Yakima River Preliminary Assessment of Temperature, Dissolved Oxygen, and pH

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Cover photo: Yakima River at Kiona, August 2015 (photo taken by Paul Pickett).

Yakima River
Preliminary Assessment of
Temperature, Dissolved Oxygen, and pH

by

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Water Resource Inventory Area (WRIA) and 8-digit Hydrologic Unit Code (HUC) numbers for the study area:

WRIAs
- 37
- 38
- 39

HUC numbers
- 17030001
- 17030002
- 17030003

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Abstract

The Yakima River has been documented as having water quality that fails to meet Washington State water quality criteria for temperature, dissolved oxygen (DO), and pH. As requested by the Department of Ecology's Water Quality Program, Central Regional Office, a review was conducted of historical information related to these three parameters in the mainstem Yakima River. This report provides a summary and assessment of the studies, models, documents, and tools available through 2015 found during this review.

Findings are presented first by geographic areas, such as reach and basin delineation, then for each parameter: hydrology, temperature, DO, pH, and nutrients. A review of recent and ongoing monitoring is also provided, including the reconnaissance survey conducted in August and September 2015.

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Purpose of This Document

As requested by the Department of Ecology's Water Quality Program, Central Regional Office, a study was conducted of historical information regarding temperature, dissolved oxygen (DO), and pH conditions in the mainstem Yakima River. The purpose is to begin building a foundation of knowledge for managing pollution sources. Ecology will use this information as a first step to support strategies for pollution reduction throughout the Yakima River. The knowledge gathered here can also be applied to planning and management for both fish restoration projects and water storage and delivery.

First geographic issues are discussed, such as reach and basin delineation. Then findings are provided for each parameter: hydrology; temperature; DO, pH and nutrients. A review of recent and ongoing monitoring is also provided, including the reconnaissance survey conducted in August and September 2015 (Appendix A). These findings are then synthesized and discussed by geographic areas. Conclusions and recommendations will be provided in a separate document for possible future studies to further characterize these parameters and to protect water quality of the mainstem Yakima River through Clean Water Act mechanisms.

Background

Problem Description

The Yakima River Basin drains the east slopes of the Cascades and enters the Columbia River near the cities of Richland and Kennewick (Figure 1). The upper basin lies in Kittitas County, the central basin in Yakima County, and the lower basin in Benton County. Ellensburg, Yakima, Kennewick, and Richland are the largest municipalities in the basin, and there are many other smaller cities.

Water use and control within the Yakima Basin are of primary interest to people working in community development, agriculture, irrigation storage and delivery, and restoration of fish runs to the river. During the first half of the 20th century, federal projects created reservoirs, cleared habitat, and built levees and large networks of canals to support agricultural and municipal development. In the latter decades of the century, Congress and courts mandated that fishery concerns be addressed.

The Yakima River is a highly managed system. The U.S. Bureau of Reclamation (Reclamation) owns and operates five major reservoirs in the system: Keechelus Reservoir (Yakima River), Kachess Reservoir (Kachess River), and Cle Elum Reservoir (Cle Elum River) at the upstream end of the Upper Yakima Valley; and Bumping Lake (Bumping River) and Rimrock Lake (Tieton River) on tributaries of the Naches River (Figure 2). In addition, below the confluence of the Kachess and Yakima Rivers, the Easton Diversion Dam serves to reregulate flows and provide a diversion to the Kittitas Reclamation District.

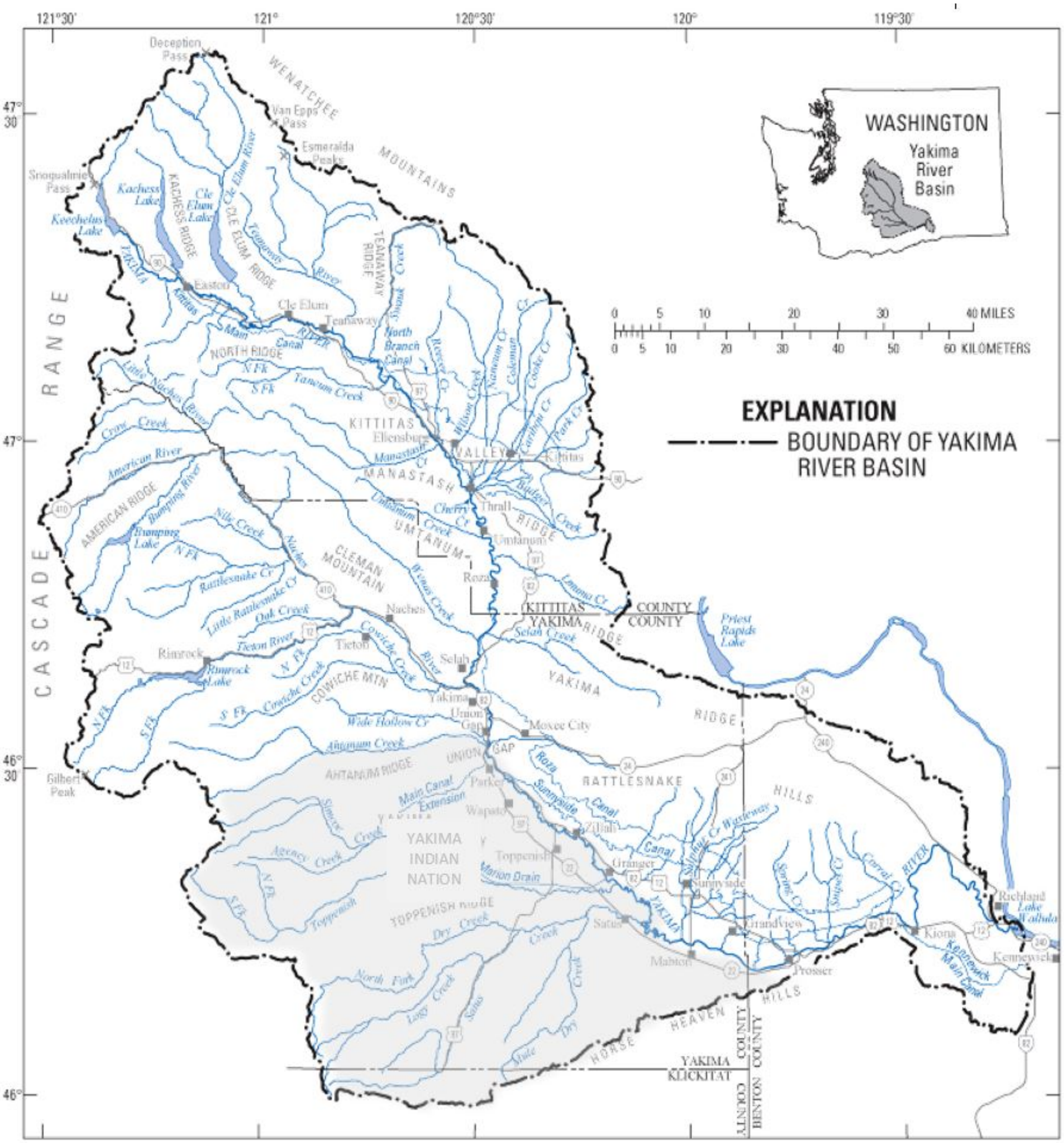


Figure 1. Yakima River Basin.

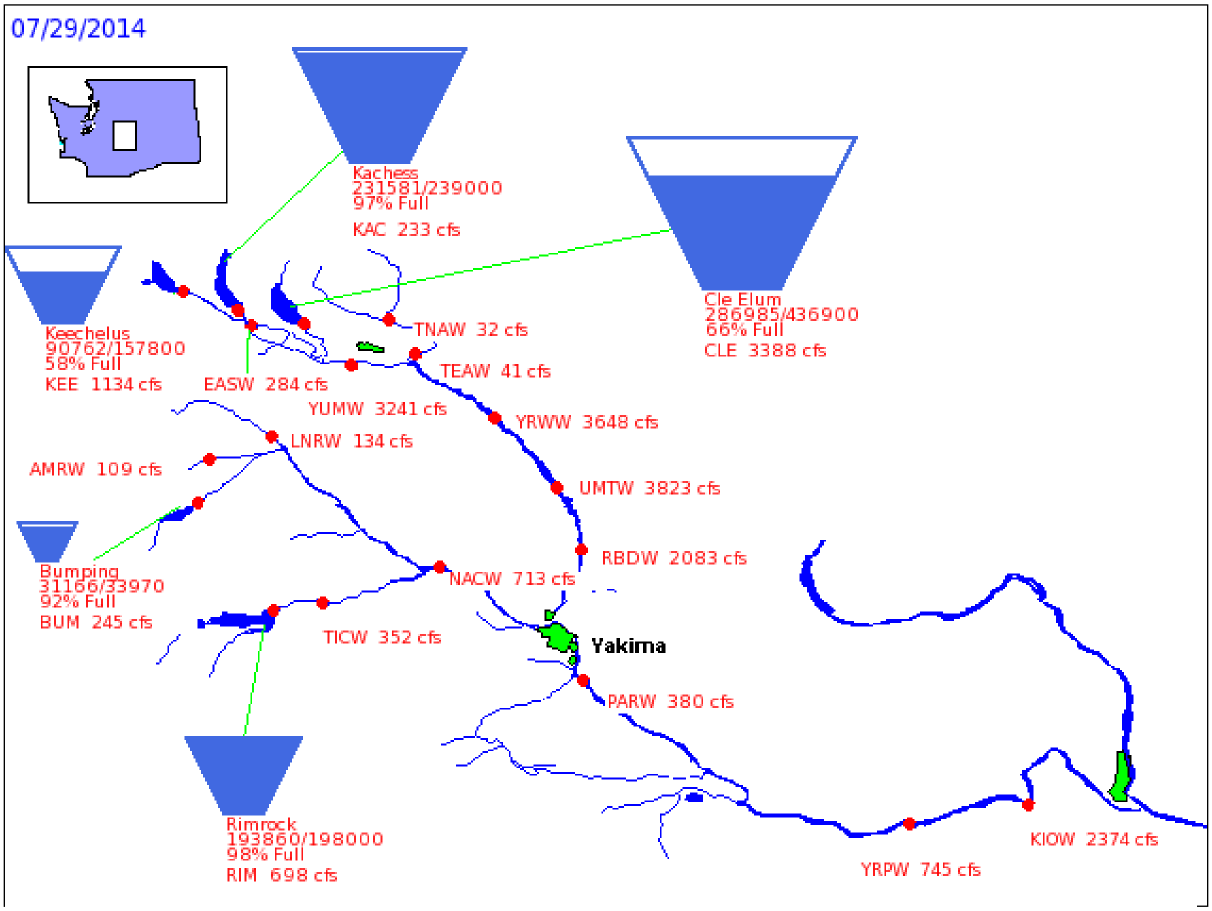


Figure 2. Yakima Basin water management system.
(from: http://www.usbr.gov/pn/hydromet/yakima/yaktea.html)

In the last few years, the Washington State Department of Ecology (Ecology) participated with federal agencies, tribes, environmental groups, and irrigators in the development of the *Yakima Basin Integrated Water Resource Management Plan* (YBIP[1]). For the first time since the basin was settled, people representing diverse interests are formulating a plan to meet their diverse goals. However, the focus of the YBIP is on water supply and fisheries. Although the YBIP addresses water quality through fishery habitat management and project permitting, compliance with the Clean Water Act (CWA) has not been an explicit element.

[1] http://www.ecy.wa.gov/programs/wr/cwp/YBIP.html

Water Quality Standards and 303(d) Listings

Ecology, under its delegated CWA authority, has established water quality standards as state regulations (Ecology, 2011). These standards identify designated uses for the state's waters, establish numeric criteria to protect those beneficial uses, and describe mechanisms to implement the standards, such as setting pollution limits and providing goals for water cleanup projects. The criteria that apply for temperature, dissolved oxygen (DO), and pH in the mainstem Yakima, Kachess, and Cle Elum Rivers below the three major Reclamation reservoirs are summarized in Table 1.

Table 1. Water Quality Criteria for the study area.

	Dates	Criteria		pH
		Temperature[1]	DO[2]	
Yakima River from Keechelus Reservoir to Cedar Creek	Annual	12 ºC	9.5 mg/L	6.5 to 8.5[3]
Yakima River from Cedar Creek to above Lake Easton	Sept 15-May 15	13 ºC	9.5 mg/L	6.5 to 8.5[3]
	May 16-Sept 14	16 ºC	9.5 mg/L	6.5 to 8.5[3]
Yakima River from above Lake Easton to the Cle Elum River, and Cle Elum River below Cle Elum Reservoir	Sept 15-June 15	13 ºC	9.5 mg/L	6.5 to 8.5[3]
	June 19-Sept 14	16 ºC	9.5 mg/L	6.5 to 8.5[3]
Kachess River	Annual	16 ºC	9.5 mg/L	6.5 to 8.5[3]
Yakima River from Cle Elum River to the mouth	Annual	21 ºC	8.0 mg/L	6.5 to 8.5[4]

[1] When natural conditions exceed the criterion or are within 0.3 ºC of the criterion, no temperature increase of greater than 0.3 ºC is allowed. When background conditions are below the criterion, other limitations to heating apply.
[2] When natural conditions are below the criterion or within 0.2 mg/L of the criterion, human conditions considered cumulatively may not cause the DO of the water to decrease by more than 0.2 mg/L.
[3] Human-caused variation within this range shall be less than 0.2 units.
[4] Human-caused variation within this range shall be less than 0.5 units.

Every two years, states are required to prepare a list of water bodies that do not meet water quality standards. This list is called the CWA 303(d) list. In Washington State, this list is part of the Water Quality Assessment (WQA) process. WQA listings are placed in categories according to their status. For this report, listings in two categories are discussed. Category 4(a) comprises listings that currently have the total maximum daily load (TMDL) of pollutants determined that will meet water quality standards, and a water quality cleanup plan developed, approved by EPA, and underway. Category 5 is the CWA 303(d) list: water bodies where data have shown impairment by pollutants. The CWA requires Ecology to complete a TMDL analysis and develop a water cleanup plan for Category 5 waters.

In 2008, the National Marine Fisheries Service (now NOAA Fisheries) and the U.S. Fish and Wildlife Service issued Biological Opinions for the U.S. EPA's approval of Ecology's revised water quality standards (NMFS, 2008; USFWS, 2008). The Biological Opinions comment that, because Ecology did not change the special conditions criterion of 21 ºC for the mainstem Yakima River below the Cle Elum River, EPA did not include it as a proposed action, and therefore it was not part of the Services' Opinion. However, they specifically discuss temperature barriers in the Yakima River as part of the environmental baseline in their effects analysis. The TMDL process was noted in several places as the mechanism to ensure compliance with Water Quality Standards to determine the "natural thermal potential" of water bodies.

The Biological Opinions specifically cite an Ecology letter to the U.S. Environmental Protection Agency (EPA) stating that "the State has agreed to address the special temperature provisions in the TMDL process" (Ecology, 2008). This letter notes that the TMDL process includes an assessment of the estimated natural condition, and that the TMDL sets pollutant allocations to protect natural conditions. Ecology also notes that if the TMDL determines that natural conditions temperatures are lower than the special conditions criterion, "we would view that as a basis to revisit the special temperature criterion".

Table 2 shows the eight Category 4A listings for temperature in the upper Naches River, American River, and Bumping River, where a TMDL has been established. Table 2 also shows the fourteen 303(d) listings for temperature impairment in the mainstem Yakima River and its major tributaries, including one for the Cle Elum River, three for the Tieton River, two for the South Fork Tieton River, five for the Naches River, and three for the Yakima River. In addition, there are five pH listings in the Yakima River and one pH listing in the Naches River; and four dissolved oxygen (DO) listings in the Yakima River. A TMDL study is underway for the Category 5 temperature listings in the Tieton River and Naches River below the Tieton River.

On the current Water Quality Assessment, a total of 106 Category 4A listings in the three Water Resource Inventory Areas (WRIAs) cover the Yakima and Naches River basins – WRIAs 37, 38, and 39. These represent water bodies where EPA has approved TMDLs for toxics, turbidity, temperature, and bacteria. In these three WRIAs there are also 317 Category 5 listings on the 303(d) list. Many of these are TMDLs that are underway but not approved, and some will be future studies. This study is focused on temperature, DO, and pH in the mainstem Yakima River, and will not address the other listings.

Before investing significant resources in water quality studies of the Yakima Mainstem, the Central Regional Office Section of the Water Quality Program (WQ-CRO) requested a survey of existing monitoring data, modeling, and other relevant information. They also requested an evaluation of how compliance with the CWA could fit into the structure of the YBIP, and technical assistance on how YBIP projects affect water quality.

Table 2. Temperature, dissolved oxygen, and pH Category 5 (303[d] list) and Category 4A (TMDL completed) listings in the Yakima River and major tributaries.

Water Resource Inventory Area	Waterbody Name	Parameter	Listing ID & Map Link	Category
38 - Naches	American River	Temperature	8314	4A
38 - Naches	Bumping River	Temperature	39332	4A
38 - Naches	Naches River	Temperature	48447	4A
38 - Naches	Naches River	Temperature	48449	4A
38 - Naches	Naches River	Temperature	48450	4A
38 - Naches	Naches River	Temperature	48451	4A
38 - Naches	Naches River	Temperature	48452	4A
38 - Naches	Naches River	Temperature	48453	4A
39 - Upper Yakima	Cle Elum River	Temperature	8347	5
38 - Naches	Tieton River[1]	Temperature	48471	5
38 - Naches	Tieton River[1]	Temperature	48472	5
38 - Naches	Tieton River[1]	Temperature	48474	5
38 - Naches	Tieton River, S.F.	Temperature	39334	5
38 - Naches	Tieton River, S.F.	Temperature	48495	5
38 - Naches	Naches River[1]	Temperature	8336	5
38 - Naches	Naches River[1]	Temperature	48443	5
38 - Naches	Naches River[1]	Temperature	48444	5
38 - Naches	Naches River[1]	Temperature	48445	5
38 - Naches	Naches River[1]	Temperature	48446	5
37 - Lower Yakima	Yakima River[1]	Temperature	8311	5
39 - Upper Yakima	Yakima River[1]	Temperature	3727	5
39 - Upper Yakima	Yakima River[1]	Temperature	8370	5
38 - Naches	Naches River	pH	6735	5
39 - Upper Yakima	Yakima River	pH	11218	5
37 - Lower Yakima	Yakima River	pH	6734	5
37 - Lower Yakima	Yakima River	pH	11199	5
37 - Lower Yakima	Yakima River	pH	11195	5
37 - Lower Yakima	Yakima River	pH	15018	5
39 - Upper Yakima	Yakima River	DO	11225	5
37 - Lower Yakima	Yakima River	DO	8309	5
37 - Lower Yakima	Yakima River	DO	11177	5
37 - Lower Yakima	Yakima River	DO	15008	5

[1] Scheduled to be addressed by the Tieton and Lower Naches temperature TMDL study.

Project Purpose and Study Objectives

This project is a study that serves as the first phase of a long-term initiative to ensure compliance with the CWA in the Yakima Basin and to integrate water quality compliance strategies with the YBIP. A Project Work Plan Memo (Pickett, 2015a) describes the purpose, objectives, and scope of this study.

As requested by the Water Quality Program, this report provides the results of this study:

- A summary and assessment of existing studies, models, documents, and tools that have been developed for or are used to address water quality in the mainstem Yakima River.
- An assessment of temperature, DO, pH, and nutrient-induced limitations to water quality in the mainstem Yakima River.
- Results of the reconnaissance surveys in August and September 2015.

Methods

The Yakima River Basin is one of the most intensely studied basins in Washington State. To meet the project objectives, a detailed search was conducted of existing literature on water management in the Yakima River Basin. Information was reviewed that addressed water quality problems with temperature, dissolved oxygen, and pH. This report focuses on information since the year 2000, although relevant literature from earlier years was also reviewed. Over 40 sources are listed in the References section.

In addition, when it became clear that the summer of 2015 was likely to be an extreme year for water supply shortages, a reconnaissance survey was planned to collect data on temperature, DO, and pH to confirm past listings and investigate areas with limited data. A Project Work Plan Addendum (Pickett, 2015b) outlines plans for this monitoring that took place in August and September 2015.

