce diversions during the warmer hours of the day or during warmer weather window. Likewise, morning releases from re-regulation reservoirs could help buffer mid-day temps downstream.

1.2 About This Literature Review

This review aims to compile relevant literature and available models in the Yakima River Basin related to salmonid migration and water quality along the Yakima River. While this review is not exhaustive, it is designed to help support and develop a Science and Technology conducting proposal to be submitted in June of 2021. To this end, Section 2 discusses previous studies in the Yakima River Basin, with Section 2.1 discussing how weather and streamflow temperatures are coupled, Section 2.2 focusing on studies that investigated water quality along the Yakima River, and Section 2.3 focusing on migratory fish habitat studies. Section 3 continues by discussing studies outside of the Yakima River Basin that explored the effect of pulsed flows on downstream water quality. Section 4 discusses the available data and models of different reservoirs and rivers within the Yakima River Basin. The report concludes by discussing possible next steps and future research needs to better understand how upstream reservoir releases and other management practices may impact downstream water quality and anadromous fish migration along the Yakima River.

2 Yakima River Basin Studies

The following section summarizes studies undertaken in the Yakima River Basin that are relevant to fish migration. These include studies investigating water quality within the Basin, specifically dissolved oxygen (DO) and temperature. In addition, this section will review fish habitat studies detailing the migratory patterns of fish within the basin and how their habitat is linked to water quality.

2.1 Climate and Stream Temperatures in the Yakima River Basin

Water temperature in the Yakima River is strongly impacted by air temperature and weather patterns; therefore, it will be necessary to understand if different water management options can have more of an impact on downstream water quality during certain weather patterns. While many different weather variables can impact stream temperatures, air temperature has been found to be one of the best predictors of stream temperature. For instance, Mantua et al. (2010) found a non-linear regression model using weekly historic average air temperature to predict weekly historic average water temperature to be applicable to several sites in the Yakima River Basin. These regression models also took into account that some sites located in snow-melt dominated systems experience a seasonal hysteresis, where stream temperatures lag in response to air temperatures.

Lilga (1998) also investigated the relationship between measured stream temperature, flow rate, air temperature, heat flux and solar radiation at three sites along the lower Yakima (Parker, Prosser and Kiona). She used field data from 1987-1996 and performed linear single and multiple regressions on hourly and daily climate and flow data and stream temperature. Results indicated that flow rate did not have a significant impact on stream temperatures most likely due to the influence of irrigation return flows. Multiple regressions using air temperature, streamflow, heat flux, and solar radiation during one week intervals in the summer of 1996 were found to better estimate stream temperatures than single regressions. Similar to Mantua (2010), air temperature was found to be the most significant predictor variable, although the regressions did not take into account that the highest streamflow temperatures often lagged the highest recorded air temperature by up to half a day. Regressions were also able to explain the stream temperature trends the best at Kiona as compared to Parker and Prosser. It will be very useful for this project to conduct rigorous statistical analyses on historical stream temperatures and weather variables in the Yakima River Basin to help determine how weather and stream temperatures are coupled.

In addition, it will be very useful to use the river water quality models developed for this project to explore the impact of different weather parameters on stream temperature. Looking at the sensitivity of modeled stream temperature to different variables such as air temperature, solar radiation, relative humidity, wind speed and cloud cover will help inform water managers when different management actions might be the most impactful. Sensitivity analyses conducted on water temperature models within the Yakima Basin have also found that water temperatures in the lower Yakima are most sensitive to air temperature (J. Vaccaro, 1986) and solar radiation followed by relative humidity and wind speed (Voss et al., 2008). Voss et al. (2008) found that air temperature and solar radiation played a larger role in changing stream temperatures in the lower Yakima during July than they did during irrigation season, indicating other factors such as streamflow or diversions can also influence stream temperatures. Vaccaro (1986) modeled streamflow temperatures using a Lagrangian temperature model on the entire mainstem of the Yakima River during the 1981 growing season. His model sensitivity analysis showed that air temperature (solar radiation was not modeled) was the dominant variable responsible for changing stream temperature, and that its importance increased the farther downstream a monitoring station was. A 4°C increase in air temperature resulted in a 2.34°C in water temperature at Prosser and a 1.46°C increase in water temperature at Umtanum. Wind speed was found to be a relatively insensitive variable and did not change stream temperatures much.

Doing rigorous statistical analyses on historical weather and streamflow data combined with model sensitivity analyses on both climate variables and reservoir releases will help address the driving mechanisms associated with temperature changes in the Yakima River.

2.2 Water Quality Studies

Water quality along the Yakima River varies substantially with higher quality water residing in the upper ecoregions while water quality starts to deteriorate farther downstream as the river enters the

Columbia Basin ecoregion and irrigated agriculture return flows influence the Yakima River. Both natural and anthropogenic sources of contaminants, along with flow regulation, control water quality in the Yakima River Basin. In 1986 Congress appropriated funds for the USGS to refine the National Water-Quality Assessment (NAWQA) Program. As part of this program, the USGS collected and synthesized water quality data on Yakima River (Cuffney et al., 1990; Morace et al., 1999). Given the lower Yakima River reach is the principle concern for this project and improving migratory fish passage, synthesis of water quality data will focus primarily on this lower reach.

In 1990, the USGS investigated the distribution of fish in relation to physical and chemical conditions along the Yakima River (Cuffney et al., 1990). Fish communities within the basin were primarily composed of salmonids, sculpins, and cyprinids. This study measured more than 140 physical, hydrologic, and biogeochemical variables at 25 different sampling sites along the Yakima River. Of these variables, water temperature was measured, along with other chemical markers such as total organic carbon, turbidity, and nitrogen and phosphorus species; however, this study did not measure DO levels in the river. Results from this study show that in the upper two ecoregions, most sites were not ecologically impaired; however, down in the lower Columbia Basin ecoregion most sampled sites were labeled as moderately or severely impaired with regards to their water quality. This impairment resulted primarily from high levels of nutrients, pesticides and turbidity associated with the surrounding agricultural intensity. While this study directly correlated biological indicators such as fish community tolerance to the measured variables, it did not investigate the impact of temperature on salmon migration or the distribution of salmon specifically.

The USGS also published a study in 1999 (Morace et al., 1999) that included a surface water quality assessment of the Yakima River Basin. This study collected samples from water years 1986-1991 that included several different water quality constituents (pH, DO, temperature, nutrients, etc.) and media samples from seven sample sites along the Yakima River. In addition, this study synthesized data from multiple water quality studies conducted in response to NAWQA (ex. Cuffney et al., 1990). Of all the DO samples taken (317 at non-headwater streams), only 9% did not meet the Washington State Water Quality Standard of 8 mg/l. However, during a summer, low-flow sampling conducted in July of 1987, almost one half of the 39 sites sampled did not meet the State standards for DO. Most of these sites were in the Lower Valley and impairment was attributed to the effects of agricultural return flow, urban runoff and point source discharges. In general, DO concentrations upstream of Granger were generally higher than downstream. Temperature samples failed to meet State standards more often than DO samples, with 12% (of 1,152 samples) failing to be under 16°C if measured in a headwater stream or under 21°C for all other stream orders. Of the 23 samples taken in headwater streams, over a quarter of them failed to be under 16°C while only 13% of the 1,049 other samples taken in lower order streams failed to be under 21°C. All temperature exceedances in the headwater streams occurred during July and August, while all others typically occurred from June-September. In general, Yakima River temperatures were higher downstream than upstream. Most of the warming was associated with low flows downstream from the Wapato and Sunnyside Canal diversion and slow stream velocities.

During a USGS study in the early 2000s, eutrophication of the lower Yakima River was investigated (Wise et al., 2009). Within this study, temperature and DO was continuously monitored at three sampling sites on the Yakima River throughout the 2004-2007 growing seasons. The three sites were located at Kiona (river mile – RM 30), Mabton (RM 55), and Zillah (RM 87). At all three sites, water temperatures exceeded 20°C by early June in 2005 and remained above 20°C until early September. Water temperatures during 2006 were cooler longer and did not exceed 20°C until mid-June or early July but at Kiona temperatures reached 30°C by late July. DO concentrations displayed a similar seasonal trend, with lower minimum DO concentrations during the low flow season. Minimum daily DO concentrations plummeted to 3 mg/l multiple times during 2004 and 2005 at Kiona, but otherwise typically remained above 5 mg/l at the other two sites and at all sites during 2006–2007.

In 2016, The Washington State Department of Ecology (Ecology) published a comprehensive review of historic water quality along the mainstem of the Yakima River (Pickett, 2016). This review included detailed findings on the hydrology, temperature, DO, pH, and nutrient composition of each reach and ecoregion along the Yakima River through 2015. The conclusions of this study were very similar to the above mentioned studies (and also included results from those studies; Cuffney et al., 1990; Morace et al., 1999; Wise et al., 2009) where water quality deteriorated the farther downstream samples were taken with the most adverse effects observed during the low flow season in mid- to late-summer. This study does note that three cold water releases from Cle Elum Reservoir dropped downstream temperatures in the Yakima River by 3°C in late summer therefore initiating the movement of hundreds of sockeye and summer chinook salmon. These pulses were released once in 2014 and twice in 2015.

The review concluded by summarizing the water quality implications for individual reaches of the river. A brief synopsis of these conclusions follows.

- **Upper Yakima River to Easton Basin:** Given these waterbodies are critical salmonid spawning habitat and typically have temperature and DO issues, this area is of high priority for additional study. Conditions in these waterbodies are strongly influenced by the operation of the three reservoirs.
- **Kittitas Valley**: This area stretches from below the confluence of the Cle Elum River and into the Yakima Canyon above Umtanum Creek. There are fewer temperature and DO issues within this reach as compared to above and below this area; however, continuous monitoring in 2015 has shown temperatures rising above 21°C during the late afternoon and falling below the 5 mg/l DO during the night. Most previous grab sampling campaigns have missed these extremes.
- **Yakima Canyon and Selah Reach**: This area extends from Umtanum Creek downstream to the confluence of the Naches River. Sampling in 1998, 2001 and 2015 all show temperatures above the 21°C threshold and pH has also been an issue in this area. This reach contains the Roza Dam, which many studies have identified as a critical reach for salmonid migration.
- **Naches River to Sunnyside Diversion:** This area experiences slightly better water quality than the reach upstream of it; however, temperature has still been found to exceed the 21°C criteria.
- **Wapato to Prosser:** Both the USGS eutrophication study (Wise et al., 2009) and the 2015 survey conducted for this review found extremely adverse water quality in this reach, especially given it has been labeled at crucial for salmonid migration. Mid-day temperatures were consistently above 21°C with the temperatures well above 25°C in the downstream areas which is considered lethal for salmonids. This reach contains the start of the area of concern for this project due to the large quantity of water diversions pull out of this reach.
- **Prosser to Richland:** This area continues to have deteriorating water quality the farther downstream the river progresses with temperature being the largest issue. Below the Prosser Dam, only fall Chinook are known to spawn in the area, and all other migratory fish only

need to pass through these waters. Therefore, remedial efforts are focused on diminishing the temperature barrier during the appropriate times and released pulses of water from the Reclamation project during mid-summer cool weather have been hypothesized to have some impact on water temperatures and might help trigger a burst of migration (Pickett, 2016).

In the lower Yakima River, macrophyte growth is dominated by water stargrass (*Heteranthera dubia*) and can cause substantial diel fluctuations in DO and pH. Stargrass became a concern in the lower Yakima in the late 1990s as improvements in water clarity allowed more sunlight to pass through the water column and enhance plant growth (Appel et al., 2011). Stargrass consumes oxygen during the night hours, leading to a daily minimum in the early hours of the morning. Stargrass also increases pH through plant respiration and photosynthesis, causing daily fluctuations that may stress aquatic organisms. Although a statistical relationship between stargrass abundance and water depth or velocity was not significant, the USGS found that in the Kiona reach from 2005 to 2007, macrophyte biomass was consistently lower and less variable where depths were greater than 8 ft and velocities greater than 1.8 ft/sec (Wise et al., 2009). Given these interdependencies between stargrass and water quality, it is possible that even if reservoir releases or different management options are able to lower the temperature of the water in the lower Yakima, pH and DO may still present a problem for fish migration. It will be useful to understand how coupled water quality is in these lower reaches to stargrass growth, weather patterns and pulsed flows. It is possible that different flow management options may improve water quality through not only lowering water temperatures and increasing flow rates, but in diminishing the abundance of large macrophytes such as stargrass.

Overall, results and conclusions across the different water quality studies along the Yakima River all emphasize the deteriorating water quality in the lower Yakima River south of Parker. Water quality in the lower Yakima varies substantially in response to seasonal weather patterns, water quality operations and macrophyte growth. It will be important to consider not only the impacts of these drivers on water temperature, but also on dissolved oxygen levels in the river. Both constituents impact salmonid health and migration ability.

2.3 Fish Habitat Studies

In addition to investigating water quality along the Yakima River, a handful of studies have looked at what areas of the Yakima River are better suited for the migratory patterns of salmon. For instance, a study conducted at the University of Washington tagged 19 adult spring chinook salmon in the Yakima River and followed their migratory patterns while monitoring the ambient water temperature and fish internal temperature (Berman & Quinn, 1991). Results indicated that all of the salmon used the Yakima River Canyon located between RM 117 and RM 140 as holding habitat until spawning time. Yakima River Canyon provides many deep pools, large quantities of riparian vegetation for shading, a number of side channels with cooler waters and abundant topographic shading therefore providing holding habitat for adult salmon. In August, as spawning time approached, the fish moved to their spawning sites located both above and below the Roza Diversion Dam (RM 130). It was estimated that ten fish spawned from RM 164.6 to 202.5, four fish spawned from RM 124.8 to 126 and five fish spawned from RM 107 to 116. Over the course of the fish migration, Yakima River water ranged from 10°C on June 1st to approximately 16°C by August 30th at RM 183 and from approximately 13°C to 16°C at RM 140.4. Around August 31st, there was no measurable difference in water temperature between RM 140.4 and 183.

A similar study was conducted in 2019, where 60 adult sockeye salmon were tagged and monitored on the Yakima River from June through October (Kock et al., 2020). Results showed that water temperatures exceeded 20°C from mid-June to mid-September and only one tagged fish migrated upstream to Roza Dam. All other fish did not migrate upstream until the end of September when water temperatures were lower. Additionally, this study investigated whether or not the tagged fish appeared to spend time at known cool-water input areas or thermal refuges. Interestingly, most fish spent less than 30 minutes at any given site, indicating the fish were attempting to actively migrate past the sites rather than spend long periods of time in the thermal refuges.

In 2017, the Yakima System Operations Advisory Committee (SOAC) investigated the impact of flowrate and water temperatures on adult sockeye upmigration through the lower Yakima River to Roza Dam (SOAC, 2017). The analysis looked at 2013-2016 and found that the majority of fish passage events coincided with a daily minimum stream temperature at or below 68°F (20°C). They also investigated the impact of flowrate on fish passage to Roza Dam and no clear trends were found.

In addition to looking at factors that impact upmigration of adult salmon on the Yakima River, it is important to recognize the factors that may impact juvenile salmon migration back to the ocean. The rate of juvenile salmonid survival in the lower Yakima River is alarmingly low with predation by both fish and birds being largely responsible for the survival rate (Geoffrey A. McMichael, 2017). Interestingly, factors such as the increased clarity in the lower Yakima River over the past 20 years has led to large blooms of stargrass which are known to lower DO and increase pH. Predatory fish, such as walleye and smallmouth bass are more likely to tolerate these adverse water quality conditions than salmonids, increasing the predatory fish populations (Geoffrey A. McMichael, 2017). Increased clarity also means decreased turbidity, and research has shown a positive correlation between juvenile salmonid migration survival and turbidity. Predation has also been shown to be lower in more turbid waters, likely due to the increase in reactive distance that predatory species such as smallmouth bass have in turbid waters. McMichael (2017) goes so far as to suggest that pulse flows at the right time might be able to curb the reproductive success of these predatory fish or increase turbidity thus decreasing successful predation. Pulsed flows also have the possibility to lower water temperature downstream which might decrease predation rates as fish are poikilotherms, which means water temperature drives their metabolism. When McMichael et al. (G. A. McMichael et al., 1999) modeled how predation rates would change in the lower Yakima River as water temperatures dropped from 13.2°C to 11.2°C during the month of May, he found that predation rates were reduced by 23%. Therefore, it is possible that pulsed releases of water from upstream reservoirs might not only enhance upstream adult salmon migration, but they might help juvenile salmonid survival as well as they migrate back out to the ocean.

3 Pulsed Flows and Water Quality

Very few studies have looked at the direct impact of reservoir releases on downstream water temperature or dissolved oxygen concentrations. A study conducted in the early 1990s in France investigated the impact of summer water releases from dams on downstream water temperature and quality over a 200 km reach (Malatre & Gosse, 1995). In this study they monitored the impact of reservoir releases on downstream water quality from two different types of reservoirs: (1) a deep reservoir that is thermally stratified in the summer (maximum depth = 49 m) with a deep outlet and

(2) two shallower reservoirs that undergo minimal summer thermal stratification (maximum depths = 20 m) and have outlets closer to the surface. The deeper reservoir maximum degree of stratification occurs in July and August where the difference between the surface (25°C) and bottom (10°C) of the lake can reach 15°C. During a ten day period of increasing water releases from 6 to 26 m^3/sec, temperature, dissolved oxygen, and other water quality parameters were measured up to 200 km downstream of the releases.

Following releases from the deeper reservoir, a cooling impact was observed at 25 km downstream (10°C change in temperature) and still at 100 km downstream (2-3°C change in temperature). Given these temperature decreases, they estimated a 1°C decrease in river water temperature 200 km from the dam, although these samples were not available. The shallow reservoirs with outlet temperatures 3°C above river water temperatures were found to increase river water temperature with a 1-1.5°C impact 30 km downstream and a negligible impact 100 km downstream. Water releases from the shallow reservoirs were found to have a negative impact on downstream dissolved oxygen with DO levels decreasing from 6.8 to 3.6 mg/l approximately 25 km downstream primarily due to the resuspension and submersion of riverbanks and the draining of oxidizable organic matter. The drop in DO was negligible 100km downstream.

There are a few known studies that have looked at the impact of reservoir releases on stream temperatures on the Yakima River: one study that used a modeling approach (J. Vaccaro, 1986) and one study that looked at field data (Reclamation & Ecology, 2014). Vaccaro (1986) used a Lagrangian temperature model (Jobson, 1980) of the entire Yakima mainstem to show the impact of changes in reservoir outflow temperatures on downstream temperatures. He found that during the irrigation season a 4°C increase in reservoir outflow temperature at all five reservoirs resulted in a 1°C increase in water temperatures at Umtanum but only a 0.01°C in water temperature at Prosser. However, water management operations during the model simulations were maintained and Vaccaro did not investigate whether an increase in flow rate might also impact downstream water temperatures.

In 2020, pulsed reservoir releases from Bumping and Rimrock reservoirs were used to lower water temperatures in the lower Yakima River with the intention of aiding fish migration. Figure 2 shows two pulsed releases from Rimrock in April at the start of irrigation season. The first release ramped up outflow over a five day period from approximately 300 cfs to 1700 cfs which resulted in streamflow temperatures decreasing at Kiona by almost 12 degrees Fahrenheit. After the pulse release, stream temperature took 3-4 days to rebound back to their original temperature. The second release had similar impacts on streamflow temperature, although the release was smaller with an increase of around 850 cfs and thus a smaller decrease in temperature was observed at Kiona of around 8.5 degrees Fahrenheit.