Findings

The approach to presenting this information will be to first explain some important geographical issues, such as how different studies have divided the Yakima River into reaches. Then studies of hydrology are reviewed based on the topic area that motivated the studies. Finally, temperature and DO/pH/nutrients will be discussed in separate sections, but in chronological order to show the evolution of knowledge in this basin. Then the Discussion section will synthesize the findings, leading to Conclusions and Recommendations.

Geographic Considerations

The geography of the Yakima River Basin presents challenges for comprehensive study because of its size and complexity. The basin begins at the crest of the Cascades, with its cool temperatures and seasonal snowpack, while its confluence with the Columbia River near Richland lies in one of the hottest and driest areas in Washington. As a result, different studies have sought to divide the basin into subregions or reaches that characterize the relevant environmental conditions. These delineations can be based on the distribution and life cycle of salmon, land use, floodplain structure, aquatic ecology, surface hydrology, groundwater hydrology, climate, or other factors.

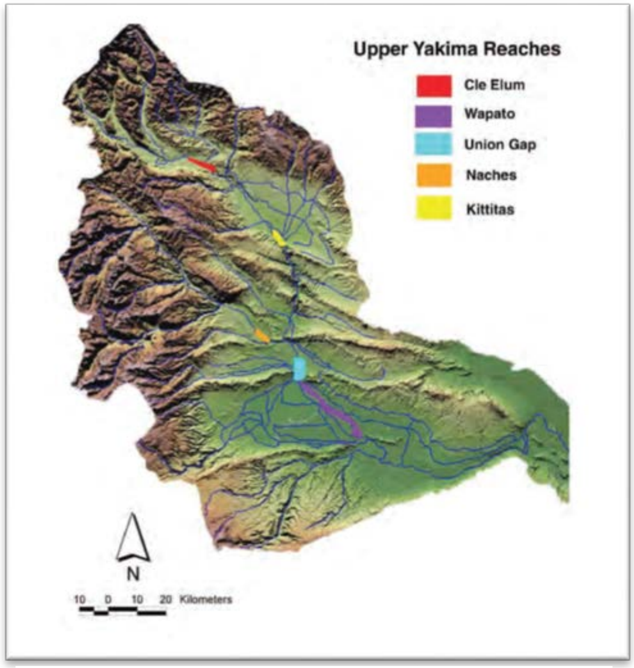


Figure 3. Upper Yakima floodplain reaches. (Stanford et al. 2002).

The Reaches Project report (Stanford et al., 2002) is one of the most influential studies for basin fishery restoration. This study evaluated fish habitat and floodplain conditions for five reaches in the Yakima Basin (Figure 3): Cle Elum, Kittitas, Naches, Union Gap, and Wapato. Although this is not a comprehensive delineation, it does indicate high-priority habitat restoration areas supported by local fisheries knowledge.

A variety of studies have delineated the basin by groundwater basins. The most recent was the USGS report on Yakima Basin groundwater modeling (USGS, 2011a). This study identified 6 groundwater basins that define reaches of the Yakima River (Figure 4):

- Roslyn (from Kachess and Cle Elum Reservoirs to the Horlick area downstream of the Teanaway River)
- Kittitas (the Kittitas Valley from Horlick to the head of the Yakima Canyon)
- Selah (from the outlet of the Yakima Canyon to Selah Gap)
- Yakima (from Selah Gap to Union Gap)
- Extended Toppenish (Union Gap to Benton City/Kiona)
- Eastern Benton (from the Benton City/Kiona to the mouth)

An earlier study (USGS, 2006a) identified similar basins to those in the modeling study, but ended the Toppenish Basin at Granger and identified a Benton Basin from Granger to Kiona.

Reclamation's evaluation of aquatic ecosystems (Reclamation, 2008) notes that the Sunnyside Dam marks the upstream boundary of the lower Yakima River.

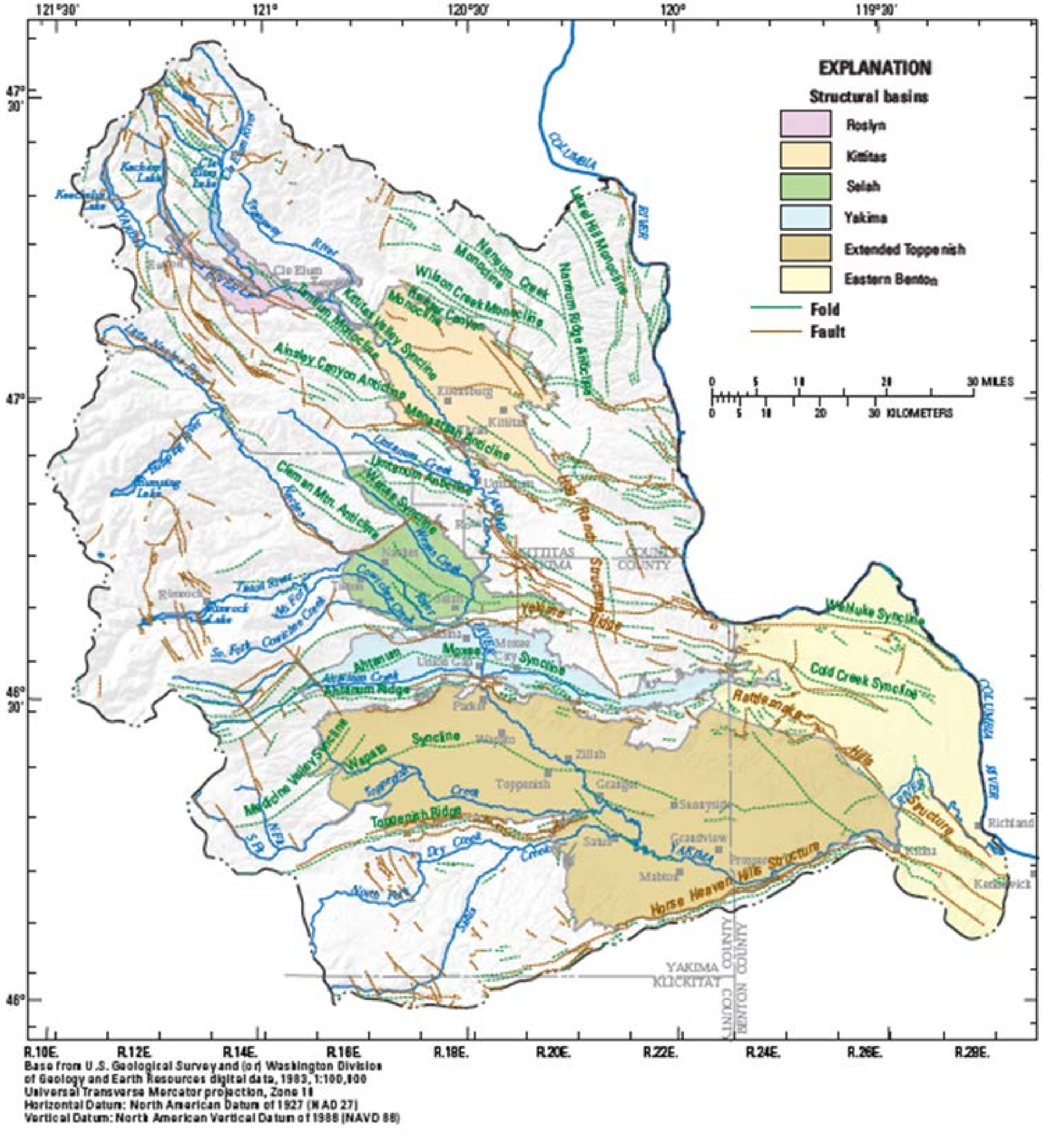


Figure 4. Location of six structural basins and geologic structure, Yakima River Basin aquifer system, Washington. (USGS, 2011a).

Considering interactions between ground and surface waters, Vaccaro identified gaining and losing reaches in the mainstem Yakima River (USGS, 2011b). They overlay on the groundwater basins described above (Figure 5), with potential subdivisions of the Toppenish Basin: Union Gap to Granger, Granger to Prosser, and Prosser to Kiona.

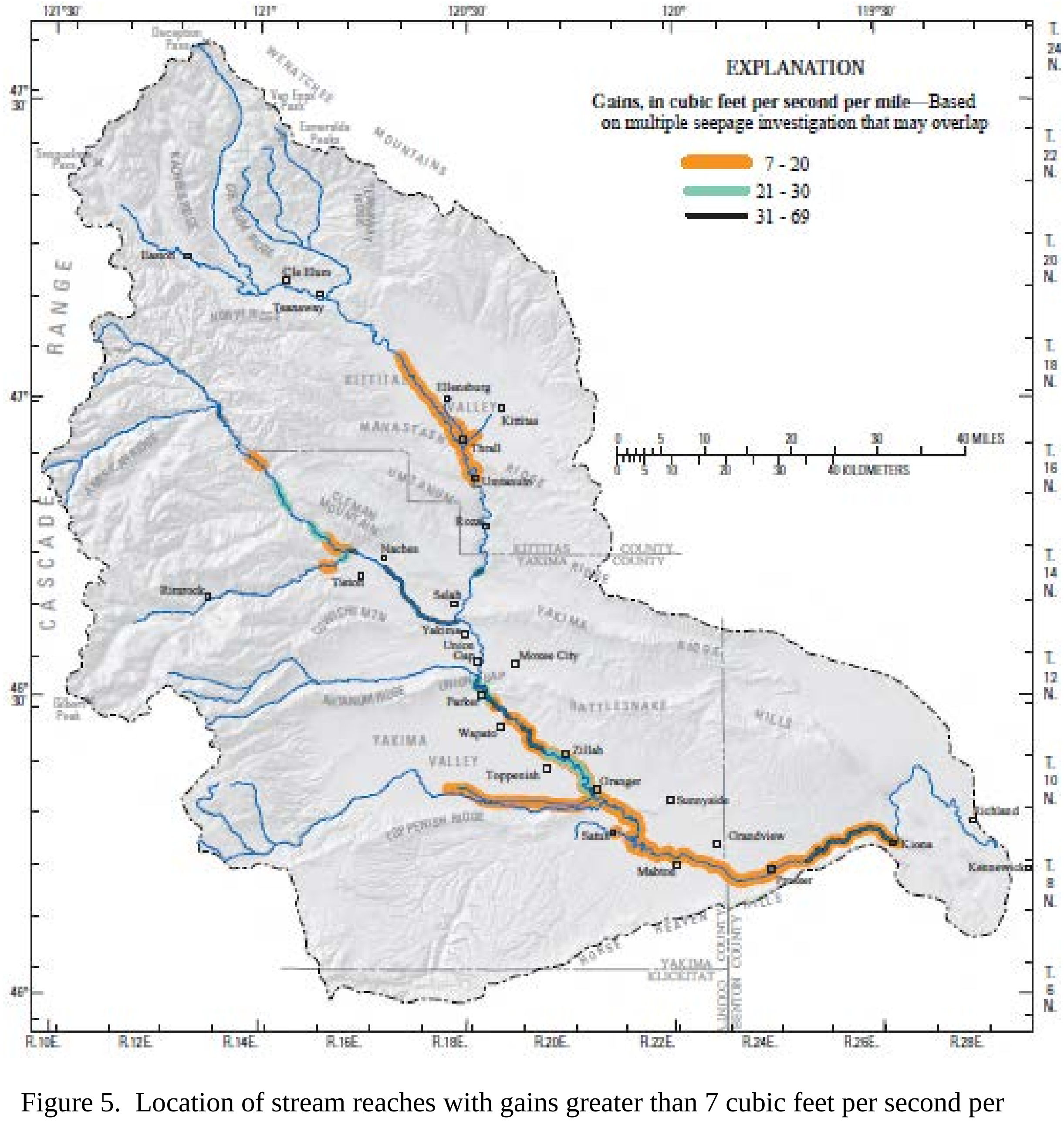


Figure 5. Location of stream reaches with gains greater than 7 cubic feet per second per mile, Yakima River Basin, Washington. (USGS, 2011b).

From a water quality perspective, the USGS study of eutrophication in the lower basin (USGS, 2009a) identified the following reaches from the Yakima Canyon outlet to Richland (Figure 6):

- Zillah reach (outlet of the Yakima Canyon to Sunnyside – above the confluence of Satus Creek with the Yakima River)
- Mabton Reach (Sunnyside to Prosser)
- Kiona Reach (Prosser to Richland)

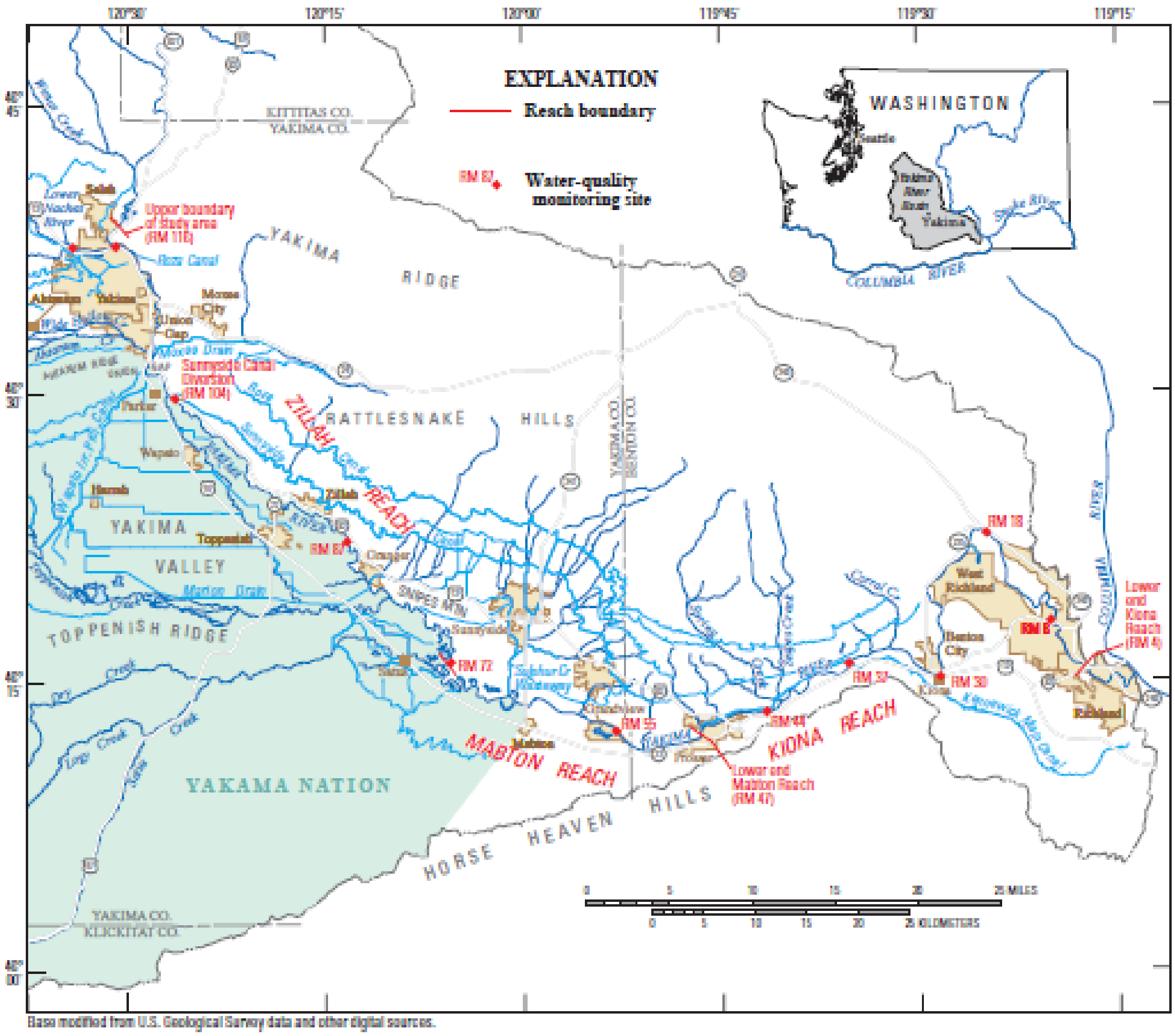


Figure 6. Eutrophication study area with reaches. (USGS, 2009a).

Structural features of the mainstem Yakima River also suggest delineations to be considered:

- Lake Easton serves as the reregulation reservoir for Keechelus and Kachess Reservoir releases, and the diversion point for the Kittitas Reclamation District.
- The Yakima Canyon is a critical hydrologic division of the basin. The irrigation systems of the Kittitas Valley converge before entering the canyon, while the next diversion occurs at Roza Dam.
- Two major diversions occur at the Roza Dam, creating a reach of reduced flows from the dam past Selah to the Naches River confluence. This "by-pass reach" may be particularly sensitive beginning in late summer when "flip-flop" operations reduce flows from the reservoirs upstream of Roza Dam and use the two Naches Basin reservoirs for lower Yakima Valley supply.
- The Naches River is the single largest tributary to the Yakima River. It is an integral part of Reclamation's management of flows in the basin through its dams and reservoirs on the Bumping and Tieton Rivers. Although not directly a part of this study, the Naches has a significant impact on the mainstem from its flows and temperature, and possibly also from its nutrient loading.
- The Prosser Dam creates an impounded area and is the site of the diversion into the Chandler Canal. This diversion creates a bypass reach from Prosser Dam to the Chandler power plant.

Political boundaries create other significant divisions of the basin:

- The boundary between Kittitas and Yakima Counties crosses the Yakima River in the middle of the Yakima Canyon.
- The boundary between Yakima and Benton Counties crosses the Yakima River upstream of Prosser.
- From Ahtanum Creek above Union Gap to Mabton, the Yakima River is shared between Washington State on the east bank and the Yakama Nation Reservation on the west bank.

From the perspective of environmental data, there are many long-term monitoring stations (Table 3) on the Yakima River that are potentially significant to delineating reaches as part of study design for the mainstem Yakima River:

- Four Ecology core ambient water quality monitoring stations
- Four USGS flow gaging stations
- Twelve Reclamation flow gaging stations

There are many irrigation diversions and return flows, as well as wastewater treatment outfalls, which would affect the design of a water quality study. There are also a variety of other ways that the Yakima River could be delineated based on other environmental parameters. The reach delineations described above address the principal considerations from the literature relevant to potential water quality studies.

Table 3. Long-term flow and water quality monitoring stations on the mainstem Yakima River.

Station ID	Station Name
Ecology ambient monitoring stations	
39A090	Yakima R near Cle Elum
39A055	Yakima R @ Umtanum Cr Footbridge
37A205	Yakima R @ Nob Hill
37A090	Yakima R @ Kiona
USGS gages	
12484500	Yakima River at Umtanum, WA
12500450	Yakima River above Ahtanum Creek at Union Gap, WA
12508990	Yakima River at Mabton, WA
12510500	Yakima River at Kiona, WA
Reclamation gages	
EASW	Yakima River at Easton
YUMW	Yakima River at Cle Elum
YRWW	Yakima River near Horlick
UMTW	Yakima River near Umtanum
RBDW	Yakima River below Roza Dam
PARW	Yakima River near Parker
YRPW	Yakima River near Prosser
KIOW	Yakima River at Kiona
YRTW	Yakima River at Terrace Heights Bridge
YRCW	Yakima River at Crystal Springs
YGVW	Yakima River at Euclid Rd. Br. near Grandview
ELNW	Yakima River near Ellensburg

Hydrology and Water Management

Because flows in the Yakima River are so highly managed, studies that address flow are common. Relationships between flow and water quality parameters are discussed in the following sections. Several studies are nonetheless of interest for providing a context for flow management and potential tools for modeling.

Fish Habitat Studies – 1999-2002

Relationships between flow and fish habitat have been the focus of numerous studies. In a key 1990s report, "Report on Biologically Based Flows" (SOAC, 1999), the Systems Operations Advisory Committee provided ten recommendations that would support the determination of biologically-based flows. These include:

1. Review and Synthesize Existing Yakima River Ecosystem Data
2. Develop an Historic Flow Regime Template
3. Development of a Watershed Hydrologic Model
4. Develop and Implement a Normative Flow Regime
5. Investigate Longitudinal, Lateral, and Vertical Connectivity

6. Assess Status of the Food Web
7. Develop a Stream Network Water Temperature Model
8. Evaluate Salmonid Microhabitat Conditions
9. Develop a Salmon Pre-smolt Production Model
10. Adaptive Environmental Assessment and Management

These recommendations laid the groundwork for many studies conducted in the last 15 years.

Haring (2001) provided a detailed analysis of limiting factors affecting salmonids. Regarding flow, the report notes that "there is broad consensus that salmon require…instream flows that mimic the natural hydrology of the watershed, maintaining adequate flows during low flow periods and minimizing the frequency and magnitude of peak flows (stormwater)…"

In a table of habitat conditions, Haring rates the Yakima River as:

- Fair for peak and low flows from Keechelus Dam to Wilson Creek
- Fair for peak flows and good for low flows from Wilson Creek (head of the Yakima Canyon) to Union Gap
- Poor for peak flows and fair for low flows from Union Gap to Prosser
- Poor for peak and low flows from Prosser to the mouth

The report notes several data gaps regarding flow:

- Review of Flip-Flop Flow Management
- Water Budget
- Identification of Instream Flows Necessary to Support Normative Ecosystem Function
- Groundwater/Surface Water Interactions

Snyder and Stanford (2001) provided a review of ecological studies, focusing on flow and salmon. This work was used by Haring (2001) and also by the Reaches Study (Stanford et al. 2002). Among their findings regarding flow, they identify several "primary roadblocks" to restoration:

- Interactions of wild fish with exotic and hatchery fish
- Alterations of the flow regime
- Water quality, in particular nutrients and pesticides
- High temperatures
- Reductions in habitat heterogeneity and floodplain connectivity

The Reaches Project (Stanford et al., 2002) continued the work begun by Snyder and Stanford. Key findings related to flow include:

- The importance of ground-surface water interactions in five floodplains. The reduction in floodplain inundation has reduced cool hyporheic return flows during the summer.
- The interaction of flow, sediment, and floodplain ecological functions. Channel incision due to reduced sediment supply can combine with reduced low flows to dewater floodplain

reaches.

- The need for increased water supply and better management to the restoration of normative flows.

DSS and YBIP Studies

Reclamation worked with USGS over several years to develop a Decision Support System (DSS) to evaluate the effect of water management decisions. As part of that effort, USGS (2002) developed physical hydrology models for four subbasins:

- Naches modeling unit: the watershed upstream of confluence of the Naches and Tieton Rivers, plus the headwaters of Ahtanum Creek.
- Upper Yakima modeling unit: the watershed upstream of the stream-gaging station Yakima River at Horlick (below the Teanaway River) plus seven unregulated subbasins that drain to the Kittitas Valley.
- Toppenish/Satus modeling unit: the watershed upstream of the irrigation canals within the Toppenish and Satus Creek watersheds.
- Yakima Canyon modeling unit: the part of the watershed that directly contributes to or abuts the Yakima River in the Yakima Canyon (from below Wilson Creek to downstream of Wenas Creek).

USGS used their PRMS model for this analysis. The model was calibrated to gaged flows, and streamflow was partitioned into surface runoff, subsurface runoff, and groundwater flow. The calibration data set consisted of 35 streamflow gages for water years 1950-94. The model was also tested against stream flow from 11 sites from 1995-98. Percent error for two-thirds of calibration values fell between -8 and 10%. Larger errors were attributed mainly to rain-on-snow events and to small watersheds with low flows and small absolute errors that produce relatively large percent errors.

USGS (2008a) developed an SNTEMP temperature model for the DSS effort. This is described in more detail in the *Temperature* section below.

USGS (2008b) reported on the development of the DSS, which included:

- The Yakima Project RiverWare (Yak-RW) model: a daily-time step reservoir and river operation simulation computer model for Reclamation’s Yakima Project created with the RiverWare software.
- River2D: a two-dimensional depth-averaged hydrodynamic model that was developed by the University of Alberta for fish habitat evaluation studies.
- The SNTEMP temperature model and a sediment model.
- A variety of salmonid biology and habitat metrics.

Beta testing was conducted on scenarios for current conditions, "no action" (current with future operational options), and for the Black Rock and Wymer Dam storage projects.

Reclamation (2008) evaluated flow-ecosystem relationships using the DSS for the same suite as USGS (2008b). The same suite of models was employed, with the addition of HEC-RAS: a one-dimension model developed by the U.S. Army Corps of Engineers that provides river discharge, flow depth, channel top width, and cross-section averaged values of velocity. A detailed report of the HEC-RAS model development is provided by Reclamation (2007a).

The 2008 Reclamation report presented modeled hydrographs in an average water year for unregulated flows, "no action" conditions, and the scenarios for the proposed projects. These flow scenarios were then linked to habitat conditions, such as wetted channel, sediment load, and stream temperatures.

HDR and Anchor QEA (2011) conducted modeling of YBIP scenarios using Reclamation's Yak-RW software. Analyses were conducted using both existing (historical) hydrology and climate change simulations. The potential benefits of the YBIP were quantified for average and drought years, both in terms of total water supply available and of prorationing percentage during drought years.

Groundwater Studies

Beginning in 2006, the USGS developed a series of reports regarding groundwater in the Yakima Basin. One study (USGS, 2006a) characterized six groundwater basins formed from sedimentary deposits (Figure 4):

- The Roslyn Basin begins at Kachess and Cle Elum Reservoirs and follows the river valleys to the Horlick area. This basin includes the lower end of the Teanaway River.
- The Kittitas Basin includes the Kittitas Valley from above Taneum Creek to the mouth of Wilson Creek at the entrance to the Yakima Canyon, and also includes the Badger Pocket area.
- The Selah Basin includes the Selah Valley as well as the Wenas Creek Valley, the lower Naches River Valley, and part of the Cowiche Creek Valley.
- The Yakima Basin includes the river bottom between Selah Gap and Union Gap, and stretches to the west up the Ahtanum Creek Valley and to the east up the Moxee Valley.
- The Toppenish Basin includes the Yakima River Valley below Union Gap and the Toppenish Creek Valley, down to the confluence of those two water bodies at the gap between Toppenish Ridge and Snipes Mountain near Granger.
- The Benton Basin begins below Toppenish Ridge and includes the rest of the lower Yakima River Basin to the mouth.

Vaccaro and his colleagues conducted thermal profiling to map groundwater gaining reaches (USGS 2005; 2006b; 2006c). This is described in more detail in the *Temperature* section below.

USGS (2009b) continued their characterization of the hydrogeology of the Yakima River Basin. The goal was to assemble data for use in a regional groundwater model. The six major basins described above were divided into 19 hydrogeologic units, Columbia River basalts were divided into 3 units separated by 2 interbed units, and older bedrock was divided into 4 units. The study estimated lateral hydraulic conductivity for the units, and geochemical solutes were evaluated. Mean annual recharge rates and groundwater pumping rates were calculated.

From this information the study determined a water budget and long-term trends in aquifer levels. Groundwater recharge was estimated at 5.0 million acre-feet, of which streamflow accounted for about a half, and diversions and pumpage for irrigation accounted for the rest. Diversions represented 3.1 million acre-feet of the water budget, of which reservoir storage supplied about one-third and groundwater recharge about two-thirds.

Vaccaro studied exchanges between groundwater and surface water (USGS, 2011a). Five methodologies were used:

- An analysis of isotope ratios
- Seepage runs (Data were published separately: USGS, 2009c)
- Vertical hydraulic gradients measured with mini-piezometers
- Groundwater levels and water temperatures in shallow wells near stream channels
- Thermal profiles

The study evaluated the potential source of groundwater and found it to be almost all from atmospheric sources as opposed to deep aquifers. Gaining and losing reaches were mapped (Figure 5) and net inflows or outflows estimated.

USGS (2011b) published the results of their development of a basin-wide groundwater model. The model is based on the MODFLOW framework. The abstract states:

> *The model uses 1,000-foot grid cells that subdivide the model domain by 600 rows and 600 columns. Forty-eight hydrogeologic units in the model are included in 24 model layers.*

The model includes tributaries, agricultural drains, recharge, and pumpage. The model was calibrated to conditions for October 1959 to September 2001, and provides a 42-year record of monthly water budgets. Differences between measured and modeled streamflows at seven sites averaged less than 10%. Five scenarios provided a test of model sensitivity to pumpage type and rates.

USGS (2014b) analyzed the hydrogeology of the Upper Yakima River (above Horlick). Six distinct geologic units were identified and mapped, which support a highly complex groundwater flow system. Although isolated pockets of deep groundwater were identified, the study confirmed that stream summer baseflow was supported by sources of groundwater with local origins.

Other Studies

Many reports have noted the downstream effects on the Yakima River of Reclamation's water management, while other studies have explored how water management impacts the storage reservoirs themselves. A study of Cle Elum and Bumping Reservoirs (Reclamation, 2007b) notes that reservoir operations result in periods of filling and drawdown that affect the temperature and density regimes that govern stratification of the reservoir. This in turn affects water quality and the biological populations present.

The EIS reports for the Cle Elum pool raise (Reclamation and Ecology, 2014) and the Kachess Drought Relief Pumping Plant and Keechelus Reservoir-to-Kachess Reservoir Conveyance ("K-K Project"; Reclamation and Ecology, 2015) assess the effects of filling and drawing down the reservoirs on shoreline features and the limnology of the reservoirs. The reports also analyze the downstream intended benefits for irrigation and fish from augmented flow and altered operations.

USGS researchers conducted several analyses of the effect of climate change on the Yakima Basin, which included changes in hydrology (USGS, 2008c; 2011c; 2012; Hatten et al, 2014). The dominant effects expected are: less snowpack, a switch to a rainfall-dominated system, and hotter, drier summers.

Temperature

Elevated water temperature is by far the most studied and discussed water quality parameter in the literature. Problems with high temperatures in the mainstem Yakima River are well known and frequently discussed both in the literature and at professional meetings. A summary of studies that analyzed or referred to temperature follows.

Temperature Modeling – 1980s

In the 1980s, Vaccaro modeled temperatures in the Yakima River observed from April through October 1981 (USGS, 1985). The study domain included the Yakima, Kachess, Cle Elum, Tieton, and Naches Rivers, along with their major tributaries and the five Reclamation reservoirs, downstream to the mouth of the Yakima River near Richland. He used the SSARR streamflow routing model to simulate daily flows in the system. For temperature he developed a Lagrangian temperature model built on a USGS model from the 1960s, which estimates daily average temperatures.

Verification of the Vaccaro model showed mean errors of around 0.3 to 1.5 ^{o}C, with standard deviations of the error between 1.0 and 1.5 ^{o}C. Peak daily average temperatures occurred in mid-August, and generally increased from upstream to downstream, exceeding 18 ^{o}C at Cle Elum and reaching 25 ^{o}C at Kiona.

Four scenarios were then run:

- Reservoir releases but no diversions or return flows
- A "natural conditions" run with no reservoirs, diversions, or return flows
- Reservoir releases with 50% reduction in all diversions and return flows
- Reservoir releases with 50% reduction in the eight largest diversions and return flows in the lower basin

In the Yakima River, flows with no reservoirs (unregulated flow) were higher than flows with reservoir operations in April and May, and lower from July through September. There was a pulse of unregulated flow in October that was not present for flows with the reservoirs. Conditions in the Naches were similar, except that natural condition flows, as compared to flows with the reservoirs and diversions, were higher through mid-August, much lower in September, then higher during the pulse in October.

Temperature scenarios showed some interesting patterns:

- At Cle Elum, water temperatures for unregulated flows were much warmer in mid-August than scenarios with reservoirs but were similar at other times. In late June and early July, the scenario with the reservoir but no diversions showed cooler temperatures than other scenarios.
- At Ellensburg, Umtanum, Union Gap, and Parker, temperatures for unregulated flows were warmer than scenarios with dams from late June through early September, and cooler in late September and early October.
- At Granger, Mabton, and Kiona, differences between scenarios were minor, although patterns from upstream could still be discerned.
- In general, reservoir and irrigation operations tended to produce cooler temperatures upstream of the Yakima Canyon, but tended to increase mid-summer temperatures from Parker downstream.

Temperature Studies – 1990s

Cuffney et al. (USGS, 1991) studied the statistical relations between fish, algae, macroinvertebrates, and physical and chemical parameters. Temperature was one of many factors in the analysis, but the study notes the role of temperature as a critical factor to fish in the Yakima River.

Lilga (1998), as part of a Master's thesis at Washington State University, conducted continuous temperature monitoring in the lower Yakima River from June through November 1996. Temperatures exceeded 21 ^{o}C almost 15% of the time at Prosser and over 35% of the time at Kiona and Horn Rapids. Temperatures exceeded 25 ^{o}C about 8% of the time at Kiona and Horn Rapids.

Lilga's analysis explored the effect of flow and other drivers on water temperatures. Statistical analysis showed that air temperature was found to be the primary factor influencing stream temperature (air temperature explains just under 70% of the variability of water temperature). The efficacy of flow augmentation to reduce stream temperatures could not be assessed. Other factors impacting stream temperatures were tributary, irrigation, and groundwater inflows; and incoming solar radiation.

In May 1999, the Yakima Systems Operations Advisory Committee issued a report on biologically-based flows in the Yakima River (SOAC, 1999). As mentioned above, the report makes ten recommendations, one of which addressed temperature:

> *Develop a Stream Network Water Temperature Model – A thermal assessment is needed to identify temperature constraints to correlate with habitat availability.*"

They also note:

> *The influence of Yakima Basin water management with the interaction of natural processes on water temperature, habitat conditions and the aquatic ecology of the Yakima Basin requires further study.*

Hiebert conducted limnological surveys of the five Reclamation reservoirs in 1998 (Reclamation, 1999). Lake profiles generally showed a typical thermally stratified profile in August, with surface temperatures above 20 ^{o}C and bottom temperatures at 4 to 5 ^{o}C. The thermocline lay at about 7 meters in Bumping Lake, 15 meters in Rimrock Lake, 17 meters in Cle Elum Reservoir, 10 to 12 meters in Kachess Reservoir, and 11 meters in Keechelus Reservoir.

USGS assessed the Yakima Basin during 1999 and 2000 as part of the National Water-Quality Assessment (NAWQA) Program (USGS, 2003; 2004). Although the focus of the study was on turbidity, nutrients, and pesticides in the tributaries, field monitoring included water temperatures at the Yakima River at Kiona station.

Lower Yakima Modeling – 1995-2000

Carroll and Joy (2001) developed a water quality model of the Yakima River from the Chandler diversion at Prosser to River Mile 5.6 near the Highway 182 bridge. The study, triggered by a proposed pump exchange project, evaluated the water quality impacts of the project. The study used the QUAL2E model, which is a one-dimensional steady-state modeling framework that predicts mean daily temperature. Sampling was conducted for a variety of constituents, focusing on temperature, total suspended solids (TSS), dissolved oxygen, Biochemical Oxygen Demand (BOD) and nutrients. The model was calibrated to a survey in late July 2000, and a confirmation run was developed from a survey in late September 1999.

Temperature calibration was successful, with reasonable goodness-of-fit statistics for both calibration and confirmation. The report noted the poorest fit occurred in the Chandler bypass reach, most likely due to uncertainty around the temperature of groundwater inflows. Results from the pump exchange scenarios showed that increased flows could decrease temperatures in the Chandler bypass reach by up to 0.07 ^{o}C and below Chandler by up to 0.28 ^{o}C (Figure 7). The report notes that temperatures were well above the criterion for the modeling scenarios and were dominated by water temperatures entering the reach from upstream.

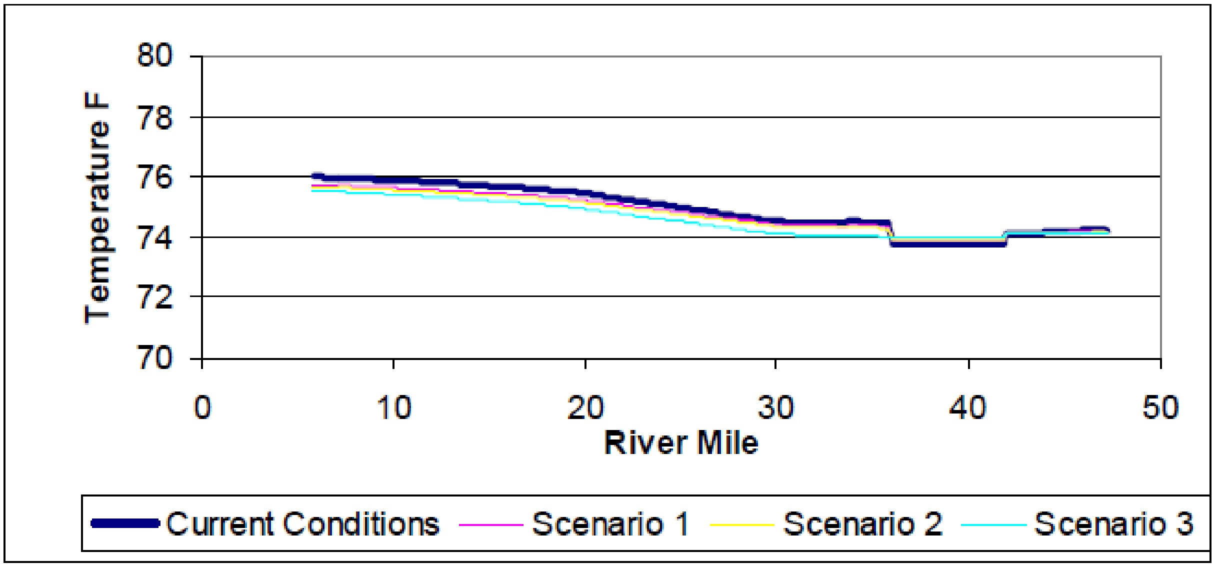
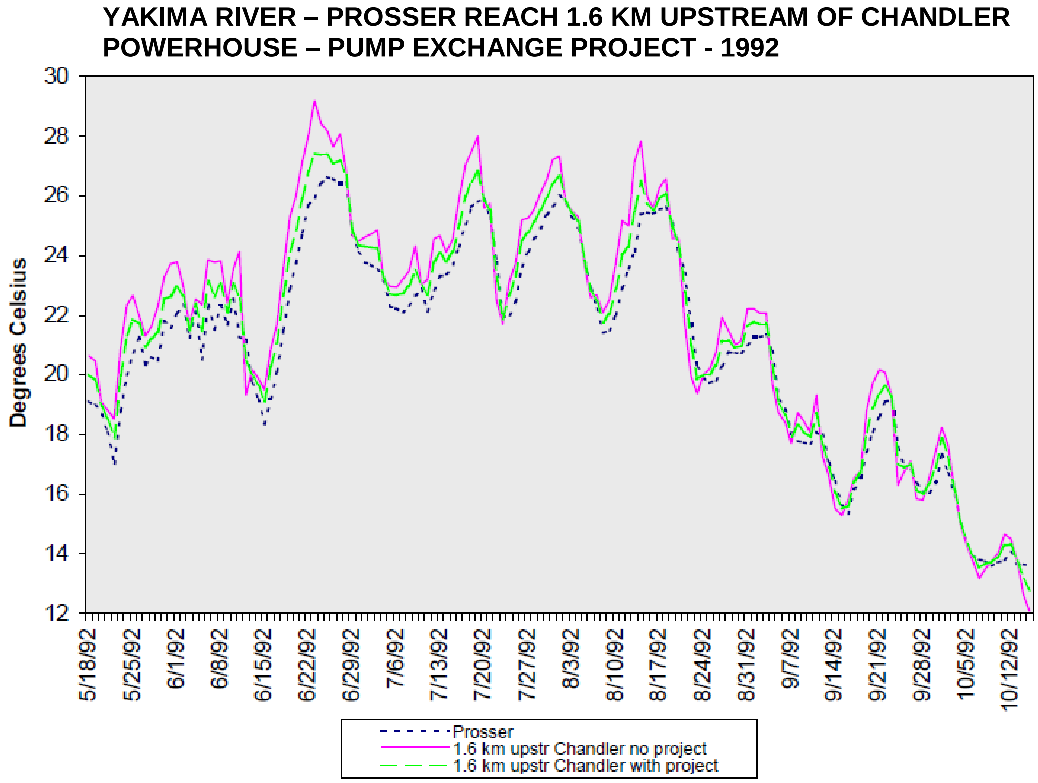


Figure 7. Results of QUAL2E simulations of temperature for operational-change scenarios compared to current conditions. (Carroll and Joy, 2001).