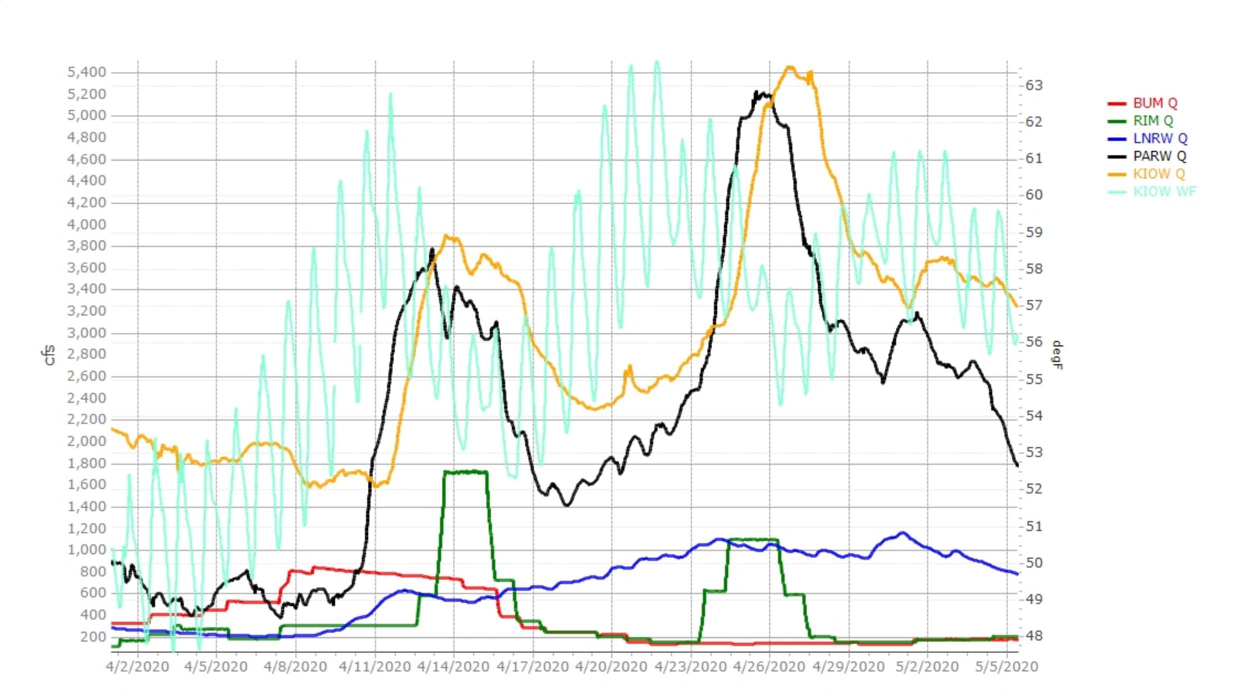

Figure 2. Reservoir releases from Bumping (BUM; red) and Rimrock (RIM; green) reservoirs and their relation to flowrate (KIOW Q; gold) and stream temperature (KIOW WF; light blue) at Kiona. Flowrates at Parker (PARW Q; black line) and the Little Naches River near Nile (LNRW Q; dark blue line) are provided for reference. Flowrates are in cubic feet per second (left y-axis) and temperature is in degree Fahrenheit (right y-axis).

4 Yakima River Models and Available Data

4.1 Data

The Yakima River Basin is a well-studied area and many long-term data sources are available. There are four Ecology water quality monitoring stations located at Cle Elum, Umtanum, Nob Hill and Kiona and four USGS flow gages located at Umtanum, Union Gap, Mabton and Kiona (Table 1). In addition, there are 17 Reclamation gages located along Yakima River and at the Reclamation owned dams (Table 1). Depending on the gage, these monitoring stations provide hourly to daily information on parameters like water surface elevation, inflow/outflow rates, water temperature and some meteorological data.

In addition to these continuous monitoring stations, there are a few other sampling campaigns that might provide useful data for this study. For instance, water quality data was collected monthly from Cle Elum Reservoir by Reclamation from September 2003 to October 2005 (Reclamation, 2007b). There were three sample sites in Cle Elum: (1) an uplake site, (2) a site at the deepest point midlake, and (3) a site downlake near the dam. In addition, there was a site at the inflow waters and the outflow waters. At each site water column profiles were collected from the surface of the water to the bottom at 1 or 5m increments depending on depth. Sampled characteristics included water temperature, dissolved oxygen, specific conductance, and pH. Secchi depth was also recorded. Additionally, composite samples for chlorophyll a, zooplankton and phytoplankton were collected at all lake sites in the 0-10m, 10-20m and 20-30m depth ranges and at 1m. Discrete water samples were also collected at 1m below the surface and 0.5m above the bottom for total phosphorus, orthophosphorus, dissolved nitrate-nitrite nitrogen, ammonia nitrogen, total Kjeldahl nitrogen, total organic carbon, and dissolved organic carbon.

The Benton Conservation District also has a few ongoing studies in the Lower Yakima that may be complementary to this study. Temperature has been monitored in the Yakima Delta since 2012 and data from 2016 onwards can be found at the Environmental Information Management System (EIM; https://apps.ecology.wa.gov/eim/search/default.aspx) under study IDs IAA_C1600150 and IAA_C1800180. In addition, temperature and DO data from multiple projects involving water stargrass (vegetation that severely depletes DO during baseflow conditions) and cold water refuge work can be found at the National Water Information System (NWIS) database. A list of sites with water quality data in the NWIS is listed below:

- Kiona - https://waterdata.usgs.gov/nwis/uv?site_no=12510500
- Prosser - https://waterdata.usgs.gov/wa/nwis/uv?site_no=12509489
- Van Giesen - https://waterdata.usgs.gov/nwis/uv?site_no=12511800

Additional temperature data for streams in the Yakima River Basin can be found at the NorWeST stream temperature database. This database hosts stream temperature data collected from many different agencies and projects conducted in the American West. Data can be downloaded here for the 'Upper Columbia-Yakima' processing unit: https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST/StreamTemperatureDataSummaries.shtml. In addition to these point measurements, forward-looking infrared (FLIR) thermal datasets are also available for the mainstem of the Yakima in 1997 and 2020 that could be used for model development.

Table 1. Continuous flow and water quality monitoring stations in the Yakima River Basin

Station ID	Station Name	Variables Measured
Ecology ambient monitoring stations		
39A090	Yakima River near Cle Elum	ST, pH, SC, DO
39A055	Yakima River @ Umtanum Cr Footbridge	ST, pH, SC, DO
37A205	Yakima River @ Nob Hill	ST, pH, SC, DO
37A090	Yakima River @ Kiona	ST, pH, SC, DO
USGS gages		
12484500	Yakima River at Umtanum, WA	Q, H
12500450	Yakima River above Ahtanum Creek at Union Gap, WA	Q, H
12508990	Yakima River at Mabton, WA	Q, H
12510500	Yakima River at Kiona, WA	Q, H, ST, SC, DO, pH, Turb, N
Reclamation Hydromet river gages		
EASW	Yakima River at Easton	Q, H
YUMW	Yakima River at Cle Elum	Q, H, ST
YRWW	Yakima River near Horlick	Q, H, ST
UMTW	Yakima River near Umtanum	Q, H
RBDW	Yakima River below Roza Dam	Q, H
PARW	Yakima River near Parker	Q, H, ST
YRPW	Yakima River near Prosser	Q, H, AT, ST
KIOW	Yakima River at Kiona	Q, H
NACW	Naches River near Naches	Q, H, ST
CLFW	Naches River near Cliffdell	Q,H, AT, ST
YRCW	Yakima River at Crystal Springs	Q, H
YGVW	Yakima River at Euclid Rd. Br. near Grandview	Q, H
ELNW	Yakima River near Ellensburg	Q, H
Reclamation Hydromet reservoir gages		
CLE	Lake Cle Elum	RS, FE, H, AT, P, Q, I
KEE	Keechelus Reservoir	RS, FE, H, AT, P, Q, SD, SWE
KAC	Kachess Reservoir	RS, FE, H, AT, P, Q, I
RIM	Rimrock Reservoir	RS, FE, H, AT, P, Q, I, AT
BUM	Bumping Reservoir	RS, FE, H, AT, P, Q, I

*Q=discharge, H = gage height, AT. = air temperature, ST = stream temperature, RS = reservoir storage, FE = forebay elevation, P = precipitation, SD = snow depth, SWE = snow water equivalent, I = running average inflow, SC = specific conductance, DO = dissolved oxygen, Turb = turbidity, N = nitrate + nitrite

4.2 Models

There are a number of hydrology, water management and water quality models within the Yakima River Basin. All of the available models were investigated for their relevance to this project and applicability to modeling the impact of water management operations on downstream water quality in the Yakima River Basin. The models and their references are briefly described below.

Hydrology Models

- Precipitation-Runoff Modeling System (PRMS; Leavesley et al., 1983) model of four upper subbasins in the Yakima River Basin: Naches, Upper Yakima, Toppenish/Satus, and the Yakima Canyon (Mastin & Vaccaro, 2002). This model has been used to estimate recharge to the Yakima River Basin aquifer from 1950-1998 (Vaccaro J.J., and Olsen, 2007).
- Deep Percolation Model (DPM; Vaccaro, 2007) of 17 sub-areas within the Yakima River Basin that all have extensive human activities, principally agriculture and urban areas. Most of these areas were along the mainstem of the Yakima below the confluence of the Naches River and extended from the city of Yakima to the city of Richland. This model was used to calculate recharge from 1950-2003 as part of the same study that used PRMS to calculate recharge in the upland, forested areas (Vaccaro J.J., and Olsen, 2007).
- River 2D hydrodynamic model developed by the University of Alberta for fish habitat evaluation studies along five floodplain reaches of the Yakima River (Bovee et al., 2008). This model was used to calculate velocities, depths and Froude values for a range of flows in these reaches and estimate fish habitat by life stage.
- SWAT (Soil Water Assessment Tool) was used to simulate daily streamflow from 1983-2010 in the Yakima River Basin. The model used two different reservoir management models (the SWAT built-in reservoir management scheme and the RiverWare operations model developed by Reclamation 2012) of the five upstream reservoirs (Cle Elum, Kachess, Keechelus, Bumping and Rimrock. Reservoir management was coupled to irrigation schemes in SWAT where irrigation water was withdrawn from either reservoirs and streams or groundwater.