Modeling in support of the pump exchange project was also conducted by consultants for the Kennewick Irrigation District (KID, 2001). The SNTEMP model was applied to predict daily average (mean) and daily maximum water temperatures, under current conditions and with the project in place. The model was calibrated to conditions from 1995, 1997, and 2000. Scenarios were run using 1992 as a drought year and 2000 as an average water year.

Results from this effort indicated more dramatic reductions in temperature than found by Carroll and Joy (Figure 8):

> *During drought years the Project could reduce mean daily water temperatures on average by 0.35°C, with a maximum single day decrease of as much as 1.82°C. Maximum daily water temperatures were decreased in the Chandler bypass reach under drought year conditions on average by 1.13°C, with an extreme cooling day of 2.83°C.*
>
> *In this same reach in an average water-year, the predicted average cooling influence of the Project on mean daily temperatures was 0.20°C with a largest, single day decrease of 0.94°C. In an average water-year Project could reduce maximum daily water temperatures on average by 0.68°C, with the most extreme, single day cooling of 1.61°C.*
>
> *Flow alterations due to the Project did not significantly influence simulated water temperatures in the Yakima River downstream from Chandler Powerhouse to West Richland. The large volume of return flow water from the Chandler Powerhouse appeared to be the primary influence on water temperatures in this reach. At West Richland the maximum daily temperature was decreased by 0.49°C and 0.31°C in drought and normal years respectively, while the daily mean temperature was only decreased by 0.2°C and 0.12°C.*



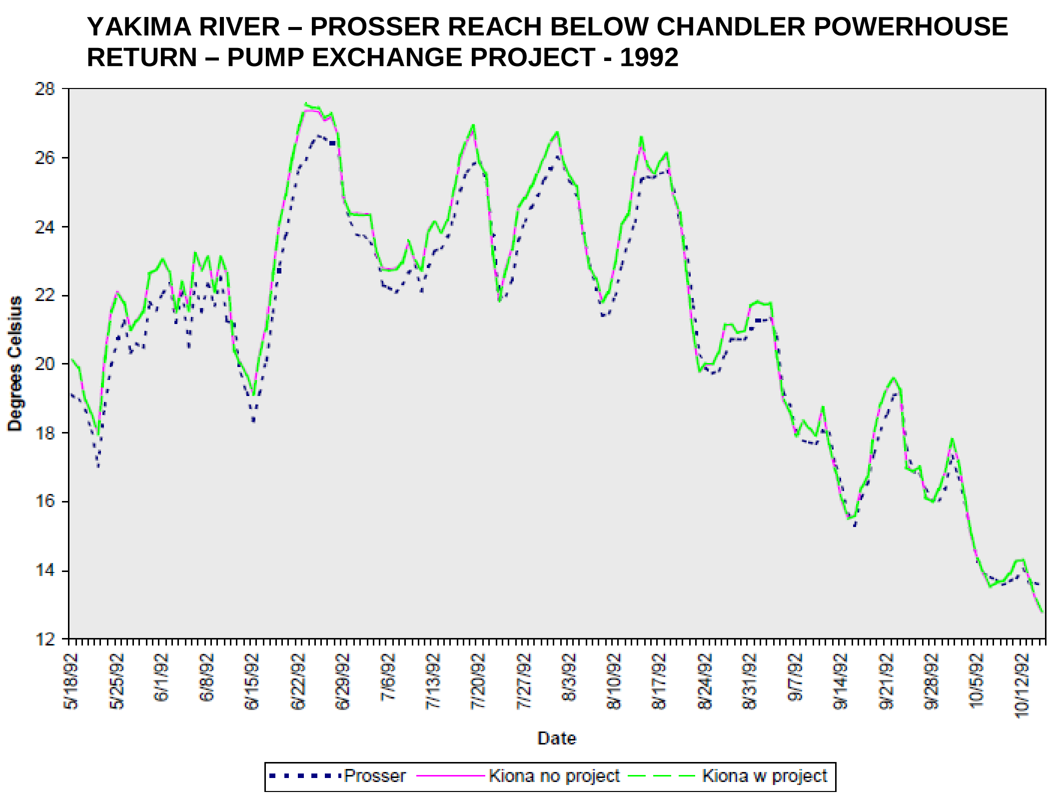


Figure 8. Simulated mean daily water temperatures with Project (green) and without Project (magenta), upstream and downstream of the Chandler Powerhouse under 1992 conditions. Water temperatures at Prosser Dam (blue) were measured in 1992.

It is not clear why the Carroll and Joy modeling results appear to contradict the KID modeling. Flow discharges used in the model were not reported by KID's consultants, so differences in flow cannot be assessed. Other differences in assumptions and input data may affect the results of the two models. However, both modeling efforts show that increased flows can reduce temperatures but that the reductions are small compared to other drivers for water temperatures in the Yakima River.

Fisheries Studies – 2001-2008

Haring (2001) reviewed the Yakima Basin fishery and the factors impacting fish stocks. Temperature was listed as a key limiting factor in the lower Yakima River and was associated with loss of riparian function, altered hydrology, and increased erosion and fine sediment delivery. High temperatures were particularly noted as a problem from Prosser to Richland. In general, fish numbers are low downstream of Sunnyside Dam. The report identifies a temperature budget as a data gap, and in particular the influence of groundwater inflows on mainstem temperatures.

Haring notes that 21 ^{o}C is the temperature that begins to become a barrier, and 25 ^{o}C is the threshold for lethality. At lower temperatures, temperature triggers fry emergence, adult migration and juvenile outmigration. Periods of high temperature can delay or truncate migration. Haring also notes the importance of thermal refugia and floodplains with associated temperature regimes. However, human alterations of flow, riparian vegetation, floodplains, and groundwater regimes may have increased the impact of high temperatures on fish populations.

The Snyder and Stanford (2001) review of river ecology and the interaction of flow and salmon identified several issues related to temperature:

- Implementation of normative flow regimes could improve temperatures.
- More research is needed to understand water and temperature budgets.
- The loss of spring flooding recharged groundwater adjacent to the river, which in turn provided reserves of cool flows during the summer.

The Reaches Study (Stanford et al., 2002) assessed the ecology of major floodplain reaches of the Yakima River and has been highly influential for directing fishery restoration actions. A key finding of the study relevant to temperatures is the importance of floodplain aquifers, which create areas of springs and groundwater upwelling that are critical fish habitat. Spring flooding recharges alluvial aquifers, which then cool thermal regimes in the summer. However, cumulative anthropogenic effects – changes from normative mainstem flows, loss of floodplain, the effect of irrigation return flows, and modification of shoreline hydrology – have reduced or eliminated these cool habitat areas.

Key factors for thermal regimes that benefit fish include:

- Groundwater upwelling in side channels and in spring brooks along the edge of the main channel
- Intact riparian forest helping to reduce heating in side-channels and spring brooks and adjacent to the stream bank
- Less influence and greater distance of the cool water inflows from irrigation return flows

Metrics that indicate the presence of cool water regimes include:

- Elevated near-shore water table in the spring driving groundwater inflows during the summer
- Hyporheic groundwater containing river macroinvertebrates and with ionic chemistry resembling river water
- Positive piezometric heads indicating a vertical hydraulic gradient and upwelling in the channel

Fish survey results from the Reaches Study supported the conclusion that salmonids were using these areas of thermal refugia to survive periods of low flow and high temperatures. Normative flows, especially replication of spring freshet flows, would help improve conditions for creating cool hyporheic flow in the summer.

In the summer of 2001, Vaccaro used a thermal profiling method to identify reaches with cool groundwater inflows (USGS 2005; 2006b; 2006c). The method involves drifting the river with a data logger in tow. Data from GPS and CTD (conductivity, temperature, depth) measurements were taken at 1-3 second intervals. Reaches that showed cooling during the summer were associated with tributary and side channels, springs, and geomorphic controls.

Bureau of Reclamation researchers studied the limnology of Cle Elum and Bumping Lakes (Reclamation, 2007b). The two lakes were monitored approximately monthly from September 2003 to October 2004, and Cle Elum Reservoir was monitored through October 2005. Some sampling events were skipped due to inaccessibility and snow conditions. Monitoring stations included inflow and outflow sites and three lake sites: uplake, deepest location, and downlake.

Monitoring parameters included vertical profiles of temperature, DO, pH, and conductivity; Secchi depth; chlorophyll-*a*, phytoplankton, and zooplankton; and nutrients and organic carbon. Temperature profiles showed both lakes to be dimictic, with isothermal profiles and turn-over in the spring and fall. Summer temperatures in Cle Elum Reservoir ranged from just above 5 ^{o}C at the bottom to over 18 ^{o}C at the surface, with a thermocline at about 17-18 meters. Bumping Lake summer temperatures ranged from 7 to 8 ^{o}C at the bottom to over 20 ^{o}C at the top, with the thermocline at about 5 meters depth.

System Modeling – 2008-09

USGS developed a temperature model for the Yakima River based on monitoring (USGS, 2008a). The SNTEMP modeling framework was used and the study domain was from the Roza Dam to the Prosser Dam. SNTEMP is a steady-state model that calculates daily average temperatures, and then estimates daily maximum temperatures from a separate algorithm.

The abstract describes the input data:

> *Flow and water temperature data for model input were obtained from the Bureau of Reclamation Hydromet database and from measurements collected by the U.S. Geological Survey during field trips in autumn 2005. Shading data for the model were collected by the U.S. Geological Survey in autumn 2006. The model was calibrated with data collected from*

April 1 through October 31, 2005, and tested with data collected from April 1 through October 31, 2006.

The study assessed the model quality with calibration and testing data sets. The root mean square errors ranged from 1.3 to 2.2 ^{o}C, while the mean error ranged from -1.3 to 1.6 ^{o}C. A sensitivity analysis found that water temperatures in the model responded primarily to air temperature and solar radiation. Relative humidity showed a moderate effect, while wind speed and channel width had little effect. Sensitivity to flow was not tested.

The USGS SNTEMP model was applied in several other studies. USGS developed a decision-support system to evaluate flow and temperature in the Yakima River (USGS, 2008b). The system used Reclamation's RiverWare system operations software to evaluate the five reaches identified in the Reaches Study (Stanford et al., 2002). A total of 13 habitat, water supply, sediment, and geomorphological parameters were analyzed, including maximum temperature based on the USGS SNTEMP model. Detailed temperature regimes for up to five life stages of six species were evaluated.

Several alternatives were analyzed with the decision-support system, including current conditions, future operations and conservation alternatives, and several proposed storage projects (Black Rock and Wymer). Temperature decreases were reported for Union Gap and Wapato reaches under the storage project scenarios, although a couple scenarios showed temperature increases. Operations and conservation scenarios showed little or no temperature changes. Temperatures were rolled up into scoring metrics for the final analysis of the alternatives.

Reclamation conducted an aquatic ecosystem evaluation of the Yakima River that included results from the SNTEMP model (Reclamation, 2008). The evaluation applied a suite of models, which included HEC-RAS, RiverWare, the decision-support system, sediment models, and fisheries models such as EDT. Temperature issues mentioned in the report include:

- Ecology's study of temperatures in the Naches River
- Limitations to the SNTEMP model:
  - For daily maximum temperatures, it is useful for comparison of scenarios, but not for accurate absolute values.
  - The model only addresses a portion of the Yakima River.
- Analysis of the thermal regime of the Yakima River was limited by inability to restore the historical hydrograph and the absence of connectivity with the historic floodplain.
- The analysis addressed both the direct impacts of temperature and impacts exacerbated by temperature: predation, sediment, and pathogens.
- Temperature and related factors were identified as key factors affecting abundance of all seven Chinook salmon and Steelhead populations evaluated.
- An appendix provides an assessment of potential Wymer Dam release temperatures.

USGS conducted a study of eutrophication in the lower Yakima River (USGS, 2009a). The study area extended from just upstream of Selah to about 4 miles above the river's mouth near Richland. Surveys were conducted and water quality monitored between April 2004 and September 2007. An extensive data set for temperature was developed and analyzed. Key findings related to temperature effects on eutrophication include:

- The growth season for macrophytes is initiated and ended by water temperatures.
- Water temperatures correlate with high pH and DO, which may be the result of the effect of temperature on both physical and biological processes.

Over the four years studied, water temperatures at Kiona exceeded the criterion of 21 °C about two-thirds of the time from July through September of every year. During the rest of the year the criterion was exceeded from 4% to 22% of the time, depending on the year. Temperatures at Mabton were monitored only in 2005 and exceeded the criterion 64% of the time in the summer months and 14% of the time during the rest of the year. Temperatures monitored near Zillah exceeded the criterion 48% and 33% of the time during the summer months of 2005 and 2006, respectively. Outside those months the criterion was exceeded 4.5% of the time in 2005 and 0.6% of the time in 2006. Temperature results are illustrated in Figures 9 and 10.

The report recommended further modeling and continuous monitoring to better understand the interactions of temperature with aquatic plant growth and DO and pH conditions.

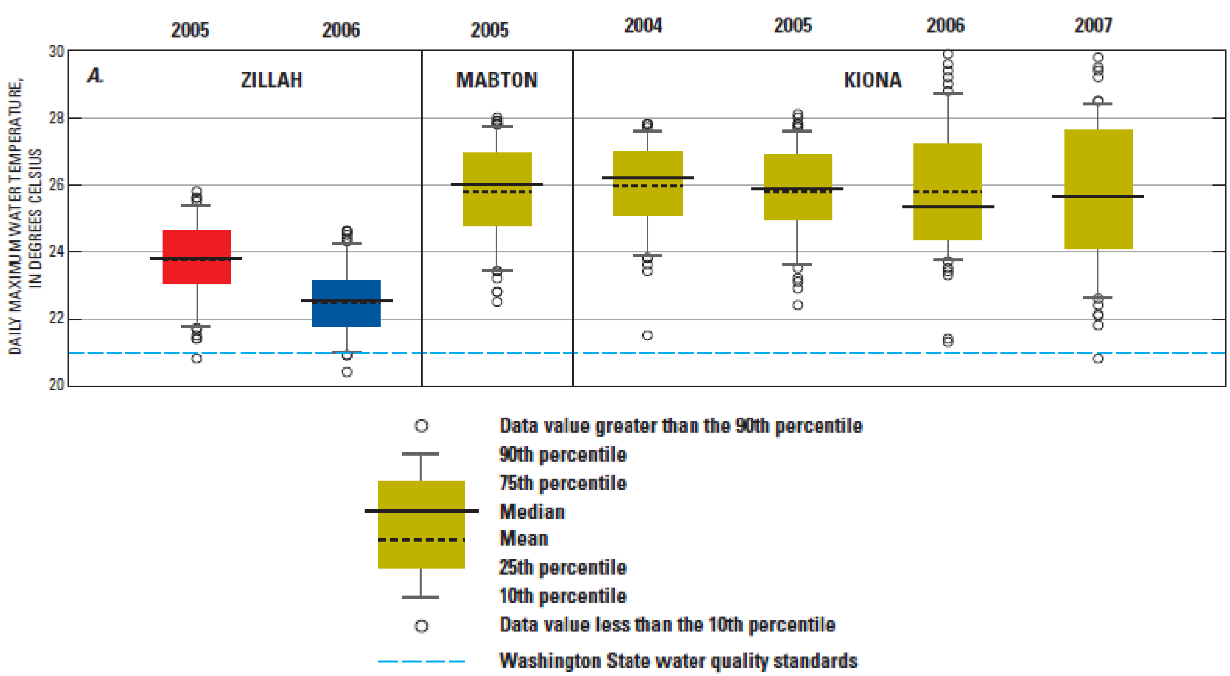


Figure 9. Summary of daily maximum water temperature for the Yakima River at Kiona (RM 30), Mabton (RM 55), and Zillah (RM 87), Washington, July 1-August 31, 2004-07. (USGS, 2009a).

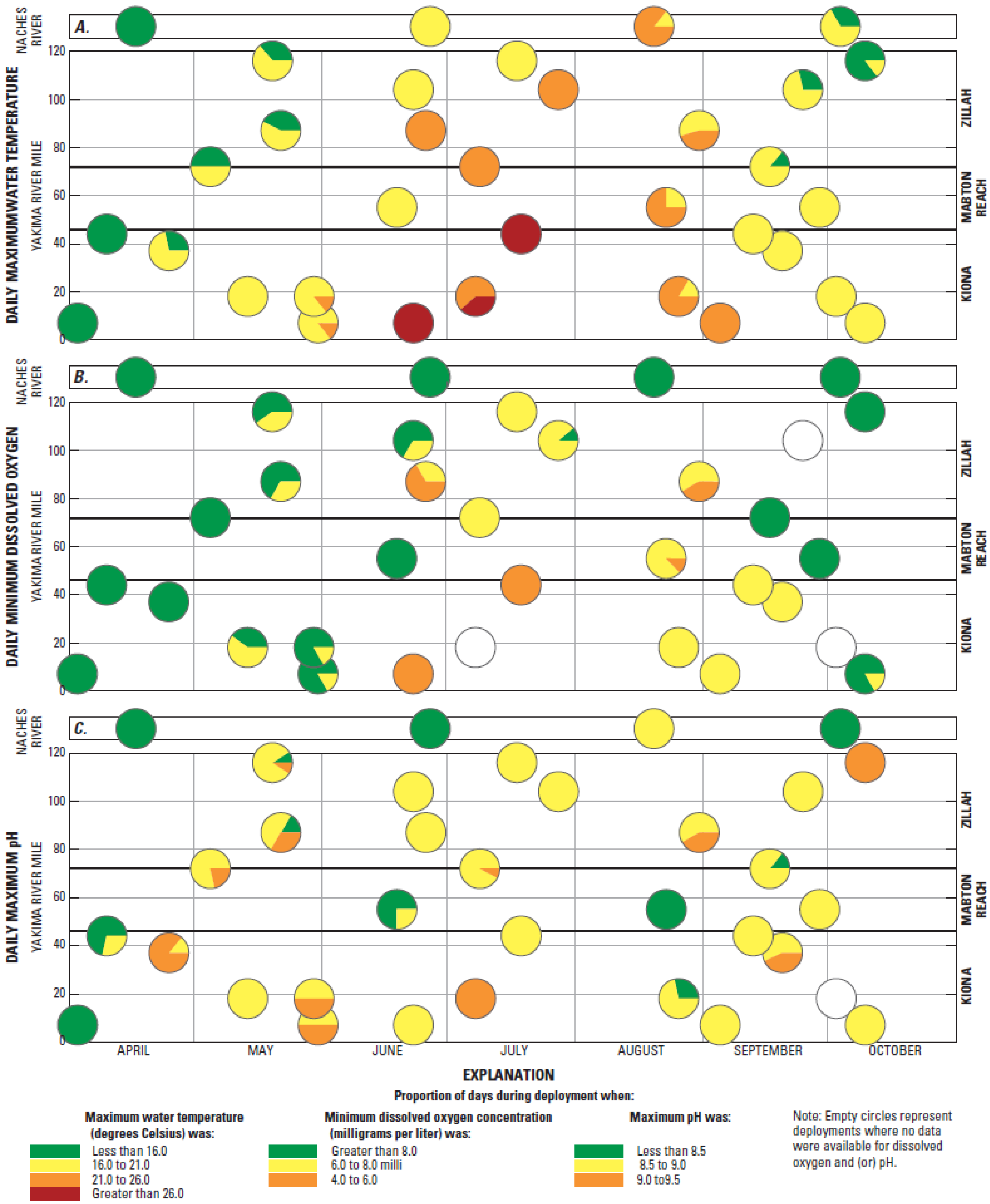


Figure 10. Summary of results from short-term continuous water-quality monitoring for (A) water temperature, (B) dissolved oxygen, and (C) pH, Yakima and Naches Rivers, Washington, April–October 2004. (USGS, 2009a).