Water Management Models

- Yakima Project RiverWare model that covers the five major reservoirs in the Basin, operation of these reservoirs, irrigation releases, flow requirements, groundwater return flows on a daily timestep from 1925-2018 (Bovee et al., 2008). This model has been updated recently and runs the current level of demand for the simulated time period.
- HEC-RAS 1-D model developed by the U.S. Army Corps of Engineers to provide flow depth, top width and cross-section averaged values of velocity of select reaches along the Yakima and Naches Rivers (Reclamation, 2007a).

Water Quality Models

- A SNTEMP model was used to model temperature during 2005-2006 in the Yakima River from Roza Diversion Dam to Prosser Dam (Voss et al., 2008). SNTEMP is a steady-state model that calculates daily average temperatures.
- A SNTEMP model was used to model the impact of removing the diversion points of the Kennewick and Columbia irrigation districts from the lower Yakima River to a pumping plant on the Columbia River (Thomas Payne & Associates & Monk, 2001). The model was applied from the Prosser Diversion Dam to the city of West Richland and calibrated with data from 1997 and 2000. Then two different years were used (1992 – drought year and 2000 – average year) to simulate the impacts of the proposed diversion change on Yakima River water temperatures.
- A CE-QUAL-W2 model was developed of Lake Kachess and Lake Keechelus and then coupled to a fish bioenergetics model to explore management strategies related to improving kokanee salmon habitat (Berger & Wells, 2017). The models simulate the period from January 1, 2014 to November 25, 2016. The models simulate flow, water level, temperature, dissolved oxygen, nutrients and three zooplankton groups.
- A QUAL2Kw model of the lower Yakima River was proposed analyze eutrophication issues (Ecology, 2017). The proposed modeled area is 112 miles long (Figure 2 – green line), from Selah Gap above the Naches River to a few miles upstream of the Yakima River's confluence with the Columbia near Richland. Currently, the model is fully developed from Prosser to Richland with the upper portions still in development. Model development in the upper parts of this reach from Union Gap to Prosser are difficult due to the lack of appropriate calibration data and the hundreds of diffuse irrigation return flows that this part of the river receives. The QUAL2Kw model can now simulate non-steady, non-uniform flow using kinematic wave flow routing which will allow for a continuous simulation of the river with changing channel velocity and depth in response to changes in flow. This model will simulate continuous changes in temperature, nutrients, algal/macrophyte biomass and DO including diel variations. It is a one dimensional model, which is typically appropriate for most riverine systems.
- A QUAL2Kw model of the upper Naches River (Figure 2 – dark red line), was developed to simulate temperatures for the total maximum daily load (TMDL) study conducted by the Department of Ecology (Ecology) in 2004. Ecology's Shade model was also used to estimate effective shade all the upper Naches River, which was then averaged over 1000m intervals for input into the QUAL2Kw model. This model was run in a steady-flow condition which assumes that flow remains constant over a 1 day period. However, climate variables are allowed to vary diurnally. It appears this model only simulated a one week period in 2003 and a one week period in 2004 (the hottest weeks of the year). This model does not simulate dissolved oxygen dynamics.
- A QUAL2Kw model of the lower Naches and Tieton Rivers (Figure 2 – orange line), was developed to simulate temperatures for the TMDL study conducted by the Department of Ecology (Ecology) in 2015. Ecology's Shade model was also used to estimate effective shade along all modeled river reaches, which was then averaged over 1000m intervals for input into

the QUAL2Kw model. This model was run dynamically (similar to the lower Yakima River QUAL2Kw model), where flow was not assumed to be steady over the course of a day. Only a temperature model. Does not simulate eutrophication or DO.

- A QUAL2Kw model of Taneum Creek and upper Naneum Creek was developed by Ecology to simulate temperatures for the TMDL study in 2004-2005. Ecology's Shade model was also used to estimate effective shade along all river reaches, which was then averaged over 1000m intervals for input into the QUAL2Kw model. This model was run in a steady-flow condition (similar to the upper Naches River model) which assumes that flow remains constant over a 1 day period. However, climate variables are allowed to vary diurnally.

Overall, there are a few models available that will help in the development of a water management tool to help inform decisions related to instream flows and salmonid migration. The most likely candidate for a river water quality model is QUAL2Kw as there is already a model constructed of parts of the lower Yakima and a fair number of the dominant branches into the Yakima. Currently, Ecology is working on extending the model to the Naches River junction and this project might be able to help provide adequate calibration data to support this development. Dynamics from the Keechelus and Kachess Reservoirs most likely do not need to be incorporated as there is an Ecology stream continuous stream monitoring gage downstream of these reservoirs right before the confluence with the Cle Elum River and the Yakima River. By combining river water quality models and using the RiverWare water management model that is already developed for this area to inform realistic water management scenarios, it could be possible to better understand the interwoven dynamics between weather, water management practices and downstream river temperatures.

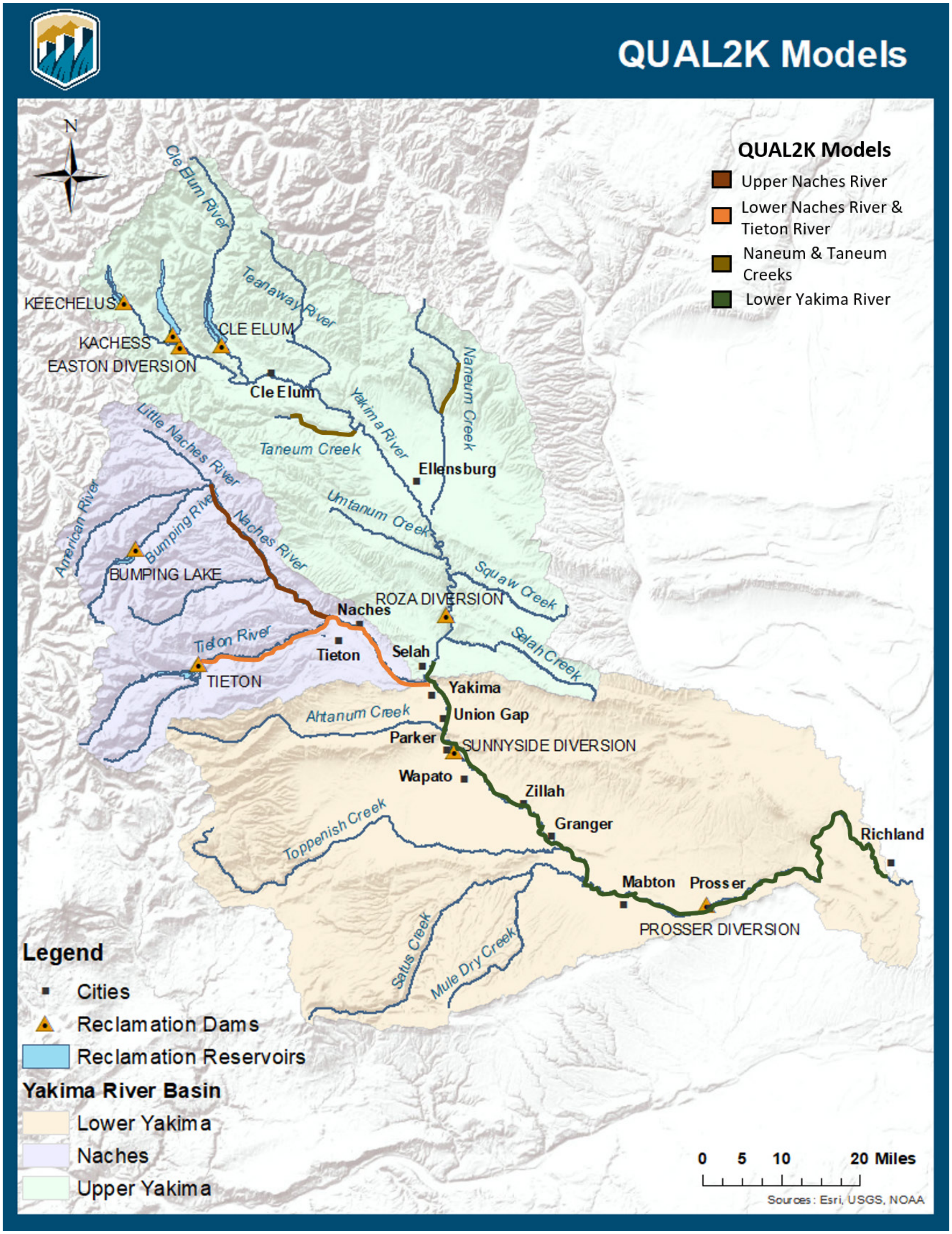

Figure 3. Map of the developed QUAL2KW water quality models in the Yakima River Basin.

5 Conclusions

The overall objective of this project is to develop a tool water managers can use to better understand when they can release water from upstream reservoirs or use other management techniques for the benefit of salmonid migration downstream. After a thorough review of the literature, data and models available from previous studies in the Yakima River Basin, it is apparent that this is a well-studied area. This tool will likely use two different types of models, a river water quality model and a water operations model. For instance, these models might look like:

1. A river water quality model of the entire Yakima River from Cle Elum Reservoir down to the Columbia confluence. This model will likely need to be linked to a model of the Tieton and Naches branches of the Yakima River.
2. A water management model detailing instream flow requirements, irrigation requirements and reservoir operations.

It is possible that pulsed releases of cold reservoir water (Reclamation & Ecology, 2014) combined with other management practices could lower Yakima River water temperature at specific places downstream so as to remove the thermal barrier and allow for salmonid migration upstream. For these releases to be effective, the dam outlet needs to be located well below the thermocline and the lake strongly stratified. Given the reservoir depth profiles and outlet dynamics, it is probable that releases from Cle Elum Reservoir and Rimrock Reservoir would have the most influence on downstream temperatures. This was verified for Cle Elum Reservoir three times in 2014 and 2015, when Reclamation released a pulse of water from Cle Elum which was thought to trigger a bout of salmonid migration downstream by lowering the water temperatures. Releases from Rim Rock Reservoir might be even more beneficial as the travel times from Rim Rock to the lower Yakima River are much shorter than the travel times from Cle Elum Reservoir to the lower Yakima River.