Climate Change Impacts – 2011-2014

The Yakima Basin is considered one of the watersheds in Washington that is most vulnerable to the impacts of climate change. The University of Washington Climate Impacts Group (https://cig.uw.edu/) has issued multiple reports using the Yakima Basin to demonstrate the shift from a "transition" basin – mixed snow/rain regime – to a rain-dominated basin. The principle impact identified was a shift from an annual hydrograph characterized by a spring snowmelt freshet to a hydrograph dominated by winter rain. In addition, summers will be warmer and dryer. Although the extent to which conditions in the 2014-15 water year can be attributed to climate change has not been determined, researchers describe these conditions as a "sneak preview" of what can be considered the "normal" climate later in this century.[2]

Several studies have looked at the potential effects of climate change on the Yakima Basin. Maule et al. (2011) reported on work at USGS linking global climate change models to the existing structure of Yakima modeling. Projected future temperatures and precipitation were fed into the existing suite of watershed, river management, temperature, fish, and decision-support models. Altered hydrology and increased water temperatures were evaluated for their impact on fisheries and on socio-economic factors.

Hatten et al. (2014) provide an introduction to a special issue of the journal *Climatic Change*, which included five articles on the effects of climate change in the Yakima Basin. The abstract states the following:

> *Our simulations indicate that future summer will be a very challenging season for salmonids when low flows and high water temperatures can restrict movement, inhibit or alter growth, and decrease habitat. While some of our simulations indicate salmonids may benefit from warmer water temperatures and increased winter flows, the majority of simulations produced less habitat. The floodplain and tributary habitats we sampled are representative of the larger landscape, so it is likely that climate change will reduce salmonid habitat potential throughout particular areas of the basin. Management strategies are needed to minimize potential salmonid habitat bottlenecks that may result from climate change, such as keeping streams cool through riparian protection, stream restoration, and the reduction of water diversions.*

Two articles from this journal were particularly relevant to conditions in the mainstem Yakima River. Hardiman and Mesa (2014) used a bioenergetics model to evaluate the effect of rising temperatures on steelhead growth. Stream temperature models showed a 1-2 ^{o}C increase in daily mean water temperatures, resulting in an increase in growth in the spring but less growth in the summer.

Jenni et al. (2014) explored "a gap between management needs and the information that is available or is being collected." Researchers held workshops in the Yakima Basin to explore management needs and share a framework for climate change research in order to ensure future research is relevant. Attendees had a major focus on the Yakima Basin Integrated Plan since the Programmatic EIS had just been issued. Four key issues were identified by stakeholders. One of

[2] For example, a media report: http://m.spokesman.com/stories/2015/nov/04/pacific-northwests-2015-weather-likely-to-be-repea/

these was the "addition of modeling focused on predicting climate-driven changes to water temperatures in the lower main stem Yakima River, critical habitat for ocean and spawning migrations of Pacific salmon."

YBIP EIS Documents

Ecology issued a Final Programmatic Environmental Impact Statement (EIS) for the *Yakima Basin Integrated Water Resource Management Plan* (YBIP) in March 2012. Since that time, the YBIP's primary project areas have moved into various phases of development. Two water supply projects – the Cle Elum Pool Raise Project, and the Keechelus-to-Kachess Conveyance and Kachess Drought Relief Pumping Plant Project – have gone through project-specific environmental review. Environmental review documents are available at: https://www.usbr.gov/pn/programs/yrbwep/2011integratedplan/index.html.

The Cle Elum pool raise EIS (Reclamation and Ecology, 2014) includes analysis of temperature conditions. The document notes the problems with high temperature in the lower Yakima River from Prosser to the mouth. Also noted are the 303(d) listings for temperature above and below the reservoir, but the issue is deferred to the TMDL process.

Limnology of the reservoir was reviewed, noting conditions that were discussed above regarding the study by Reclamation (2007b). The depth of the outlet is cited as a reason that downstream temperature should remain cool. Downstream temperatures in mid-summer in 2003 through 2005 were measured as high as 21.2 ^{o}C and as low as 16.4 ^{o}C. Temperature measurements in the Cle Elum River in August 2015 were 19.7 and 19.8 ^{o}C (see Appendix A).

Several scenarios are provided to describe how the additional storage provided by the pool raise could be used to augment instream flows. One scenario envisions that "water would be released in a pulse or pulses and would be timed to coincide with cool temperature periods when river temperatures are acceptable to fish. The size and duration of pulse would be variable and would likely use 4,000 to 7,000 acre-feet to achieve the goal of aiding fish migration." The Cle Elum enhanced storage could either provide that pulse or replace water from other reservoirs used for the pulse.

The EIS provides an example from 2014 when a pulse of water was released during cool conditions in late July. Water temperatures dropping from over 25 ^{o}C to less than 22 ^{o}C triggered the movement of hundreds of sockeye and summer Chinook salmon. A similar event occurred in late August and early September 2015.

The EIS discusses the effect of the Cle Elum pool raise on temperatures above, below, and in the reservoir. It states the expectation that temperatures in the lake would change very little, given the very small change in surface area, and that outflow temperatures would change little because of the depth of the outlet. The EIS notes that temperatures affected by the project may not meet state standards and calls for additional analysis at the time of permitting.

A second EIS analyzes the Kachess Drought Relief Pumping Plant and Keechelus Reservoir-to-Kachess Reservoir Conveyance (or "K-K"; Reclamation and Ecology, 2015). The EIS provides a review of limnology. Data for Keechelus Reservoir was reported for 6 seasons between 1998 and 2011. The reservoir stratifies, with the highest observed surface temperature at 21.6 ^{o}C and bottom temperatures just above 4 ^{o}C. The metalimnion occurred roughly around 11 meters depth. Temperatures below this depth were less than 12 ^{o}C during all 5 surveys.

The EIS notes only one temperature in the Yakima River below Keechelus Reservoir exceeding 16 ^{o}C, at 17.6 ^{o}C. The reconnaissance surveys (Appendix A) in August 2015 measured temperatures of 19.9 and 20.7 ^{o}C at the Crystal Springs bridge. The water temperature at this site had dropped to 15.5 ^{o}C on September 1.

Reclamation also surveyed Kachess Reservoir during the same 6 seasons as Keechelus Reservoir. Kachess Reservoir also forms thermal stratification in the summer, with a maximum surface temperature of 22.1 ^{o}C, and bottom temperatures of 4 ^{o}C. The thermocline is usually between 10 and 12 meters depth, with temperatures above 16 ^{o}C found above this depth, and temperatures below this depth remaining less than 12 ^{o}C. The EIS notes that temperatures in the Kachess River below the reservoir exceeded the 16 ^{o}C criterion twice, and during the 2015 reconnaissance survey (Appendix A) temperatures of 19.7, 17.6, and 17.5 ^{o}C were recorded on August 4, 12, and September 1, respectively.

The K-K EIS notes the 303(d) listings in and below the reservoirs, including temperature listings above and below Lake Easton. The EIS includes a discussion of the TMDL process and scheduled TMDLs, but does not analyze the effect of the reservoirs on these listings.

Impacts from the project include the potential for warmer temperatures in Kachess Reservoir during draw-down from the pumping plant. Under these conditions the reservoir is likely to return to its original configuration of an upper and lower lake connected by a shallow channel, resulting in a much shallower pool and potentially a loss of stratification leaving only warm surface water. The EIS states that there would be little effect on temperature of moving water from Keechelus Reservoir to Kachess Reservoir during normal or wet years, but there could be higher water temperatures in Keechelus Reservoir following drought years.

Reconnaissance Survey – 2015

To support this assessment, several reconnaissance surveys were planned and executed in August and early September 2015 (Pickett, 2015b). The goal of the survey was to supplement existing temperature, DO, and pH data during 2015 drought conditions. A detailed report on results is provided in Appendix A.

Key findings include the following:

- Upstream of the confluence of the Cle Elum River, the more stringent temperature water quality criterion of 16 ^{o}C applies. The Kachess and Cle Elum Rivers below their respective reservoirs and the Yakima River from below Keechelus Reservoir to the Cle Elum River confluence were consistently out of compliance for temperature.
- The Yakima River in the Kittitas Valley exceeded temperature criteria in mid-August, but water quality compliance problems in this area were the least severe.
- Temperatures increase as the Yakima River flows downstream through the canyon and below Roza Dam through Selah. Temperatures exceeded the criterion of 21 ^{o}C at the station in

Selah just above the Naches River confluence in early August, and at all stations in mid-August.

- Below the Naches River, water quality conditions steadily worsen in the downstream direction, with daytime water temperatures rising to extraordinary levels as the river nears its mouth. These temperature levels were consistent with past surveys.

Dissolved Oxygen, pH, and Nutrient Issues

DO, pH, and nutrients are linked through the primary productivity of phytoplankton, periphyton (attached algae), and aquatic macrophytes (rooted plants such as stargrass). Primary productivity is when plants and algae use photosynthesis to create their own food and structural materials.

The photosynthesis during the day of algae and vegetation uses dissolved carbon dioxide (which forms carbonic acid) and generates dissolved oxygen. During the afternoon, the uptake of carbon dioxide reduces carbonic acid and raises the pH of the water, while the generation of DO may cause supersaturated DO levels.

At night the reverse occurs: respiration uses up DO and releases carbon dioxide resulting in lower pH and DO levels. The result are sinusoidal swings in DO and pH that can cause pH to exceed its criterion in the afternoon and DO to fall below its criterion late at night. These swings in pH and DO represent a "productivity signal" that can be measured through water quality monitoring.

Productivity is usually driven by nutrient levels, just as fertilizers grow crops. In some cases other factors, such as turbidity or scour, may limit productivity despite a surplus of nutrients. So understanding DO and pH problems may lead you back through measuring algal and plant biomass to monitoring nutrient levels in the water column and sediment.

Reservoir Limnology – 1990s

Ecology (1995; 1996) conducted a statewide assessment of lakes from 1989 through 1994, which included the Keechelus, Cle Elum, and Easton reservoirs. All three reservoirs were characterized as oligotrophic based on the Carlson Trophic Status Index, using chlorophyll-*a*, total phosphorus, and Secchi Depth data collected by Ecology. The study also collected data on total nitrogen, solids (TNVSS), and fecal coliform bacteria.

Hiebert (Reclamation, 1999) reported on the limnology of the 5 major reservoirs, with the following DO profiles in August 1998:

- Bumping Reservoir DO levels showed peak levels and supersaturation at about 10 meters depth. Surface DO was also supersaturated but fell below 8 mg/L mid-lake due to warm temperatures. DO near the bottom fell to near 5 mg/L.
- Rimrock Reservoir showed some curious patterns, with subsaturated DO levels below 8 mg/L through most of the water column. The one measurement that was supersaturated and above 8 mg/L was at 1 meter depth. DO near the bottom fell below 6 mg/L.

- Cle Elum Reservoir had DO that was slightly supersaturated in the epilimnion (above 14 meters depth), although sometimes below 8 mg/L. DO levels near the bottom were at times slightly subsaturated but above 8 mg/L, while at other times below 8 mg/L but at saturation.
- Kachess Reservoir had DO near the surface that was supersaturated but below 8 mg/L, peak DO at about 14 meters depth, and DO near the bottom around 7 mg/L.
- Keechelus Reservoir had supersaturated DO in the epilimnion and peak DO levels at about 14 meters depth, with bottom DO subsaturated but still above 8 mg/L.

Profiles in the lake showed little variation in pH, with all measurements within criteria. With regard to trophic status, Rimrock Lake had chlorophyll-*a* levels and a Secchi depth that placed it in the mesotrophic range. The other 4 lakes had characteristics that designate them as oligotrophic.

Lower Yakima River Modeling – 2000

Carroll and Joy (2001) modeled the lower Yakima River with the QUAL2E model from above Prosser Dam to the Highway 182 bridge 5 miles above the mouth. Modeling of DO was limited by the fact that phytoplankton alone could not explain the DO diurnal variations, so they used a simple assumption (negative SOD) to estimate Periphyton DO productivity. The study did not evaluate pH.

Calibration to DO and BOD was reasonable, but the model did not perform as well with chlorophyll-*a*. The system was clearly light-limited at the time, and the authors felt some of the complications had to do with the algorithms for light-limitation. Nutrient levels were reproduced reasonably well, although dissolved P increased in the Chandler bypass reach for reasons that were not clear. The pump exchange project was predicted to have little effect on dissolved oxygen, although increased flows were expected to increase algal levels due to decreased settling. Diurnal swings in DO that resulted in levels below the water quality criterion were expected to continue.

Fisheries and Water Quality Studies – 1999-2009

The USGS Yakima Basin NAWQA studies (USGS, 2003; 2004) collected data on nutrients in tributaries and in the mainstem at Kiona. The study found that “forms of nitrogen and phosphorus are highly water soluble, and concentrations in some agricultural drains were high enough to support nuisance-level growths of algae.” The study also noted that “concentrations of total phosphorus have begun to decrease in the major agricultural tributaries in the Lower Valley.”

Haring (2001) notes the importance of dissolved oxygen for salmon, but does not single it out as a limiting factor for salmon in the mainstem Yakima River. The author notes that areas of cool hyporheic groundwater flow may have higher DO, while areas of low flow may have lower DO, especially in deeper pools. The effect of low-elevation reservoir releases on downstream DO is also noted. The importance of pH for salmon is also noted but only mentioned with regard to pH 303(d) listings in the lower Yakima River.

In the Reclamation (2007b) study of the limnology of Cle Elum and Bumping Reservoirs, conditions similar to Hiebert's study (Reclamation, 1999) were found:

- Cle Elum Reservoir had an "orthograde" oxygen profile, with depressed oxygen in the warmer epilimnion, higher DO in the metalimnion. DO decreased again towards the bottom, but remained above 6.5 mg/L.
- DO in Bumping reservoir also showed maximum levels near the metalimnion, but levels at the bottom were lower, dropping below 2 mg/L.
- In both reservoirs, pH tended to be highest near the surface when algae activity was highest, and lowest near the bottom, sometimes dropping below 6.5.
- Chlorophyll-*a* levels and Secchi depths for both lakes indicated oligotrophic conditions.

USGS Eutrophication Study – 2003-2007

The USGS eutrophication study of the lower Yakima River (USGS, 2009a) provided significant insights into DO, pH, nutrients, and productivity in the river. The study divided the lower Yakima into three reaches:

- **Zillah Reach:** From upstream of the Naches River confluence near Selah to just above Satus Creek near Sunnyside. This reach had "abundant periphyton growth and sparse macrophyte growth, the lowest nutrient concentrations, and moderately severe summer dissolved oxygen and pH conditions in 2005."
- **Mabton Reach:** From the end of Zillah Reach downstream to the Prosser Dam. This reach had "sparse periphyton and macrophyte growth, the highest nutrient conditions, but the least severe summer dissolved oxygen and pH conditions in 2005."
- **Kiona Reach:** From the end of Mabton Reach to 4 miles above the mouth near Richland. This reach "had abundant macrophyte and epiphytic algae growth, relatively high nutrient concentrations, and the most severe summer dissolved oxygen and pH conditions in 2005."

Aquatic plant and periphyton growth caused wide diurnal swings of DO and pH, resulting in high daytime pH levels and low nighttime DO levels that were frequently outside state criteria. Figures 10 and 11 illustrate the patterns of DO and pH found at three continuous monitoring stations.

Nutrient levels were generally ample to support aquatic periphyton and macrophyte growth. The study explored nutrient-productivity relationships:

- In the Zillah Reach: "periphytic algal growth generally was not nutrient-limited and frequently reached nuisance levels." Nutrient levels dropped in the downstream direction but were still at measurable levels. Physical factors (scour and sloughing) and grazing could have been limiting periphyton growth. Reducing nutrients to a level where they control periphyton growth may require addressing both surface and groundwater levels.
- The Kiona reach was dominated by aquatic macrophyte growth, in particular water stargrass (*Heteranthera dubia*). Macrophytes did not appear to be affected by nutrients in the water column, suggesting that they rely mostly on sediment nutrients. Variation in macrophytes density appears to be driven by water quantity – deeper water with velocities that scour root systems – and turbidity.

Prior to the extensive sediment controls put in place after 2000, turbidity appears to have reduced macrophyte growth. Low-flow years, such as 2005 and 2015, allow macrophytes to flourish. Macrophyte growth is less extensive in years with deep, fast, turbid flow from a snowmelt freshet that continues into the early summer. Conditions for macrophytes also appeared to be ideal in the other reaches; the reason that macrophytes are prevalent in the Kiona Reach but not upstream is unclear.

The USGS eutrophication study was designed to collect the data for modeling of DO, pH, nutrients, and aquatic growth. However, the modeling that this study envisioned has not yet occurred.

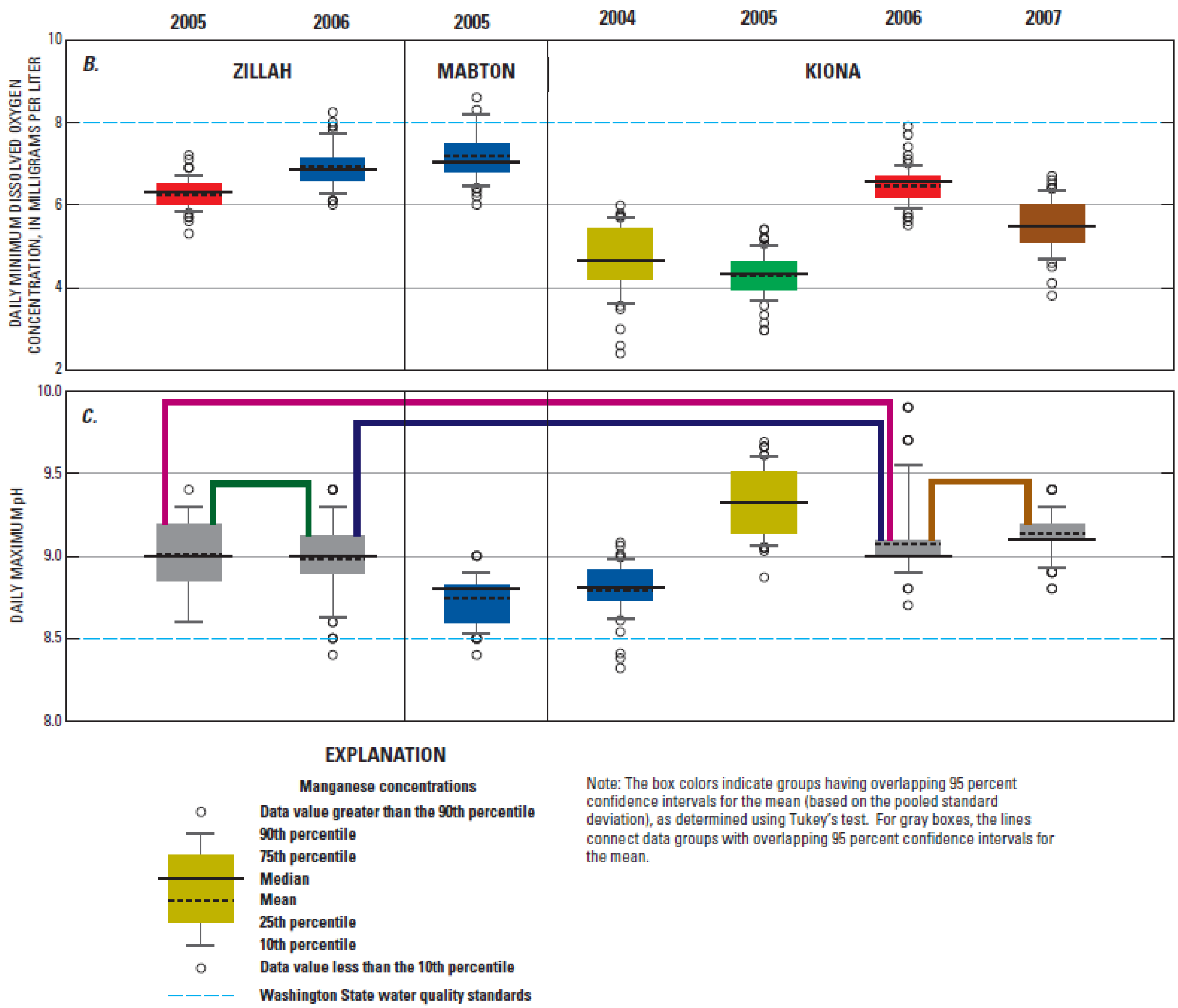


Figure 11. Summary of daily minimum dissolved oxygen concentration and daily maximum pH for the Yakima River at Kiona (RM 30), Mabton (RM 55), and Zillah (RM 87), Washington, July 1-August 31, 2004-07. (USGS, 2009a)

USGS Nutrient Load Model – 2013

USGS (2013) published the results of nutrient modeling using their SPARROW framework. As summarized by the abstract, the report found that:

> *In most catchments of the Yakima River Basin, the TN and TP in streams is from natural sources, specifically nitrogen fixation in forests (TN) and weathering and erosion of geologic materials (TP). The natural nutrient sources are overshadowed by anthropogenic sources of TN and TP in highly agricultural and urbanized catchments; downstream of the city of Yakima, most of the load in the Yakima River is derived from anthropogenic sources.*

The SPARROW model is a hybrid statistical and mechanistic model that can be used to estimate long-term steady-state nutrient loading from the landscape. The model uses a statistical analysis of catchment attributes to predict nutrient loading, and is calibrated to observed instream loading. Given the nature of the model, results should be viewed for general patterns of geography and source, rather than being predictive of local conditions.

Figures 12 (a) and (b) shows the pattern of loading by source categories from upstream to downstream, with the percentage from different sources shown in color using the left scale, and the total load in black using the right scale. In the upper basin overall loading is low, with forest, grazing, and farm fertilizers as the predominant sources. Below the Naches River, loading increases steadily in the downstream direction, with point sources, farm fertilizer, and confined animal manure becoming the predominant sources.

Figures 13 and 14 show the spatial distribution of estimated nitrogen and phosphorus loading yields by catchment basin. In general, urban and agricultural areas show the greatest loading yields. However, forest and grazing lands represent a slightly higher proportion of phosphorus as compared to their contribution to nitrogen.

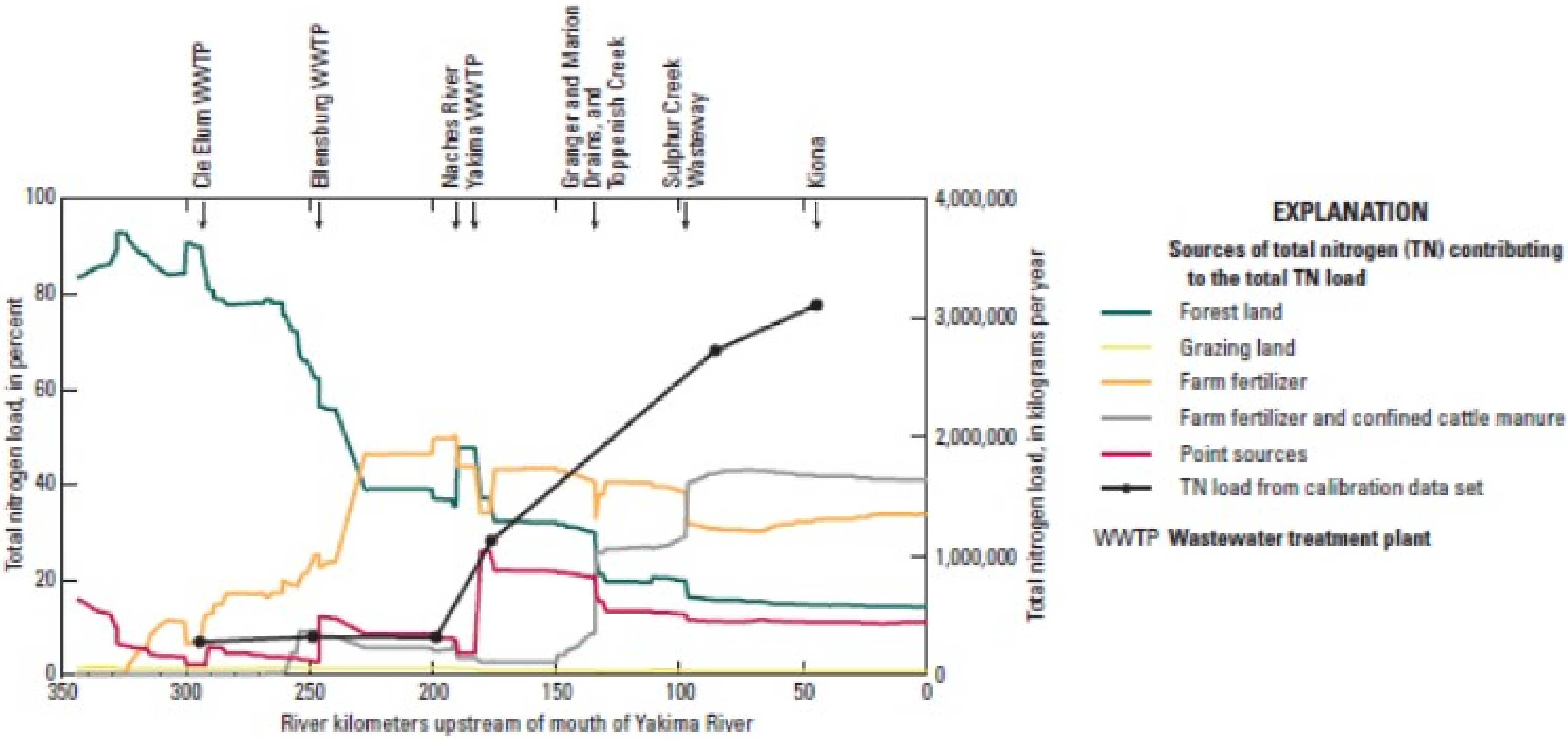


Figure 12 (a). Sources of total nitrogen contributing to the total load in the Yakima River.

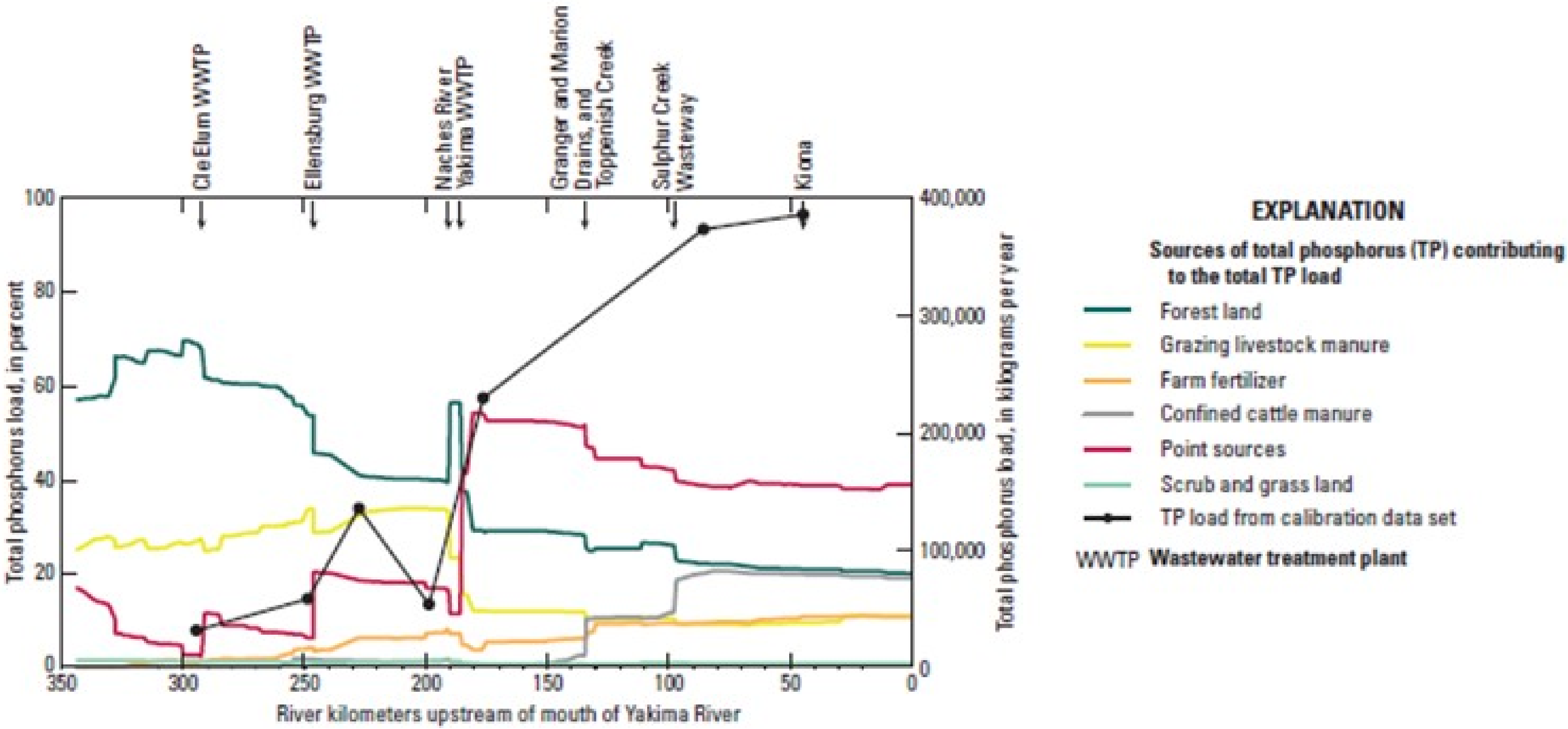


Figure 13 (b). Sources of total phosphorus contributing to the total load in the Yakima River.

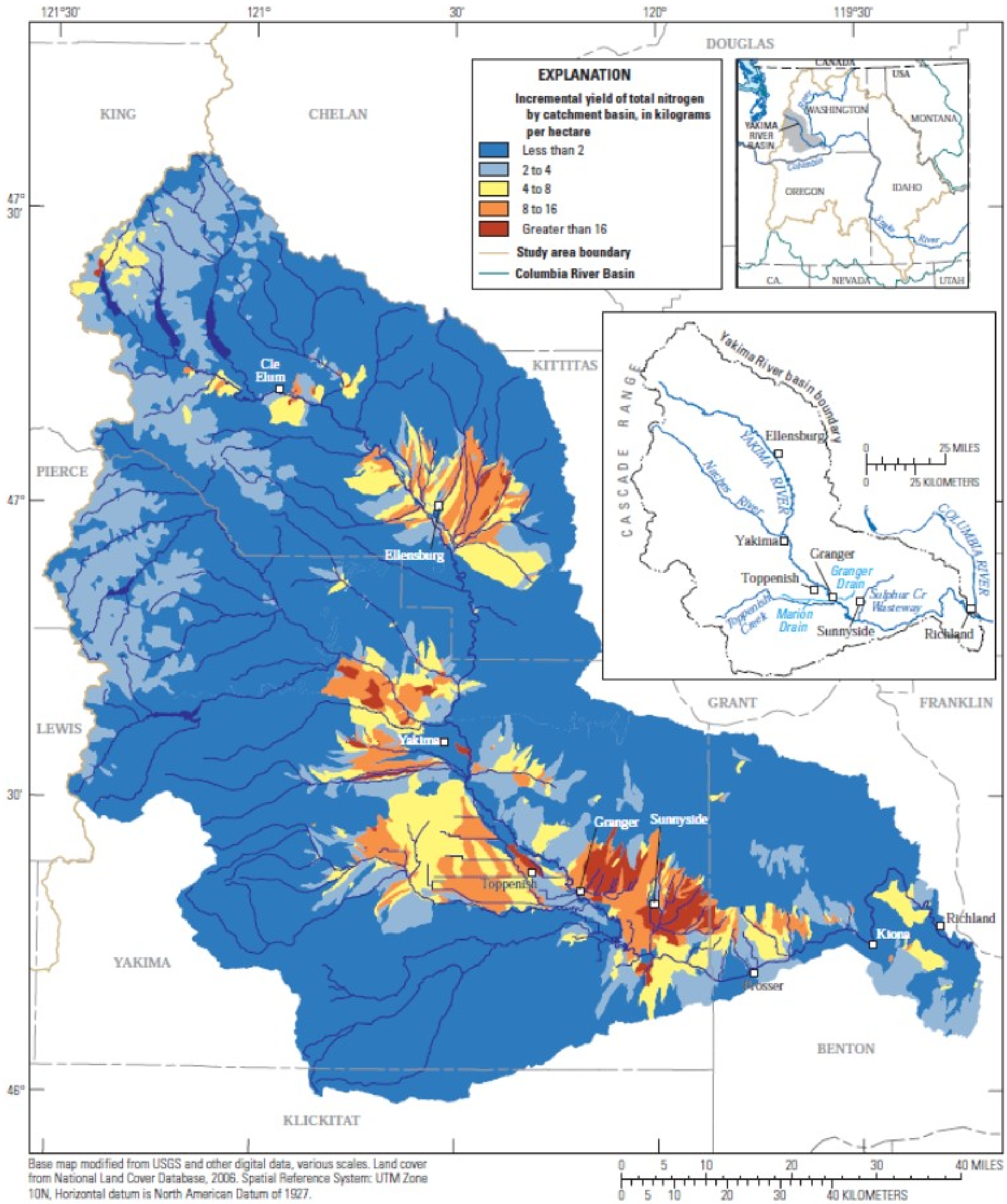


Figure 14. Incremental yield of total nitrogen for the Yakima River Basin.

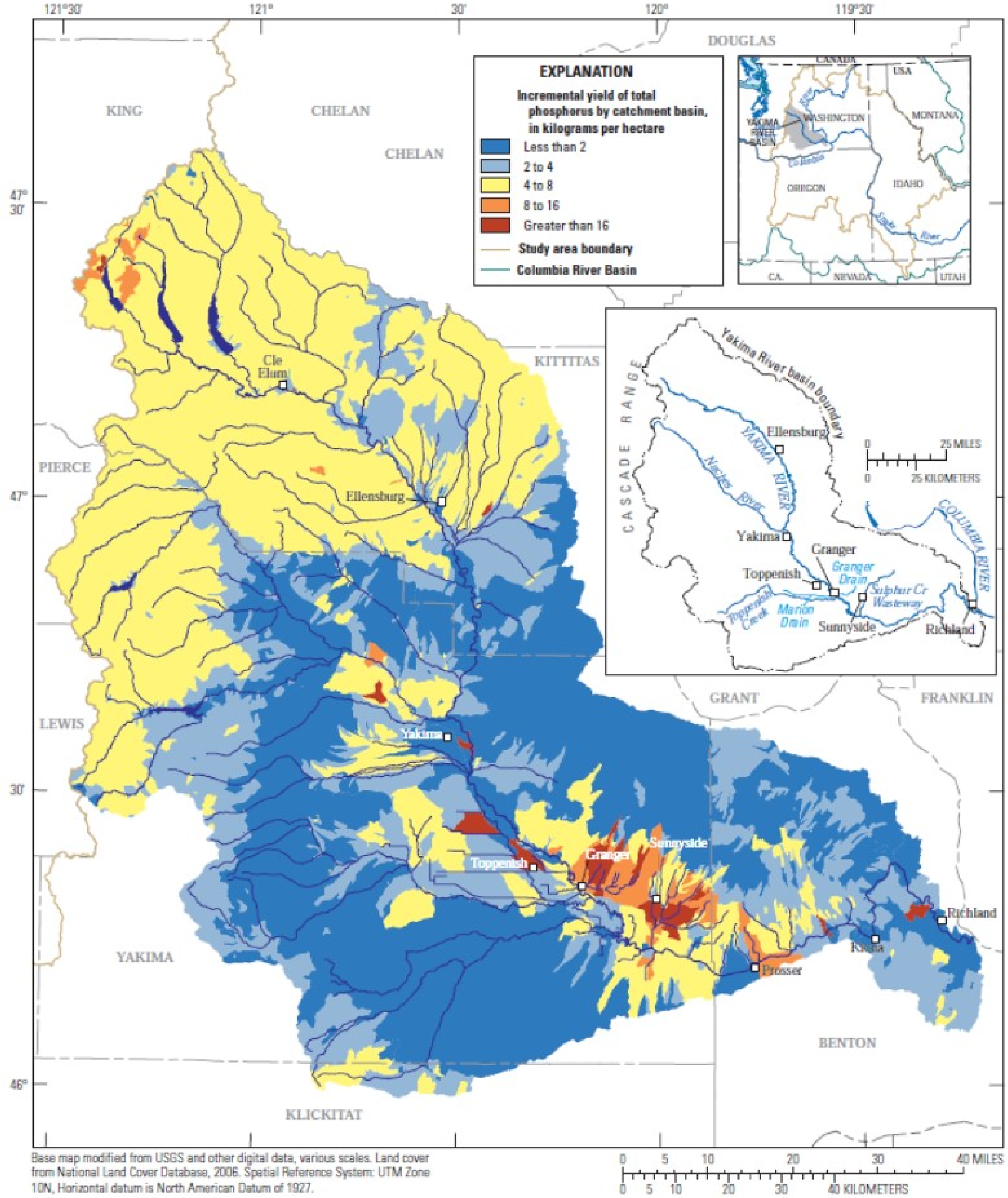


Figure 15. Incremental yield of total phosphorus for the Yakima River Basin.

YBIP Project EIS Reports – 2014-2015

As mentioned earlier, the Cle Elum Pool Raise EIS (Reclamation and Ecology, 2014) provides a summary of the limnology of Cle Elum Reservoir. Ecology's lake surveys from 1989 and 1990 showed oligotrophic conditions, with elevated phosphorus and supersaturated DO. DO and pH profile patterns were described from earlier studies, noting that DO remains above 6 mg/L at the reservoir bottom, and pH is mostly between 7 and 8. The study notes that the reservoir nutrient levels are likely lower than for the original lake before the project due to the absence of marine nutrients from anadromous fish. The EIS did not expect the Pool Raise project to significantly affect DO or pH levels in the reservoir or downstream.

The K-K EIS (Reclamation and Ecology, 2015) summarized the limnology of Keechelus and Kachess Reservoirs that has been reported above. DO in the Kachess River fell below the criterion of 9.5 mg/L on two occasions. The proposed operations – transferring water from Keechelus to Kachess and pumping Kachess low during drought conditions – are expected to reduce DO in the reservoirs during drought operations. The EIS expects DO to be reaerated in the Kachess Reservoir outlet as it passes through an outlet rip-rap structure. No impact on pH is expected from the proposed projects.

Reconnaissance Survey – 2015

Key findings of the reconnaissance survey regarding DO and pH in August and early September 2015 (Appendix A) include the following:

- Upstream of the confluence of the Cle Elum River, the more stringent DO water quality criterion of 9.5 mg/L applies. The Yakima, Kachess, and Cle Elum Rivers and its major tributaries were consistently out of compliance for this parameter. DO below Lake Easton was consistently subsaturated. Levels of pH fell within criteria.
- The Yakima River in the Kittitas Valley showed the productivity signals of high pH and supersaturated DO, but these parameters met criteria.
- Productivity impacts grow as the Yakima River flows downstream through the canyon and below Roza Dam through Selah, with data showing problems with pH and DO compliance.

Below the Naches River confluence, productivity signals increase in the downstream direction, with daytime pH and DO supersaturation rising to extraordinary levels as the river nears its mouth. DO and pH levels were consistent with past surveys. Variation in daytime pH and DO levels at stations between Parker and Kiona suggest that productivity levels may differ between reaches.

Ongoing Monitoring and Studies

Several agencies conduct regular water quality monitoring in the mainstem Yakima River and major tributaries. These include:

- Department of Ecology water quality monitoring stations: four long-term and two basin stations. There are also other stations with historical data – 14 stations on the Yakima River and two stations on the Cle Elum River. On the Naches River there are one long-term station and three stations with historical data.