In order to capture the dynamics of reservoir releases on downstream water quality, it is possible, although not likely, that a reservoir water quality model will need to be developed. In order to model the impact of different reservoir releases on downstream water, the temperature of the water released from the reservoirs must be known. Ideally, historic measured temperatures can be used as input into the river water quality model assuming consistent trends with climate, season, and water management operations.

Once all of the models are developed, it would be beneficial to run many simulations combining different flow and weather years with different durations and magnitudes of reservoir releases and diversion schemes. The results of these model simulations will help to better understand when cool-water reservoir releases or other management practices might trigger salmonid migration upstream. In addition to model simulations, a rigorous statistical analysis of weather variables and stream temperature would be beneficial to better understand how weather patterns and stream temperature are coupled. Following these simulations and analyses, a user-friendly forecast tool will be created to help water managers enhance fish migration in the Yakima River Basin. This forecast tool will likely take the form of a web-based dashboard where the user can input the upcoming weather, current flow conditions and different water management operations and the dashboard will output graphs and tables of the projected temperature and dissolved oxygen trends at points of interest downstream.

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The Development of a Temperature and Dissolved Oxygen Water Quality Model to Inform Water Management Options to Benefit Yakima River Salmon Migration

Appendix A

Proposal ID: 22045

Submitted By: Kristin Marie Mikkelson, kmikkelson@usbr.gov

Bureau of Reclamation
Research and Development Office
Science and Technology Program

Contents

SECTION I - Proposal Summary Information

Proposal Description

The Yakima River, in Washington State, is a tributary of the Columbia River. In the headwaters upstream of irrigation diversions andreturns the Yakima River provides high quality habitat for Sockeye, Coho, and Chinook Salmon and Mid-Columbia steelhead. However, high water temperature and low dissolved oxygen levels in the lower Yakima River create migration barriers that may become lethal for migrating salmonids or create a migratory block. The lower Yakima River is the only migratory pathway in the Yakima Basin for juvenile salmonids (a family of fish that spawn in fresh water but spend most of the lives in the ocean) migratingdownstream to the ocean and adults returning upstream to their natal streams to spawn.

The goal of this project is to develop a predictive water quality model that can advise water managers when flow management optionscan be used to change or maintain water quality conditions downstream and enhance salmon migration and survival. Specifically, the water quality model and results will be integrated into a user-friendly, water management tool that will help managers determine when cold upstream releases of reservoir water or altering diversions could benefit fish migration in the lower Yakima. The tool will be in the form of a web-based dashboard, where the user can indicate current flow conditions, future weather patterns and different water management options with output showing temperature and dissolved oxygen patterns at different locations in the lower Yakima River. Use of the model and tool will be disseminated to water managers in the Columbia-Pacific Northwest Region through a workshop and targeted outreach. In addition, findings will be disseminated to the scientific community through publication in a peer-reviewed scientific journal.

This project is a collaboration with the Columbia-Pacific Northwest Region including colleagues from the CPN Regional Office Water Management group, the Columbia Cascade Area Office, and the Yakima Field Office. In addition, the Washington Department of Ecology is an identified collaborator who has already provided relevant data and models from the Yakima River Basin. This project is also receiving funding support from the Yakima Basin Integrated Plan and general technical support from the Yakima Nation, NOAA fisheries, Washington State Department of Fish and Wildlife and the local Irrigation Districts. Other partners include the United States Geological Survey (USGS) and the Benton Conservation District who will provide in-kind data, reports, and generaltechnical assistance.

Performance Period

2022 - 2024

Tags

environmental flows, fish migration, migration barriers, reservoir operations, water quality

Benefiting Regions

Interior Region 5 & 6: Missouri Basin & Arkansas Rio-Grande Texas Gulf	Interior Region 7: Upper Colorado Basin	Interior Region 8: Lower Colorado Basin	Interior Region 9: Columbia Pacific Northwest	Interior Region 10: California Great Basin	Denver Office
N	N	N	Y	Y	N

Field-Based Research Location

The field instrumentation and data collection will take place in the Yakima Basin.

Project Type

Conducting

Conducting Type

Development

Technology Readiness Level (TRL)

TRL-4 Component and/or system validation in laboratory environment

Technology Transfer/ Intellectual Property

Proposal discloses IP that should be or is protected through its narration (unlikely) No

Principal Investigator intends to use IP provided by partner that should be or is protected No Principal Investigator intends to develop IP (with or without partner) that they anticipate will need protection No

Security Sensitive Information

No

Regional Director Need

Yes

This proposal is in direct response to the Columbia-Pacific Northwest Region's need to develop a temperature and dissolved oxygen model of the Yakima River to inform water management options and thus benefit salmonid migration. Coordination has occurred between Richard Visser who is at the area office and Jennifer Johnson, a regional coordinator, and both have contributed to the development of this proposal.

Department Priorities and Reclamation Goals

Yes

Research Area - Research Category - Research Need

Research Area: Water Operations and Planning

Research Category: Water Operations Models and Decision Support Systems

Research Need: 1. Develop approaches and tools to support real-time, collaborative, multi-objective water management decision making.

SSIP Description: This proposal directly addresses the SSIP need described above. The main objective of this proposal it to develop a water management tool that can inform reservoir releases and diversions within the Yakima River Basin to help eliminate migration barriers for anadromous salmon. This tool will be developed through the integration of multiple river water quality models and a basin-wide operations model, which is also a SSIP need.

Prize Competition

Prize Title: None

Prize Solution: N/A-Not Applicable Prize Competition Description: None

SECTION II - Research Strategy

Research Question

The Yakima River Basin is located entirely in the state of Washington and drains an area of approximately 6,155 square miles. Within this heavily irrigated basin lies the Yakima River, which flows 214 miles from the outlet of Keechelus Lake in the Cascades, to its mouth downstream from Horn Rapids Diversion Dam near Richland. The river then joins the Columbia River which flows west into the ocean. The Yakima River Basin is divided up into three subbasins: (1) upper Yakima Basin, (2) lower Yakima Basin, and (3) Naches River Basin. The upper Yakima Basin contains three Reclamation reservoirs that reside in the steeper headwaters of the basin before releases flow down into the lower, flatter elevations. The Naches River Basin contains two storage reservoirs and is a large contributor of streamflow to the Yakima with steeper, more mountainous reaches than the other two basins. The lower Yakima River Basin is separated from the upper Basin by a natural break in Ahtanum Ridge called Union Gap and is dominated by irrigated agriculture while containing more urban areas than the other two basins.

Historically, salmon migrated from the ocean up the Columbia River and into the Yakima River to spawn; however, with the construction of multiple dams along the Yakima, altered instream flows, and reduced instream and floodplain habitat, salmon populations have been substantially diminished or extirpated in the Yakima Basin over the past 100 years. These changes to the riverine ecosystem have contributed to an altered thermal regime within the Yakima River that has made it difficult for migratory salmonids to survive and spawn. In the middle of summer, water temperatures in the lower Yakima River have been shown to surpass 24°C (75°F), preventing the migrationof many salmonids. This phenomenon is known as a 'thermal block' where migration ceases when river temperatures reach 18-24°C (64-75°F) depending on the river (ex. Appel et al., 2011; Macdonald et al., 2000).

Not only have agriculture and urban areas impacted salmonid habitats but projected climate change in the Yakima River Basin is anticipated to affect river temperatures and thus fish habitat. Hatten et al. (2014) linked a watershed model, a river operations model, a two-dimensional hydrodynamic model and two climate change scenarios to project how an increase in temperature might impact salmonid habitats on the Yakima River. Results indicated that 75% of the 28 different discharge-habitat responses exhibited a decrease in habitat quantity under scenarios with a 1-2°C increase in mean air temperature. Given the current temperature regimes within the Yakima River and the projected increase in future air temperatures and thus water temperatures, it is imperative to understand how different water management practices might alleviate thermal blocks and enhance salmonid survival.

To this end, the main objective and research question of this proposal is:

- How can different water management techniques be used to enhance salmonid migration and survival in the lower Yakima River whenweather and flow conditions create migration barriers?

To accomplish this objective and answer this question, this project aims to develop a basin-wide river water quality model which will then be altered to run in a forecast mode. The predictive water quality model will then be run using an ensemble of different initial conditions, weather patterns and water management options. Water management scenarios will be determined from the use of a developed water management operations model as the Yakima Basin is a heavily managed system, which contains numerous Reclamation-owned dams anda multitude of regulated irrigation diversions.

Results from these runs will be integrated into a user-friendly, web-based dashboard which will give water managers a tool to help inform when various water management options might help enhance salmon migration.

Research Need

Historically, salmon migrated from the ocean up the Columbia River to the upper Yakima River to spawn, however; with a changing hydrograph and water quality regime and the construction of multiple dams, salmonid populations have been diminishing in the Yakima Basin over the past 100 years. Reclamation has invested significant effort into developing migratory pathways through this riverine system,such as the installation of fish ladders and fish screens at many of the diversion dams and improving instream flows when possible.

Unfortunately, these improvements alone are not always enough to ensure the survival of migratory fish. Certain salmon species, such as summer chinook and sockeye (Oncorhynchus nerka) have less flexible migration patterns and rely on migration during the hot and dry summer months. For instance, adult sockeye salmon pass McNary Dam during June-August each year and then spawn in the upper Yakima River Basin during September-November (Matala et al., 2019). In the middle of summer, water temperatures in the lower Yakima River have been shown to surpass 24°C, preventing the migration of these salmonid species. This phenomenon is known as a 'thermal block' where migration is blocked when river temperatures reach 18-24°C depending on the river (ex. Appel et al., 2011; Macdonald et al., 2000).

Given the current temperature regimes within the Yakima River and the projected increase in future air temperatures and thus reservoir andriver temperatures, it is imperative to understand how different water management practices might alleviate thermal blocks and benefit salmonid migration before these anadromous fish are gone from the basin permanently.

In 2019 and 2020, water managers have attempted to use timed releases of cool upstream reservoir water to help salmonid migration at certain points during the summer and have observed mixed results. It is uncertain how factors such as weather, the volume and timing ofwater releases, river conditions, and stage all combine to impact downstream water temperature and dissolved oxygen levels.

Unfortunately, water managers have a hard time allocating enough water to these pulse flows, as water within the Yakima Basin is highly regulated and only available in limited quantities. It is difficult for them to justify these releases when results are so uncertain. Water reliability is extremely important to downstream water users and it is imperative that these pulsed environmental flows are effective. This project will be able to model these different factors and water management scenarios, to help inform water managers as to when it is mostbeneficial to use specific management practices to enhance salmon migration and survival.

Once completed, these water management tools can be modified and applied to any basin where high water temperatures or low dissolved oxygen levels are of concern. For example, the Klamath River Basin in the California-Great Basin Region is also home to fish who migrate from the ocean to spawning grounds. Previous studies have shown elevated water temperatures in this basin are a concern for migratory fish and water managers in the basin are looking in to different water management options to improve water quality (Romberger& Gwozdz, 2018).

Previous Work

This proposal stems out of a scoping study that was awarded during the last S&T cycle. After a thorough literature, data and model review (Mikkelson et al., 2021) it was determined that investigating the impact of different water management operations using a basin-wide river water quality model could help inform water management decisions in the Yakima River Basin.

There are two finished QUAL2K models in the Naches River Basin. QUAL2K is a one-dimensional river water quality model that represents well-mixed channels both vertically and laterally and will be used for this project. A QUAL2K model of the upper Naches Riverwas developed to simulate temperatures for a total maximum daily load study conducted by the Department of Ecology (Ecology; Ecology,2008). This model simulates flow dynamics on the Naches River from the junction of Bumping River to the junction of the Tieton River.

Another QUAL2K model was developed by Ecology that simulates flow dynamics on the Tieton River from Rimrock reservoir down to the junction with the Yakima River at Selah Gap (Ecology, 2018). Both models only simulate temperature dynamics and will need to be updated to simulate dissolved oxygen. A QUAL2K model of the lower Yakima River from the junction of the Naches River down to Richland is in development by Ecology with the goal of identifying data gaps to sufficiently model this branch of the system (Ecology, 2017). This model will simulate both temperature and dissolved oxygen and will be completed during FY22 and validated with field data collected as part of this project during FY23. After combining these three water quality models, the only portion of the Yakima River leftto model is the upper Yakima from Kachess Reservoir down to Selah Gap. A continuous, calibration dataset was collected by Ecology during 2019 in the upper Yakima and will be used to calibrate this portion of the river.

Also available is a Reclamation RiverWare model developed over the entire Yakima project which covers the five major reservoirs in the Basin, operation of these reservoirs, irrigation releases, flow requirements, groundwater return flows on a daily timestep from 1925-2018. The model was recently overhauled by CPN Water Management staff and documentation is still in draft form. This operations model willbe used to develop the different water management scenarios that will be used as flow inputs for the river water quality model.

In addition to modeling river water quality and different water management scenarios, it is necessary to have a good understanding of fishdynamics and their habitat within the Yakima River. A study in the early 1990s tagged adult spring Chinook salmon and followed their migration habits (Berman & Quinn, 1991). They found salmon holding in habitat during the summer that was cooler than the mainstem flow of the river until spawning time when they moved upstream to spawn. Over the course of the migration, upper Yakima River water ranged from 10°C to 16°C.

Similar studies were conducted in 2019 and 2020, where adult sockeye salmon were tagged and monitored in the Yakima River (Kock et al., 2020, 2021). Results from both years indicate that when water temperatures were above 20 °C, few if any salmon migrated upstream to Roza Dam. In contrast, a study that tracked the migration passage of adult sockeye in the upper Yakima River (where there is rarely watertemperature issues) found that all the tagged fish were able to readily migrate upstream from Roza Dam to Cle Elum Dam (Kock et al., 2019).

In 2017, the Yakima System Operations Advisory Committee investigated the impact of flowrate and water temperatures on adult sockeyemigration through the lower Yakima River to Roza Dam (SOAC, 2017). The analysis found that the majority of fish passage events coincided with a daily minimum stream temperature at or below 20°C. They also investigated the impact of flowrate on fish passage to Roza Dam and no clear trends were found.

Benefits and Impacts

The benefit of this project will be enhanced salmonid migration and reduced water delivery interruptions. Water managers will not have to guess when a pulsed flow of water or change in diversion schedule might help alleviate downstream migration blocks. Instead, they will be able to use the dashboard or predictive model in real-time to input in the current conditions, future weather forecast and water management strategy and see what the modeled impact will be on downstream water quality. This will reduce the number of experimental releases of pulsed-flow and thus increase water delivery and reliability to downstream users. This type of data-based, decision management system would also be useful in any other basin regulating flows for instream and out of stream uses, such as the Klamath River Basin located in theCalifornia Great Basin region.

In addition, this project will help inform specific goals for future water storage projects. Currently, Cle Elum Reservoir, a reservoir located in the upper Yakima Basin, has approved a feasibility study for a pool raise to add 14,600 acre-feet of extra water storage to the upper Yakima River Basin (Reclamation & Ecology, 2014). The region has already installed new gates at Cle Elum and is working on shoreline protection with the expectation to complete the pool raise in a few years. The Cle Elum Pool Raise Project embraces the Yakima Basin Integrated Plan to restore aquatic functions and provide increased reliability of water resources in the Yakima Basin. Over time, other planned storage and conservation projects in the Yakima Basin will add water that will be available for fish migration needs. This project'smodeling will be able to provide an estimate of how much water needs to be stored and when it can be used to benefit downstream salmonid migration. These estimates will help inform how much water is needed for aquatic functions while maintaining and meeting downstream user water rights.

Facilitated Adoption

The results of this project include a calibrated, predictive water quality model of the Yakima River system and a user-friendly dashboard for fast, real-time forecasts as to how different water management options might alter downstream water quality. These tools will be disseminated to the local water managers, engineers and fisheries biologists who are making the water management decisions in the Yakima Basin. Water management decisions occur relatively rapidly and can occur on the order of 1-2 days. The Systems Operations Advisory Committee (SOAC) is responsible for making the water management operations decisions related to in-stream flows. The first step in making these decisions is getting all four members of the SOAC informed of the conditions and then a discussion ensues regardingwater management options. This is where using the water quality dashboard would be extremely beneficial and help inform the SOAC on how their water management alteration might impact downstream water temperature and dissolved oxygen. Ideally, the SOAC has at leasta day or two in advance notice before a new water management operation takes place so that they are able to line up the necessary staff to fully carry out the flow alteration. The dashboard would give up to a weeks notice on when flow and weather conditions might be conducive to a change in water management operations that could benefit salmonid migration.

To make sure that all water managers in the Yakima River Basin are aware of this dashboard and its capabilities, instruction on how to usethe model and dashboard will occur through a two day local workshop with hands-on technical guidance. A manual will detail how to use the predictive model and the web-based dashboard will contain its own set of use instructions. These results and deliverables will assist water managers in making data and science-based decisions regarding when it is most beneficial to alter water management practices to help migratory fish in the lower Yakima River.

Research Methodology

During the first year of this project, it will be necessary to obtain and update a few of the developed water quality models. As described inthe Past Work section, there are two models that are already developed and one that is in development. It will be necessary to update the Naches Branch water quality models to include DO dynamics and to also run dynamically as opposed to steady state. This involves the development of the primary productivity module which includes nutrient and carbon dynamics. We also have to verify that the flow and turbidity gages are calibrated as we will need to re-calibrate flow and turbidity during this year. Turbidity dynamics are also needed in theYakima River system to model light attenuation in the water column due to suspended solids. To do this, calibration data on the Naches branch will need to be collected during the irrigation season of FY22.

Additionally, to validate the lower Yakima water quality model that is in development, two gages that monitor flow rate and water qualitywill need to be installed and maintained during FY22. These two gages will be installed above and below Granger where all the water quality issues take place.

While field data is being collected, it will be possible to develop the QUAL2K model of the upper Yakima River. There is a sufficient calibration dataset for that portion of the system. This development will include formatting input data, calibration, validation, uncertaintyand sensitivity analyses and the evaluation of model results.

Once all the necessary branches of the Yakima River Basin have calibrated QUAL2K models, it will be necessary to merge these models into one basin-wide water quality model designed to simulate temperature and dissolved oxygen dynamics. In addition to the validation ofthis merged model, we will also be altering it to run in forecast mode so that the user can input a 7-10 day weather forecast and water management scenario (i.e., different flow inputs). Finally, the development and results of this predictive water quality model will be documented in a technical memorandum.

After the basin-wide predictive water quality model is developed, the team will determine the different weather patterns and events that will be modeled. These will be determined through a statistical analysis of past weather patterns on a 7-10 day scale. Water management scenarios will be developed by the CPN Water Management Modeling group through the use of their basin-wide RiverWare model. By using the RiverWare model, they will be able to outline various water management scenarios that might be beneficial to downstream waterquality while still abiding by the many rules and regulations present in the Yakima Basin. These water management scenarios will be coupled to the different weather patterns and various initial conditions and run through the calibrated basin-wide water quality model.

Results from these hundreds of runs will be compiled for use in a web-based, user-friendly dashboard. This dashboard will give the user theoption to specify the future weather forecast, the current flow, temperature and dissolved oxygen dynamics at certain parts of the river, and the water management option they want to employ. The dashboard will then output in graphical and tabular form how that water management option might impact downstream water temperature and dissolved oxygen at select points over a 7-10 day time period.

Following the development of this dashboard, the TSC will give a two day workshop detailing how to use the updated water quality modelin forecast mode and also how to use the dashboard. In addition, results from this project will be compiled and submitted to a peer- reviewed journal in order to inform the scientific community on how different water management options might impact downstream fish migration and habitat.