- Department of Ecology flow gaging stations: there are one telemetry station and two historic stations on the Naches River. Ecology has not conducted flow gaging on the mainstem Yakima River.
- USGS flow and water quality stations: there are four real-time flow stations on the Yakima River. Two of these also have historical water quality data. Another twelve historical stations have flow data, and some of these also have water quality data.
- The Bureau of Reclamation has a multitude of flow gages in the Yakima Basin. Thirteen are on the mainstem Yakima, and there are also stations in and below the six major reservoirs. Most of these stations also collect water temperature data, although one of Reclamation's staff indicated that there is no systematic data quality procedures for temperature monitoring.

The U.S. Forest Service has created the NorWeST regional stream temperature database[3], which includes temperature monitoring collected from across the Pacific Northwest. NorWeST includes 143 temperature data sets from at least 26 locations on the Yakima River.

During 2015 and 2016, the Washington Department of Fish and Wildlife is conducting a limnology study of Kachess Reservoir (Ecology and WDFW, 2015). Inflows, outflow, and lake profiles are being monitored. Parameters include temperature and DO, nutrients, organic matter, algae, and several fishery metrics. A Quality Assurance Project Plan is being developed but is not yet available.

Researchers have reported other studies at regional conferences and meetings which have included temperature monitoring, including detailed studies of fish mortality at Roza Dam and predation in the lower Yakima River below Prosser.

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[3] http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST/StreamTemperatureDataSummaries.shtml

Discussion

Overarching Issues

This study supports an initiative whose purpose is two-fold:

- To evaluate compliance of the mainstem Yakima River with the Clean Water Act – in particular the 303(d) list of impaired waters
- To integrate CWA compliance with the Yakima Basin Integrated Plan

Compliance with the CWA is multi-dimensional. When the State's water quality criteria are not met, section 303(d) of the CWA mandates that the TMDL be determined for pollutants causing the impairment. State water quality standards also protect the designated uses of the water through other mechanisms, such as anti-degradation provisions and narrative criteria. Legal decisions (for example, the Chelan River hydroelectric license appeal) have pointed out that the core purpose of the CWA is to protect those uses, and application of water quality criteria are one tool to achieve protection.

The YBIP is primarily focused on water supply for human use and on salmon restoration. The CWA specifically does not regulate flow or water rights, but a water quality analysis can inform water management under the YBIP. However, compliance with the CWA is closely linked to salmon restoration, since the CWA is intended to support the designated use of fish life cycle needs such as spawning, rearing, and migration. Water quality studies of the mainstem Yakima River, and any subsequent TMDL determinations, can support YBIP fishery goals and identify potential solutions, work elements, and partnerships for these shared goals.

The mainstem Yakima River is particularly challenging with regard to CWA compliance for many reasons:

- The Yakima River flows through a large basin that is diverse in terms of geology, hydrology, biomes, and human uses.
- The Yakima River has only a few major tributaries and a myriad of small tributaries and irrigation diversions and return flows, as well as several wastewater and drinking water treatment plants. Vaccaro's analysis of groundwater-surface water exchanges (USGS, 2011b) identified 60 inflows and 23 diversions on the mainstem Yakima River, of which 46 inflows and 17 diversions were from Roza Dam downstream. The USGS temperature model (USGS, 2008a) analyzed 34 inflow and 10 diversions below Roza Dam. The USGS eutrophication study (USGS, 2009a) monitored at almost 90 sites between Selah and Richland.
- Flows in the river are highly managed, which sets practical limits on implementing CWA requirements, such as a TMDL.
- The study of fishery restoration, as has been demonstrated by the literature survey above, is well advanced. CWA compliance will need to complement this restoration work rather than drive it. Water quality studies can help link fish restoration to CWA designated uses, while local fishery knowledge can help prioritize tasks for water quality restoration.

- State temperature criteria are relatively simple compared to the fishery needs identified in studies. The daily maximum temperature found anywhere in a reach or water column does not reflect the variety of temperature regimes that have been identified to support salmon, such as cool water refugia and pulses of higher flow with cooler water.
- Increased riparian shading is one of the most commonly recommended remedies for elevated stream temperatures. Although riparian vegetation has been identified as a benefit to the mainstem Yakima, it's likely that the benefit of increased shading on temperatures across the channel will be small or negligible, given the width and morphology of the river. However, creation of additional shading may be useful in creating microhabitats along the shoreline or stabilizing and cooling braided channels. Yakima fishery studies have shown that protecting salmon from temperature impacts will require a complex mixture of riparian restoration, floodplain restoration, and management of hyporheic groundwater regimes.
- Similarly, the research suggests that ability of nutrient controls to benefit DO and pH may be limited. Given that DO and pH problems are driven by periphyton and aquatic macrophyte productivity, an implementation strategy will likely also need to address flow regimes and physical controls.
- A significant portion of the mainstem Yakima River is shared with the Yakama Nation. Coordination and co-management of future water quality improvement projects between Ecology and the Yakama Nation will be critical to their long-term success.
- These issues translate into challenges both in agency policy and in relationships with local stakeholders through the YBIP.

One important observation is that the fishery community clearly places the highest priority on temperature problems, rather than on DO or pH problems. The extent of research is far greater and temperature issues are far higher in expressed priorities. However, low DO can certainly be detrimental to salmonids, especially to spawning, emergence, and juvenile rearing.

Some research indicates that high pH begins to impact salmonids at levels above pH 9 (Carter, 2008), and EPA criteria for ammonia show a rapid increase in toxicity as pH rises (EPA, 2013). Ammonia criteria are calculated from temperature and pH. At pH levels above 9 and temperatures around 27 ^{o}C as observed at the Kiona gage, the ammonia criterion drops below 0.3 mg/L. Fortunately, measured ammonia levels have been at much lower levels, probably due to plant preferential uptake and nitrification. However, a high pH makes the river highly vulnerable to toxicity from an ammonia spill.

Given all these challenges, it's clear that projects under this initiative will take many years to complete, and will be most successful if built out of components specific to geographic areas and parameters. A discussion by reaches follows.

Upper Yakima River – Easton Basin

The upstream area of the Upper Yakima Basin – which includes the Keechelus, Kachess, and Cle Elum Reservoirs and the rivers below the reservoirs – can be separated out, due to distinct regulatory and hydrologic regimes. More stringent standards apply from the confluence of the Cle Elum and Yakima Rivers upstream. In addition, there is a significant hydrogeological boundary below the Teanaway River near Horlick, where the river cuts through a bedrock outcropping that divides the Cle Elum Valley and Roslyn groundwater basin from the Kittitas Valley.

The Yakima, Kachess, and Cle Elum Rivers in this area have the following unique features:

- There are existing 303(d) listings for temperature and DO in these waters. Reconnaissance measurements in August 2015 confirmed that criteria for temperature and DO were not being met in these three rivers. There is also a listing for low pH below Lake Easton, which also should be evaluated.
- Conditions are strongly influenced by the operation of the three reservoirs.
- These water bodies have been identified as critical salmonid spawning habitat.

A water quality study of this area would likely need to include the following components:

- A study of the three reservoirs that evaluated water quality at multiple depths in the forebay and in the outlet below the dams.
- A key question that needs to be researched is the flow structure from each reservoir to the outlet under different release rates and reservoir pool elevations. From the limnology data available, the flow structure would strongly affect the depth and quality of water being entrained into the outlet flow. This issue has not been addressed by past research but appears to be key to understanding downstream conditions.
- Evaluation of water quality conditions upstream, within, and downstream of Lake Easton.
- Interactions of the Yakima, Kachess, and Cle Elum Rivers below the reservoirs with the Roslyn groundwater basin.
- If the study is extended to the hydrogeological boundary below the Teanaway, wastewater discharges from City of Cle Elum and contributions from the Teanaway River would also need to be considered.

Given the stringent water quality standards and the critical salmon habitat, this area is a high priority for study.

Kittitas Valley

Below the confluence of the Cle Elum River the less stringent water quality criteria for the mainstem Yakima River apply. This area can be considered to extend into the Yakima Canyon above Umtanum Creek, where an Ecology water quality station and USGS flow gage are located.

There are no 303(d) listings for temperature, DO, and pH in this reach in the Yakima River. However, 2015 reconnaissance monitoring during hot weather showed temperatures exceeding criteria from the bridge near the Thorp mill downstream. DO and pH levels met criteria above the canyon and did not show the effects of elevated productivity.

Also, continuous monitoring above Umtanum Creek showed temperature rising above criteria in the daytime and DO dropping below standards during the night. The timing of grab sampling at this Ecology monitoring station has typically been mid-morning when these daily extremes would have been missed.

Although the degree to which criteria are not met is less severe in this reach of the Yakima River compared to what monitoring showed in other reaches, temperature issues should still be addressed as part of a future project under this initiative. Also, the appearance of diurnal swings in DO saturation and pH indicate that productivity is rising. This suggests that nutrient sources from the Kittitas Valley, combined with geomorphic changes in the canyon, may be allowing productivity to rise and drive DO below the criteria at night. No research has been done to investigate this possibility, so further study is needed.

Yakima Canyon and Selah Reach

Reconnaissance data from August 2015 showed increasing temperatures, pH, and DO saturation from Umtanum Creek downstream to the confluence of the Naches River. There are existing 303(d) listings for pH at the Harrison Street bridge based on high pH levels measured during five years of monitoring at Ecology's water quality monitoring station. Ecology measured temperatures above the 21 ^{o}C criterion at this location in 1998 and 2001 as well as during the 2015 survey.

A key feature of this reach is a major flow diversion at Roza Dam near the downstream end of the Yakima Canyon. The Roza diversion represents the beginning of the lower Yakima Basin. Irrigation flows in the Kittitas Valley return to the river before entering the canyon, and river flows begin their distribution into the lower valley at Roza. Studies of the lower river have begun either at the Roza Dam or just upstream of the Naches River confluence. Fisheries studies have identified the reach below Roza Dam as a critical reach for salmonid migration.

Naches River

Ecology has established TMDLs for temperature in the upper Naches River and is currently conducting a temperature TMDL study of the Tieton and lower Naches River. Since this analysis focuses on the mainstem Yakima River, these studies will not be evaluated in detail. However, given the scope of these studies and based on the literature review, some gaps in information exist that may require further study:

- The effect of reservoir releases on the Tieton and Naches Rivers have so far not been included in TMDL studies. The Rimrock Reservoir appears to be the most nutrient-enriched of the 6 major reservoirs and is the largest reservoir built where no lake previously existed. Like the three Yakima headwater reservoirs, the interaction of productivity, stratification, draw-down, and release rates is not well understood and could significantly affect downstream water quality.
- There is an existing 303(d) listing for pH in the Naches River near Yakima. This is both a water quality problem in itself and could represent the influence of nutrients that could continue to affect the mainstem Yakima River. A study of this listing should be planned as part of a future project under this initiative.

- The Naches River is the single largest tributary to the lower Yakima River. Water supply management has a significant effect on the Naches River and the Yakima River downstream of the Naches. Water quality studies and CWA compliance should be integrated with YBIP implementation as part of this broader initiative.
- Also, if loading limitations are set on the lower Yakima River, nutrient loading should be characterized in the Naches River, because it is potentially a significant loading source.

Naches River to Sunnyside Diversion

Below the confluence of the Naches River, water quality is slightly ameliorated but continues to exceed criteria. Temperatures of above the criterion have been measured during two years at Ecology's water quality monitoring station "at Nob Hill" (just upstream of the Nob Hill Boulevard/ Highway 24 bridge), as well as during the August 2015 surveys. Measurements of pH exceeded standards at the Nob Hill station during all years except two since 1997, resulting in a 303(d) listing for pH. Grab measurements from the 2015 reconnaissance surveys showed continued productivity signals (high pH and supersaturated DO), although pH levels dropped slightly below Nob Hill station.

The "gap-to-gap" reach – from Selah Gap to Union Gap – was identified as a critical recovery reach in the Reaches Project report. This reach has been and continues to be a high priority for floodplain restoration efforts by fisheries groups, Yakima County, Reclamation, and the Army Corps of Engineers.

Yakama Nation reservation boundaries begin at the mouth of Ahtanum Creek, and the Yakima River is a shared jurisdiction from that point downstream to Mabton.

Just below Union Gap two major diversions provide water to the Wapato and Sunnyside Canals.

Wapato to Prosser

Studies have identified this reach as critical for salmonid spawning, rearing, and migration, yet water quality information is limited. Both the USGS eutrophication study (USGS, 2009a) and the 2015 surveys showed a steady increase in temperatures downstream, with mid-day temperature consistently above 21 ^{o}C and downstream temperatures well above 25 ^{o}C, which has been identified as lethal for salmonids and a barrier to all life stages.

Productivity signals are strong in this reach. During the 2015 reconnaissance surveys, DO saturation and pH both showed a marked increase at the Donald Wapato bridge from upstream stations. The USGS eutrophication study showed DO and pH consistently not meeting criteria in the Zillah and Mabton reaches. Continuous monitoring near Grandview during the 2015 surveys also showed low DO during the night.

The USGS study identified high phytoplankton productivity in the Zillah reach. The study report was uncertain about productivity in the Mabton reach, but suggested lower productivity levels. Monitoring in 2015 near Grandview supported a reduced productivity effect, but suggested that DO was being suppressed overall, possibly by BOD or sediment oxygen demand effects.

These reaches represent both declining water quality and some top priority salmonid habitat. They are a very high priority for Ecology to address.

Prosser to Richland

Research and monitoring have documented the continued deterioration of water quality as the Yakima River moves downstream. Temperature continues to rise, pH swings to high levels, and DO shows wide swings caused by productivity.

Monitoring during the reconnaissance survey showed some significant problem with water quality in the pool behind Prosser Dam. Along with high temperatures and pH, late afternoon grab measurements of DO were depressed compared to other sites. This is consistent with the measurements near Grandview and suggests an overall DO sag.

The effects of aquatic macrophytes, documented by the USGS eutrophication study, were apparent in the 2015 surveys. Continuous monitoring at Kiona showed the widest swings in DO and pH from all river monitoring. Temperatures, pH, and DO supersaturation continued to climb towards the river's mouth. Monitoring at Twin Bridges on August 13th showed a temperature of 27.9 ^{o}C, pH over 9.1, and DO saturation of 172%, representing the highest set of measurements in the system during all surveys.

Below the Prosser Dam, fishery literature only identifies fall Chinook as spawning in this reach. High summer water temperatures create a barrier that prevents any salmonid use, but this may still allow warm-water predator fish to flourish. Salmonid migration ends in the spring when temperatures rise and begins again in the fall when temperatures fall. Releases of pulses of water from the Reclamation project during mid-summer cool weather has been shown to be effective to lower water temperatures and trigger a burst of migration.

Optimizing conditions for fishery management will focus on reducing the length of the season where a temperature barrier exists, providing opportunities for migration during cool weather, and maximizing cool water refugia. From the fishery standpoint, DO and pH represent secondary considerations. Nevertheless, reducing the frequency and severity of DO and pH impairment will still have a fishery benefit.

Yakima River Delta

The Yakima River delta has been studied extensively, with the focus on Bateman Island and decreased circulation due to the Bateman Island causeway[4]. Monitoring and modeling have been conducted, documenting high temperatures behind Bateman Island. This is both adding to the thermal barrier at the mouth of the Yakima River and has provided sanctuary to warm-water predator fish. Proposals for remedial actions are being reviewed. Ecology has been providing support for this work. It will be important to include the analysis of the delta in the overall strategy to address CWA compliance in the Yakima River.

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[4] http://midcolumbiarfeg.com/what-we-do/fish-passage/yakima-delta-assessment/

Potential Pollutant Sources

There are many potential pollutant sources in the Yakima River. These could be categorized as:

- Municipal and industrial point source discharges with a National Pollutant Discharge Elimination System (NPDES) permit
- NPDES-permitted stormwater discharges
- Land application facilities with a State Waste Discharge Permit (SWDP) which may influence the Yakima River through groundwater
- Nonpoint sources (not regulated through NPDES or SWDP programs)

There are 265 facilities in the upper and lower Yakima Basins that are covered by an NPDES or State Waste Discharge permit. These include individual permits and several general permits.

NPDES municipal point source discharges into (or near) the Yakima River include:

- Cle Elum (Upper Kittitas County Regional)
- Ellensburg
- Kittitas (Cook Creek)
- Selah (Selah Ditch)
- Yakima
- Buena (unnamed tributary)
- Zillah
- Toppenish (E. Toppenish Drain)
- Granger
- Sunnyside (Joint Drain 334, Sulfur Creek)
- Wapato (Marion Drain)
- Harrah (Marion Drain)
- Mabton
- Grandview
- Prosser
- Benton City
- Richland
- West Richland

In addition, the City of Naches and Cowiche Regional wastewater treatment plants discharge to the Naches River about 12.6 and 2.7 miles upstream of the Yakima River, respectively.

Table 4 provides a summary of the types of permits in the upper and lower Yakima Basins. Many of these may not affect the Yakima River or may not discharge pollutants that affect temperature, DO, or pH. Future water quality studies will need to determine which of these discharges to include in the analysis. This list is provided to give some sense of the number and type of facilities that will need to be evaluated.

Table 4. Summary of permitted facilities in the Yakima Basin.

Permit Type	Number of permitted facilities	
	Upper Basin (WRIA 39)	Lower Basin (WRIA 37)
Irrigation System Aquatic Weed Control GP	5	4
CAFO GP	0	4
Construction SW GP	21	31
Fruit Packer GP	9	39
Industrial NPDES IP	3	7
Industrial SW GP	13	31
Industrial to ground SWDP IP	4	8
Municipal NPDES IP	4	11
Municipal SW Phase II Eastern WA GP	4	7
Sand and Gravel GP	17	14
Upland Fish Hatchery GP	1	1

GP = General Permit; IP = Individual Permit; SW = Stormwater
CAFO = Concentrated Animal Feeding Operation

Nonpoint source pollutants derive from diverse and diffuse sources. Potential sources to the Yakima River could include:

- Residential, commercial, and industrial stormwater not covered by an NPDES permit
- Agricultural runoff
- Groundwater sources from adjacent land use activities, such as livestock operations, farms, industrial sites, landscaped areas, and ponds
- Failing on-site septic systems
- Landscaping fertilizer use
- Hydromodification, such as levees, bank armoring, and channelization
- Loss of riparian vegetation
- Forest practices

Dams and impoundments can be a pollutant source. Legal case law has determined that dams are point sources that are not covered by an NPDES permit. EPA guidance considers dams and impoundments to be a form of hydromodification, which is considered a point source. There are many storage dams, diversion dams, and weirs in the Yakima River. Besides the five Reclamation storage dams already discussed, major diversion dams include the Easton, Roza, Wapato, Sunnyside, Prosser, and Wanawish Dams.

Yakima Watershed Plan

The Yakima River Basin Watershed Management Plan (Watershed Plan; EES, 2003) reviewed actions to improve water quality that could address:

- Forest practices
- Impacts from agriculture
- Municipal and industrial stormwater management
- Gravel mining
- Impacts of recreation sites
- Wastewater treatment plants
- Management of water storage facilities and groundwater

The Watershed Plan proposed a "Surface Water Quality Strategy" that identified six priority actions to improve water quality:

- Improve irrigation management
- Improve crop land management
- Address livestock impacts
- Improve interagency coordination
- Improve understanding of water quality cause-and-effect relationships
- Expand water quality monitoring activities

The Surface Water Quality Strategy also identifies actions:

- Involving coordination of agencies engaged in water quality activities
- Improving the information base for water quality decisions; and
- Addressing water-quality standards to ensure they reflect natural background conditions

Modeling Feasibility

The identification of specific analytical approaches for any proposed studies will be evaluated through Quality Assurance Project Plan development. However, the technical findings discussed above suggest some likely approaches.