Research Strategy Tasks

Task Number	Task Name	FYB	FYE	Task Description
Task-0	Project Management ($15,840)	2022	2024	•Team meetings & updates •Manage budget & schedule •Quarterly reports
Task-1	Obtain & QA/QC lower Yakima model ($13,240)	2022	2023	•Site Visit •Obtain updated lower Yakima QUAL2K model •QA/QC on updated model
Task-2	Instrument & Collect FieldData ($51,048)	2022	2023	•Install and maintain 2 additional flow and water quality gages in the lower Yakima River for at least two irrigation seasons(March - October) • DO calibration dataset on the Naches Branch including DO andtemperature loggers Acquisition of sensors & contract with Ecology
Task-3	Develop QUAL2K model ofthe upper Yakima River ($26,624)	2022	2022	•Format, QA/QC input and calibration data Calibrate QUAL2K model •Validate model results with field data •Uncertainty & sensitivity analyses •Evaluate model results
Task-4	Update Naches Branch QUAL2K model ($15,360)	2023	2023	•Update Naches Branch model to include dissolved oxygen usingcontinuous data collected in Task 2.
Task-5	Develop merged river waterquality model ($40,232)	2023	2023	•Develop a QUAL2K model of the Yakima River system by mergingthe three models •Validate model •Uncertainty & sensitivity analyses •Evaluate model results •Write TM on model development and results •TSC peer review process •TSC 508 compliance & TM finalization
Task-6	Develop weather patternsand water management scenarios ($12,280)	2022	2023	•Develop flow inputs/water management scenarios from YakimaRiver system RiverWare model •Statistical analysis of historical 7-10 day weather patterns

Research Strategy Tasks (cont.,)

Task Number	Task Name	FYB	FYE	Task Description
Task-7	Develop predictive model &run all combinations of weather patterns and scenarios ($46,200)	2023	2024	•Alter the QUAL2K model so that the model runs in a forecast mode •Write detailed instruction manual for running model in forecast mode •TSC peer review process •TSC 508 compliance & manual finalization •Run all combinations of water management scenarios & weatherpatterns through calibrated water quality model •Evaluate impacts to downstream temperature and dissolved oxygenand compile results
Task-8	Develop user-friendly watermanagement tool ($39,840)	2024	2024	Develop web-based, water quality dashboard to display all modelcombinations & results on a real-time basis
Task-9	Model Workshop & Dashboard Outreach ($16,888)	2024	2024	•Workshop preparation •Local workshop & outreach to water managers detailing how to usethe QUAL2K model in forecast model & Dashboard
Task-10	Journal Publication ($16,320)	2024	2024	•Write a journal publication about model development and the impactdifferent water management actions can have on salmon migration •Submission & review process
Task-11	Project Closeout ($5,440)	2024	2024	•Closeout meeting with all Team members •S&T closeout process •Final file management & storage

SECTION III - Research Strategy - Key Persons

Key Person	Task Number	Email	Expertise	Responsibilities	Organization	Region
Lindsay Ann Bearup	3, 4, 5, 9, 10, 11	lbearup@usbr.gov	Lindsay is a hydrologic civil engineer in the Water Resources Engineering and Management Group. She has over 10 years of experience with hydrologic and water quality modeling, including modifications to the CE-QUAL-W2 program and bug fixes provided to the developers. Lindsay also has experience using water quality models with operations models in the Three Lakes of the Colorado-Big Thompson project.	Lindsay will assist in the development of the river water quality model. Lindsay will also assist with the model workshop and dashboard outreach and the three publications.	Denver - Chief Engineer	DO
Timothy J. Clarkin	8, 11	tclarkin@usbr.gov	Tim has relevant experience in water management and dashboard development. He served on a Corps of Engineers Water Management team for three years where he made operations decisions regarding flood and salinity control, assisted in development of an operations dashboard, and standardized reporting for partners and stakeholders. In working with Reclamation, Tim has recently led an effort to develop an operations dashboard to support the Western Colorado Area Office in spring snowmelt forecasting.	Timothy will take the lead on the development of the water quality web-based dashboard.	Denver - Chief Engineer	DO

Key Person	Task Number	Email	Expertise	Responsibilities	Organization	Region
James Carroll	1, 3, 4, 5, 11	jica461@ecy.wa.gov	Jim is currently working and has worked on multiple different water quality models of the Yakima River. His model of the lower Yakima River will be available in FY22.	Jim will be completing the water quality model of the lower Yakima River and will help facilitate the transfer of this model to the TSC once complete. In order to complete this model, he will also facilitate the instrumentation of gages and collection of calibration field data needed to complete this part of the model. He also knows the Naches Branch model(s) and where gages and instrumentation will need to be deployed in order to calibrate that model for DO. He will also be available to help trouble shoot any QUAL2Kw model issues as the model of the upper Yakima River is developed and as all of the individual models are merged together.	Washington State Department of Ecology	
Jennifer M. Johnson	6, 11	jmjohnson@usbr.gov	Jennifer works at Reclamation's Columbia-Pacific Northwest Region office and is the primary developer of the Yakima Basin RiverWare model. She has ample experience as a PI for many S&T projects covering topics ranging from the integration of surface and groundwater models and climate change to investigating the impact of river regulation on groundwater supplies	Jennifer and her modeling group will use the RiverWare operations model of the Yakima River basin to develop water management scenarios. She will also assist in providing insight on all developed water management scenarios.	Interior Region 9: Columbia-Pacific Northwest	PN

Key Person	Task Number	Email	Expertise	Responsibilities	Organization	Region
Christopher J. Lynch	6, 8, 9, 11	clynch@usbr.gov	Chris is a hydraulic engineer at the Yakima Field Office and the primary river operations engineer for the Yakima River Basin.	Chris will help inform water management scenarios and will make sure the final products are relevant and useful to their daily operations and decision making process.	Interior Region 9: Columbia-Pacific Northwest	PN
Kristin Marie Mikkelson	0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11	kmikkelson@usbr.gov	Kristin Mikkelson is a hydrologic civil engineer with over 10 years of experience with water quality and quantity modeling. She has recently developed two water quality models for the Clark Canyon Reservoir in southwestern Montana and the Bottle Hollow Reservoir in eastern Utah. She has also recently been the project manager and technical lead for a Basin Study project in Arizona. She has over fifteen peer-reviewed journal articles in environmental science and engineering journals.	Kristin is the project lead and will be involved in all of the tasks. She will be the lead developer on all the water quality models and associated tasks. She will also be the lead on coordinating and implementing the model and dashboard workshop. In addition, Kristin will be the primary author on the journal publication.	Denver - Chief Engineer	DO
Patrick A. Monk	6, 9, 11	pamonk@usbr.gov	Pat will be the local expert on operational flows and fish needs in the Yakima River Basin and will review all water management scenarios. He will also help define biological thresholds for fish migration and passage and help determine the downstream locations to target improved water quality conditions. In addition, he will help facilitate the site tour and help to connect and explain the biological needs within the basin and local water operations.	Pat is a biologist for the Yakima Field Office with a multitude of experience related to fish passage and water operations within the Yakima River Basin. He is the PI of a current S& T project that is monitoring the movements of fish in the Yakima River using acoustic telemetry and also organizes the System Operations Advisory Committee. He also conducted and reviewed the results of multiple upstream reservoir releases in 2020 thought to benefit fish migration.	Interior Region 9: Columbia Pacific Northwest	PN

Key Person	Task Number	Email	Expertise	Responsibilities	Organization	Region
Caroline U. Ubing	0, 2, 11	cubing@usbr.gov	Caroline Ubing is a hydraulic engineer with Reclamation's Technical Service Center in the Sedimentation and River Hydraulics Group. She has over 8 years of experience with both 1D and 2D numerical hydraulic modeling in support of river restoration projects and the field data campaigns that accompany these projects. Caroline is currently leading an effort studying the impacts of river restoration techniques on water temperature in the Grande Ronde river. She is knowledgeable about the necessary data and tools required to study temperature in the river environment. Caroline is also the TSC Project Manager for Water, Environment and Ecosystems division.	Caroline will take the lead on the field data collection campaign. She will also help with project management.	Denver - Chief Engineer	DO
Richard H. Visser	0, 1, 2, 6, 9, 10, 11	rvisser@usbr.gov	Richard is a biologist who works for Reclamation's Columbia Cascade Area Office and is the Project Manager for the Cle Elum Fish Passage Project. He manages several financial assistance grants providing funds to Yakama Nation to conduct fish passage feasibility studies, Sockeye reintroduction, Bull Trout restoration and monitoring, and a number of habitat based restoration projects. He has over 25 years of fisheries and habitat restoration and project management experience. He has been the lead on previous S&T projects involving salmon migration in the Yakima Basin. He knows the Yakima Basin, project partners, current projects (both within and outside of Reclamation) being conducted within the basin and restoration needs and efforts.	Richard will be one of the local biological experts and provide guidance on water management scenarios and biological thresholds necessary for salmonid migration. He will also help with collaboration and outreach to local partners. He will organize and conduct site tours/visits and help connect TSC staff with local water operations managers and project partners. He will also help plan and facilitate the model workshop and dashboard outreach/guidance. He will help author all reports and the peer reviewed journal article.	Interior Region 9: Columbia-Pacific Northwest	PN

SECTION IV - Proposal Budget Detail

Fiscal Year	Fiscal Year Total Budget
2022	$120,256.00
2023	$106,168.00
2024	$72,888.00

2022

Denver - Chief Engineer

Labor	Travel	Contracts	Contract Type	Non Labor	Total	Description
$64,256.00	$3,000.00	$0.00		$49,000.00	$116,256.00	The majority of the budget is non-labor and will cover the development of the water quality model, the scenarios and the user-friendly dashboard. The non-labor budget covers the installation and maintenance of gages and sensors on the Naches Branch and the lower Yakima River for needed calibration and validation data. The travel budget covers two trips to the region: 1. initial site visit and field data reconnaissance and 2. Model and dashboard workshop.

Interior Region 9: Columbia-Pacific Northwest

Labor	Travel	Contracts	Contract Type	Non Labor	Total	Description
$4,000.00	$0.00	$0.00		$0.00	$4,000.00	This budget will help cover the development of the RiverWare operations scenarios and some of Chris Lynch's time to help inform operations scenarios.

2022						
Washington State Department of Ecology						
Labor	**Travel**	**Contracts**	**Contract Type**	**Non Labor**	**Total**	**Description**
$0.00	$0.00	$0.00		$0.00	$0.00	None of the budget directly goes to the department of Ecology although they will be assisting with the field data campaign through some of their in-kind supportas described in the partner section below.
				Total For Fiscal Year:	$120,256.00	

2023						
Denver - Chief Engineer						
Labor	**Travel**	**Contracts**	**Contract Type**	**Non Labor**	**Total**	**Description**
$99,168.00	$0.00	$0.00		$0.00	$99,168.00	The majority of the budget is non-labor and will cover the development of the water quality model,the scenarios and theuser-friendly dashboard. The non-labor budget covers the installation and maintenance of gages and sensors on the Naches Branch and the lower Yakima Riverfor needed calibration and validation data. The travel budget covers two trips to the region: 1. initial site visit and field data reconnaissance and 2. Model and dashboard workshop.

2023						
Interior Region 9: Columbia-Pacific Northwest						
Labor	**Travel**	**Contracts**	**Contract Type**	**Non Labor**	**Total**	**Description**
$7,000.00	$0.00	$0.00		$0.00	$7,000.00	This budget will help cover the development of the RiverWare operations scenariosand some of Chris Lynch's time to helpinform operations scenarios.

Washington State Department of Ecology						
Labor	**Travel**	**Contracts**	**Contract Type**	**Non Labor**	**Total**	**Description**
$0.00	$0.00	$0.00		$0.00	$0.00	None of the budget directly goes to the department of Ecology although they will be assisting with the field data campaign through some of their in-kind supportas described in the partner section below.

Total For Fiscal Year: $106,168.00

2024						
Denver - Chief Engineer						
Labor	**Travel**	**Contracts**	**Contract Type**	**Non Labor**	**Total**	**Description**
$69,888.00	$3,000.00	$0.00		$0.00	$72,888.00	The majority of the budget is non-labor and will cover the development of the water quality model, the scenarios and theuser-friendly dashboard. The non-labor budget covers the installation and maintenance of gages and sensors on the Naches Branch and the lower Yakima Riverfor needed calibration and validation data. The travel budget covers two trips to the region: 1. initial site visit and field data reconnaissance and 2. Model and dashboard workshop.

Interior Region 9: Columbia-Pacific Northwest						
Labor	**Travel**	**Contracts**	**Contract Type**	**Non Labor**	**Total**	**Description**
$0.00	$0.00	$0.00			$0.00	This budget will help cover the development of the RiverWare operations scenarios and some of Chris Lynch's time to help inform operations scenarios.

Washington State Department of Ecology						
Labor	**Travel**	**Contracts**	**Contract Type**	**Non Labor**	**Total**	**Description**
$0.00	$0.00	$0.00		$0.00	$0.00	None of the budget directly goes to the department of Ecology although they will be assisting with the field data campaign through some of their in-kind support as described in the partner section below.

Total For Fiscal Year: $72,888.00

SECTION V - Partnership

Fiscal Year	BOR	Federal Government	Non Federal Government
2022	$20,000.00	$0.00	$287,500.00
2023	$25,000.00	$0.00	$57,500.00
2024	$10,000.00	$0.00	$0.00

2022						
Partner Name	**E-Mail**	**Organization**	**Organization Type**	**Description**	**Contribution Type**	**Amount**
Charles W. Garner	cgarner@usbr.gov	Interior Region 9: Columbia-Pacific Northwest	BOR	none	Cash - Firm	$0.00
Gwendolyn Weix Christensen	gchristensen@usbr.gov	Interior Region 9: Columbia-Pacific Northwest	BOR	Wendy will provide Yakima Basin Integrated Plan funds to support the in-kind time of Jennifer Johnson's modeling team for RiverWare analysis. Wendy will also provide Yakima River Basin Water Enhancement Project Reclamation funds to support the in-kind time of Richard Visser.	Cash - Firm	$20,000.00
Raechel Chandler	rach461@ecy.wa.gov	Yakima Basin Integrated Water Resources Management Plan, Washington State Department of Ecology	Non Federal Government	Raechel has provided $30,000 in matching funds to support this project for local needs. In addition, she has provided $100,000 in matching funds to support this project and to be used for field data collection in the Yakima River Basin during FY22 and FY23.	Cash - Firm	$80,000.00
George Onwumere	george.onwumere@ecy.wa.gov	Washington State Department of Ecology, water quality program	Non Federal Government	George will provide 5 weeks of Jim's in-kind time to support the development of a merged water quality model of the Yakima Basin.	In Kind - Firm	$7,500.00

2022						
Partner Name	**E-Mail**	**Organization**	**Organization Type**	**Description**	**Contribution Type**	**Amount**
Mark Peterschmidt	mark.peterschmidt@ecy.wa.gov	Washington State Department of Ecology, water quality program	Non Federal Government	Each year Ecology allocates personnel and funds to monitoring projects such as this one, and Jim Carroll will help acquire funding and personnel for the remaining data collection so we can calibrate the Naches Branch model for DO. This includes approximately bi-weekly sampling events at 40 locations along the river system where nutrient and chemistry data will be collected ($50,000). In addition, Jim will also apply for FY22 funding to increase monitoring on the lower Yakima River branch so he can complete the calibration of that water quality model. That funding request will cover 15 DO data loggers, 40 temperature sensors and 20 synoptic sampling events collecting nutrient and chemistry data ($130,000 laboratory costs, $20,000 in dataloggers). This funding request is likely to get approved due to the under-allocation of funds last year during the pandemic.	In Kind - Not Firm	$200,000.00
					Total For Fiscal Year:	$307,500.00

2023						
Partner Name	**E-Mail**	**Organization**	**Organization Type**	**Description**	**Contribution Type**	**Amount**
Charles W. Garner	cgarner@usbr.gov	Interior Region 9: Columbia-Pacific Northwest	BOR	Chuck will provide operations funding for Chris Lynch's and Patrick Monk's in-kind support for this project. Wendy will provide Yakima Basin Integrated Plan funds to support the in-kind time of Jennifer Johnson's modeling team for RiverWare analysis. Wendy will also provide Yakima River Basin Water Enhancement Project Reclamation funds to support the in-kind time of Richard Visser.	Cash- Firm	$5,000.00

2023						
Partner Name	**E-Mail**	**Organization**	**Organization Type**	**Description**	**Contribution Type**	**Amount**
Gwendolyn Weix Christensen	gchristensen@usbr.gov	Interior Region 9: Columbia-Pacific Northwest	BOR	Wendy will provide Yakima Basin Integrated Plan funds to support the in-kind time of Jennifer Johnson's modeling team for RiverWare analysis. Wendy will also provide Yakima River Basin Water Enhancement Project Reclamation funds to support the in-kind time of Richard Visser.	Cash - Firm	$20,000.00
Raechel Chandler	rach461@ecy.wa.gov	Yakima Basin Integrated Water Resources Management Plan, Washington State Department of Ecology	Non Federal Government	Raechel has provided an additional $100,000 in matching funds to support this project and to be used for field data collection in the Yakima River Basin during FY22 and FY23.	Cash - Firm	$50,000.00
George Onwumere	george.onwumere@ecy.wa.gov	Washington State Department of Ecology, water quality program	Non Federal Government	George will provide 5 weeks of Jim's in-kind time to support the development of a merged water quality model of the Yakima Basin.	Cash - Firm	$7,500.00
Mark Peterschmidt	mark.peterschmidt@ecy.wa.gov	Washington State Department of Ecology, water quality program	Non Federal Government	None	In Kind - Not Firm	$0.00
					Total For Fiscal Year:	$82,500.00

2024						
Partner Name	**E-Mail**	**Organization**	**Organization Type**	**Description**	**Contribution Type**	**Amount**
Gwendolyn Weix Christensen	gchristensen@usbr.gov	Interior Region 9: Columbia-Pacific Northwest	BOR	Wendy will also provide Yakima River Basin Water Enhancement Project Reclamation funds to support the in-kind time of Richard Visser.	Cash- Firm	$5,000.00
Charles W. Garner	cgarner@usbr.gov	Interior Region 9: Columbia-Pacific Northwest	BOR	Chuck will provide operations funding for Chris Lynch’s and Patrick Monk's in-kind support for this project.	Cash - Firm	$5,000.00
Raechel Chandler	rach461@ecy.wa.gov	Yakima Basin Integrated Water Resources Management Plan, Washington State Department of Ecology	Non Federal Government	None	Cash - Firm	$0.00
George Onwumere	george.onwumere@ecy.wa.gov	Washington State Department of Ecology, water quality program	Non Federal Government	None	Cash - Firm	$0.00
Mark Peterschmidt	mark.peterschmidt@ecy.wa.gov	Washington State Department of Ecology, water quality program	Non Federal Government	None	Cash - Firm	$0.00
					Total For Fiscal Year:	$10,000.00

SECTION VI - Communicating Results Communication Plan

The results of this project include a calibrated, predictive water quality model of the Yakima River system and a user-friendly dashboard for fast, real-time forecasts as to how different water management options might alter downstream water quality. Throughout the project duration, collaboration and communication will occur with YFO operations staff to make sure the products being developed are relevant and useful to their daily operations and water management decisions. The development and results of the predictive water quality model will be documented in a technical memorandum (TM) and instructions detailing how to use the model and dashboard will be documented in a manual. In addition, these tools will be disseminated to the local water managers, engineers and scientists who are making the water management decisions in the Yakima Basin. Instruction on how to use the model and dashboard will occur through a two day local workshop with hands-on technical guidance. Furthermore, the overall modeled trends and results will be published in a peer-reviewed scientific journal to expand the influence of this project out into the entire scientific community. As is the case with all S&T research projects, a final report will be provided to the research office which will be a combination of water quality model TM and manual detailing how to use both the model and the dashboard.

Optional Deliverables

Infographics	Journal Article	Conference	PowerPoint Presentation	Targeted Email	Software	Video	Webcast	Workshop
N	Y	N	N	N	N	N	N	Y

SECTION VII - Implementation of Results

Other Comments

The dashboard will be hosted behind Reclamation's firewall and thus be available to internal Reclamation employees via VPN.

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Potential Technical Reviewers

1. Joel Fenolio, jfenolio@usbr.gov, Supervisory Civil Engineer, PNRO CPN office
2. Peter Cooper, pcooper@usbr.gov, Hydraulic Engineer, PNRO CPN office

SECTION VIII - Approvals

Manager: Jade R. Soddell