Given the size of the basin and the variety of issues, spatial scale is a challenge. Modeling of the entire river is not feasible, given the amount of resources it would require. A more strategic approach will be to approach the basin in several areas or regions that are individually more manageable. Multiple scales should be considered, including:

- Three major areas of the basin:
    - Easton Basin (from the three storage reservoirs to below the Cle Elum River, possibly to the geomorphic barrier near Horlick below the Teanaway River)
    - Kittitas Valley (from the Easton Basin to Umtanum Creek in the Yakima Canyon)
    - Lower Yakima Valley (from Umtanum Creek to the mouth)

- A second scale is to focus in on the major reaches identified by the *Discussion* subsections above. These reaches may be useful for planning monitoring or breaking modeling into practical reaches.
- Analysis of floodplain restoration and thermal refugia may force a focus on a finer scale, such as a shorter reach of intact or restored floodplain. Analyzing the water quality aspects of fine scale features such as groundwater seeps, wetlands, and braided channels may be impractical at the reach scale.
- Specific best management practices or restoration projects may need to be studied at the field scale for specific projects.

Regarding temporal scale, the diel pattern of temperature, DO, and pH calls for models that can predict changes at the hourly scale. The SNTEMP temperature model approximated this effect, but models are available now that can model diel changes dynamically. At the same time, analysis of seasonal changes is also important, since water quality is strongly affected by weather and flow which vary over the year on a daily basis. Again, models and computing power are now available to address this time scale.

The most likely approach to analyzing water quality in the Yakima River will be to take a step-wise approach of linked models and scaled analysis:

- The availability of the USGS groundwater model, the Reclamation operations model, and a HEC-RAS model of the Yakima River should make it possible to conduct a solid analysis of flow and hydrodynamics on an hourly time step over a year.
- The QUAL2KW[5] modeling framework seems well suited for modeling temperature, DO, and pH in the Yakima River. It has been a standard tool for modeling for many Ecology water quality studies. Features that could support modeling of the Yakima River include:
  - Time-varying flow and boundary conditions that can be run for up to a year
  - A dynamic heat budget at a diel scale
  - Hyporheic exchange with bottom and side hyporheic transient storage
  - Point and nonpoint heat and mass pollutant loads
  - The ability to model both periphyton and macrophyte productivity, using variable stoichiometry
  - A genetic algorithm to automatically calibrate the kinetic rate parameters
- Analysis of finer-scale water quality issues, such as thermal refugia, should be conducted with focused monitoring studies looking at field or shorter reaches.
- Information gaps should be filled with targeted research. This could include questions about macrophyte dynamics, interactions of ground and surface water, or the water quality benefits of floodplain restoration.

[5] http://www.ecy.wa.gov/programs/eap/models.html

Conclusions

The Yakima River drains a large basin with complex water use interactions. Widespread impairments of water quality have been documented for temperature, DO, and pH in the mainstem Yakima River.

This report documents many decades of studies related to water quality in the Yakima River and its major tributaries. Because of the intense interest in water use that provides both agricultural benefits and fish habitat, this basin has been relatively well studied, in particular for water temperature. Due to the basin's size and complexity, large gaps in knowledge still exist, but the body of knowledge described in this report provides a solid foundation for further study.

Recommendations

Additional study of water quality in the Yakima River is recommended, building on the past work documented in this report. Specific recommendations will be provided to Ecology's Water Quality Program in a separate memorandum.

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Appendices

Appendix A. Yakima River Mainstem Water Quality Study, Summary of Monitoring Results for August 3-13 and September 1-3, 2015

Methods

This survey used Hydrolab© Datasonde and Minisonde multiparameter meters. I deployed four meters for continuous monitoring and used one meter for grab measurements:

Site	Date	Model	No.
Yakima R nr Cle Elum (39A090)	August 3-13, 2015	Minisonde	43
Yakima R @ Umtanum Cr Footbridge (39A055)	August 3-13, 2015	Minisonde	37
Euclid Road (YGVW)	August 3-13, 2015	Minisonde	42
Yakima R @ Kiona (37A090)	August 3-13, 2015	Datasonde	26
Grab Measurements	August 3-13, 2015	Datasonde	33
Yakima R nr Cle Elum (39A090)	September 1-3, 2015	Minisonde	42
Yakima R @ Umtanum Cr Footbridge (39A055)	September 1-3, 2015	Minisonde	40
Euclid Road (YGVW)	September 1-3, 2015	Minisonde	18
Yakima R @ Kiona (37A090)	September 1-3, 2015	Datasonde	26
Grab Measurements	September 1-3, 2015	Datasonde	33

Data collection was described in an Addendum to the project Work Plan, which included a project description, project objectives, sampling design with schedule and locations, and reference to quality procedures following Ecology's Standard Operating Procedures (SOPs). Therefore, these data meet Study Quality Assurance (QA) Level 2 as defined for the Environmental Information Management (EIM) system.

I calibrated all meters prior to data collection using Ecology Standard Operating Procedures for Hydrolab meter monitoring. I placed the meter at Kiona in an existing deployment tube at the USGS flow gaging site, and deployed the other three meters in PVC tubes anchored to stakes in the shoreline. After retrieval of the meters, I "post-calibrated" the meters, i.e. conducted a post-deployment check of the meters against standards.

The study area and locations of measurements are shown in Figure A-1.

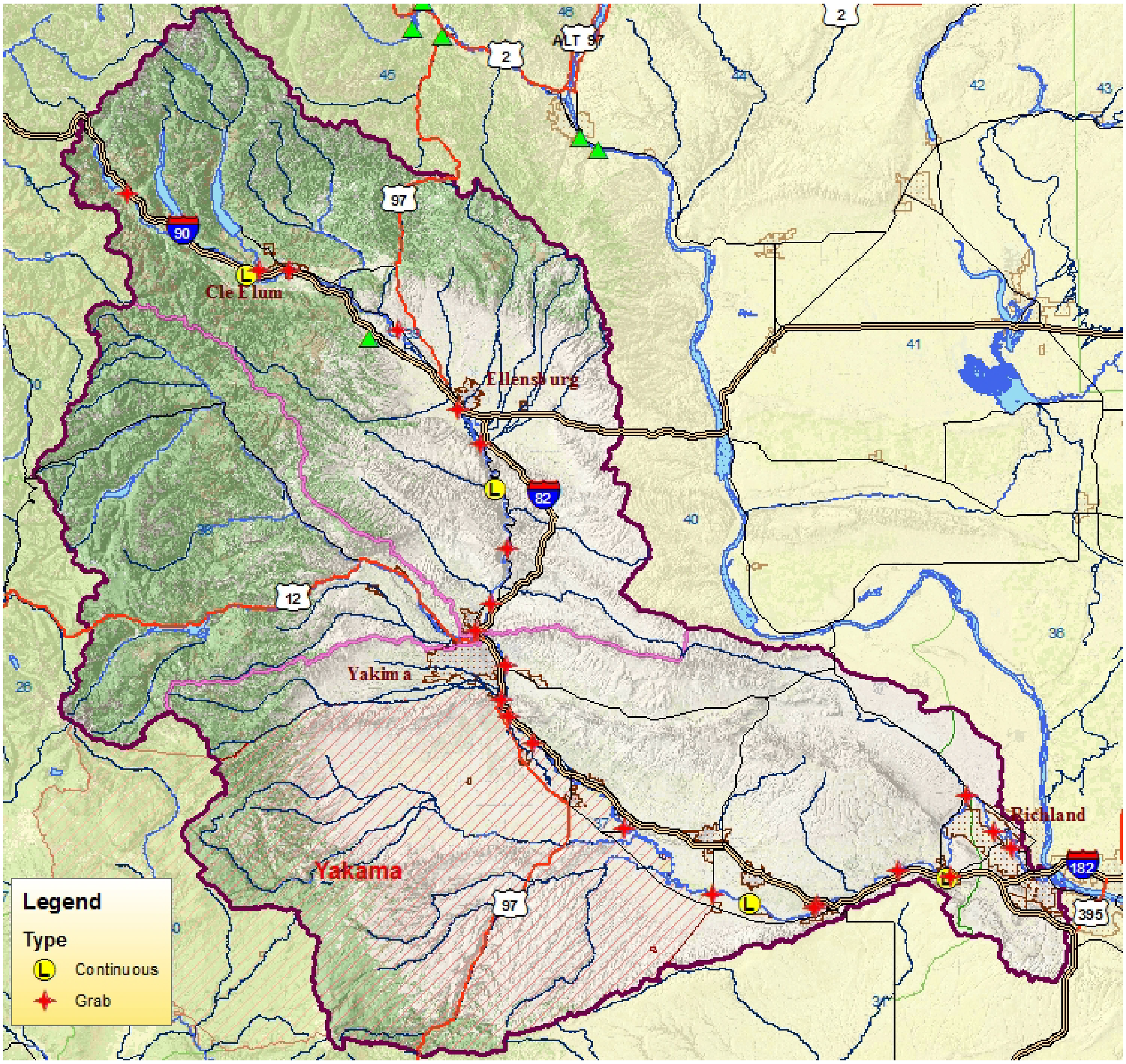


Figure A-1**.** Study Area with Reconnaissance Monitoring Locations.

Results

Field Conditions

Surveys were successful in accomplishing reconnaissance survey objectives. The surveys established the logistics for future surveys and identified areas for improvement.

Conditions during the first August survey were warm, with daily maximum air temperatures in the high 80's to low 90's (Figure A-2). Warm weather continued while the data-logging meters were deployed. The second August survey ended with two relatively hot days (daily maximum air temperatures around 100 ^{o}F. Conditions during the September survey were relatively cool, with daily maximum air temperatures beginning in the high 70's and dropping steadily during the week.

Results are provided below for grab measurements from the two synoptic surveys, and the time series obtained from 4 data-logging placements. The time series graphs include grab measurements from my survey and from monthly ambient monitoring for three of the sites.

Quality Assurance Results

The data presented and discussed here are reconnaissance data and not collected under a Quality Assurance Project Plan. Therefore, they should be considered to be "screening data" of a lower level of data quality (EIM QA Level 2).

All meters calibrated well, with one exception. During the September survey Meter 42 would not calibrate for pH, but since readings were less than 0.1 unit from the standard, the meter was accepted for use.

Post-calibration results showed a little drift for some parameters in some meters:

- Conductivity: all were within +/- 3% of standard solutions.
- pH: all were within +/- 0.15 of standard solutions.
- DO: compared to 100% saturation, 7 were within +/-1%, one was within +/- 2%, one was within +/- 3%. (One sensor failed.)

The quality of post-calibration results are acceptable for meeting the objectives of this monitoring. The observed quality metrics will be taken into account in interpreting results.

Other observations regarding the quality of monitoring data are included in the discussion below.

August survey results

The following patterns from grab measurements during the August surveys (Tables A-1 and A-2) are of interest:

- Temperature criteria were exceeded at 16 of 23 synoptic sites measured during the first week, and at 25 of 26 sites on the second week.
- The pH criterion of 8.5 was exceeded at 8 of 23 sites during the first survey and 7 of 26 sites during the second survey. Sites most strongly affected were in the furthest downstream stations, but high pH was observed at other stations between Roza Dam and Prosser.
- DO below the criteria were measured during both surveys at the 4 upstream sites with stringent criteria (9.5 mg/L). DO saturation was near 100% for all these measurements, suggesting a significant temperature effect.
- Two sites in Prosser were below the DO criterion of 8.0 mg/L in the first survey.
- Supersaturated DO levels above 110% were found in the first survey at the five most downstream stations and at the Harrison Road station near Selah, and in the second survey at all stations from the canyon (near Umtanum Creek) downstream. Supersaturated DO in the late afternoon is an indicator of suppressed DO levels in the early morning which may fall low enough to not meet water quality criteria.

The following patterns in the August data-logging time series are notable:

- At the site near Cle Elum (Figure A-3), temperatures varied diurnally between 17 and 21 ^{o}C, well above the applicable criterion of 16 ^{o}C. DO levels varied between high and low 8's, well below the criterion of 9.5 ^{o}C. Interestingly, saturation tended to be sub-saturated, dropping below 90% at night and briefly topping 100% in the early afternoon. Thus there appears to be some mechanism suppressing DO slightly, even though the daily pattern is driven by temperature. All pH levels were comfortably within criteria. Grab measurements matched the time series well.
- At the site above Umtanum footbridge (Figure A-4), temperatures rose above the criterion of 21 ^{o}C on two dates. Although dissolved oxygen fell slightly below the criterion of 8.0 mg/L during the last five nights, post-calibration drift makes these values uncertain. Values for pH were well below the criterion. The meter was covered by sediment when retrieved, which appears to have caused a dampening of pH values. However, DO and temperature appear to be unaffected. Based on the one ambient run visit, the timing of the run tends to miss the lowest DO and highest temperatures at this site.
- The site at the Euclid Road Bridge near Grandview (Figure A-5) clearly has some problems with the data. The meter when retrieved was in sediment, and the river was very murky at this site. Some kind of drain was discharging near the meter site, and the area smelled of manure. After the first five days all parameters appear to be affected, and have not been reported. However, sufficient data of reasonable quality was collected to confirm that temperatures were consistently above the criterion of 21 ^{o}C, and DO fell below 8.0 mg/L every night. Values for pH appear to remain below the 8.5 criterion.
- Data from the Kiona site (Figure A-6) appeared to be of good quality, with good correspondence to grab measurements. Water temperatures never fell below 23 ^{o}C, and went above 27 ^{o}C on the final day when air temperatures hit 100 ^{o}F, thus always exceeding the criterion and at times above the lethality threshold for salmon. Strong productivity patterns were present, with DO consistently dropping below 8 mg/L at night and pH rising to over 9 in the afternoons. DO saturation swung widely from less than 70% to as high as 170%. This is an area of dense aquatic macrophyte growth, which is a likely cause of these productivity effects.

September survey results

Results from the September survey (Table A-3) reflected the cooler temperatures and shorter days, but still showed interesting patterns:

- Temperatures exceeded criteria for 9 measurements out of 37. Three of the seven sites exceeded the criterion of 16 ^{o}C which applies above the confluence of the Yakima and Cle Elum Rivers. The other 4 sites were in the most downstream stations and just slightly exceeded the criterion of 21 ^{o}C.
- Five sites had pH levels slightly above the criterion of 8.5. Three were immediately upstream of the Naches River confluence, one was at the Donald Wapato Road bridge, and one was at Benton City.
- Four sites in the headwaters fell below the DO criterion of 9.5 mg/L. All of the sites where the criterion of 8.0 mg/L applies met the criterion except for one reading in the morning at the Kiona gage in Benton City.

- Twenty of the 23 sites from above Roza Dam downstream had supersaturated DO above 110% during afternoon measurements. The morning reading at the Kiona gage was only 81% of saturation. These data suggest that productivity was still active in the lower river, and that DO below 8.0 mg/L may have been occurring in the early morning hours.

The following patterns from continuous monitoring during the September surveys are of note:

- The meter at the site near Cle Elum ran out of batteries (due to a leaking case), but readings appear to be reasonable for the entire period (Figure A-7). Temperatures rose above the criterion of 16 ^{o}C during the day. DO again showed signs of being slightly suppressed (all values below saturation), and failed to meet the criterion of 9.5 mg/L. The criterion for pH was met the entire time.
- At the Umtanum Creek Foot Bridge site (Figure A-8), the meter deployment was modified to eliminate the problem with sediment found during the August survey. However, the DO sensor failed on the unit. All criteria were met at this site. A weak signal of productivity was indicated by the diurnal variation in pH and supersaturated DO grab measurements.
- At the site at the Euclid Road Bridge near Grandview (Figure A-9), the meter deployment was also modified, which improved the quality of the data. Diurnal patterns of productivity can be seen, and DO fell below the criterion of 8.0 mg/L during the nighttime. Temperature and pH met criteria.
- The Kiona site (Figure A-10) showed the strongest productivity signal of the four sites, with wide diurnal swings in DO and smaller swings in pH. Although temperature met its criterion during the entire period, DO fell below the 8.0 mg/L criterion in the nighttime and pH values slightly exceeded the 8.5 criterion on the final day.

Discussion and Conclusions

The reconnaissance surveys were successful in meeting their objective of characterizing temperature, DO, and pH in the mainstem Yakima River and its major headwater tributaries. Information from these surveys succeeded in filling data gaps and assessing compliance with standards during two hot mid-summer weeks and one cooler late summer week.
These surveys reveal the following key findings:

- Much more stringent temperature and DO criteria apply to the Cle Elum River, Kachess River, and in the Yakima River above the Cle Elum River. With the exception of the Crystal Springs Campground site in September, none of these sites met DO or pH criteria during the surveys, which is consistent with current 303(d) listings in this area. On the other hand, these sites consistently met pH criteria. Continuous monitoring near Cle Elum showed a weak productivity signal but also consistently suppressed DO.

  Conditions at these sites appear to be dominated by Lakes Keechelus, Kachess, Cle Elum, and Easton, with are major parts of the Bureau of Reclamation water supply system. High temperatures and low DO could be a result of conditions in the lakes upstream, although there may also be point source discharges contributing to suppressed DO in the Yakima River above Cle Elum. A more detailed study of these lakes and the rivers they drain into is needed to determine the specific causes of the observed water quality conditions.

- In the Kittitas Valley from the Cle Elum River to the Umtanum Creek Foot Bridge (upper Yakima Canyon), temperatures rose above the criterion of 21 ^{o}C during the hot weather in the second week of August. Continuous monitoring at the Umtanum Creek Foot Bridge site showed daytime temperatures peaking above the criterion. At this site the productivity signal had strengthened and DO fell below the criterion of 8.0 in the nighttime. Daytime grab measurements for pH and DO in this area consistently met criteria.

  Ecology has no 303(d) listings in these reaches of the Yakima River. However, results suggest that during hot spells daytime temperatures can exceed criteria. Also, daytime grabs appear to be missing DO levels falling below criteria during the nighttime. More extensive continuous monitoring is needed in the Kittitas Valley and Yakima Canyon to better understand the extent and severity of non-compliance with water quality criteria.

- From the Umtanum Creek Foot Bridge to the Naches River, temperatures exceeded the water quality criterion during the hot second August survey, and pH exceed the 8.5 criterion during two surveys. Combined with supersaturated DO levels, the data suggest increasing productivity as the Yakima River moves downstream through the canyon and past the Roza Dam diversions. The data confirm the 303(d) listing for pH near Selah.
- From the Naches River to Grandview, temperatures tend to climb and productivity signals strengthen as the river moves downstream. Temperatures exceeded the water quality criterion during the two August surveys, and multiple sites had pH over the criterion during all three surveys. Supersaturated DO indicated strong productivity and the potential for low DO at night. The Donald Wapato Road bridge site stood out as having strong indications of productivity. Continuous data from Euclid Road confirm the diurnal productivity swings which resulted in DO below the criterion at night.
- From Prosser to the farthest downstream site near Richland, the highest temperature and pH measurements in the river were observed. In August, temperatures approaching 28 ^{o}C, pH values exceeding 9, and DO saturation exceeding 170% were measured at multiple sites. Continuous monitoring at the Kiona site demonstrated that daytime supersaturation of DO over 160% was associated with nighttime DO levels below 6 mg/L. The pool above Prosser Dam showed some specific problems, with a daytime DO measurement below 8.0 mg/L.

  Despite cooler weather and shorter days in September, temperatures above the 21 ^{o}C criterion, pH above the 8.5 criterion, and DO saturation elevated over 120% were measured in the lower river.

In summary:

- The Yakima River and its major tributaries were consistently out of compliance with the more stringent temperature and DO water quality criteria from the Cle Elum River upstream.
- The Yakima River in the Kittitas Valley was not meeting temperature criteria and showed signs of productivity impacts, although the lack of compliance in this area was the least severe.
- Productivity impacts grow as the Yakima River flows downstream through the canyon and below Roza dam, with data showing problems with pH and DO compliance.
- Below the Naches River confluence, water quality conditions steadily worsen in the downstream direction, with daytime temperatures, pH, and DO supersaturation rising to extraordinary levels as the river nears its mouth.

Appendix Tables

Table A-1. Results for August 3-4, 2015.

				degC		s.u.		uS/cm	mg/L		%
Site Description	**RM**	**Date**	**Time**	**Temp**	**crit.**	**pH**	**crit.**	**Cond**	**DO-C**	**crit.**	**DO-sat**
Yakima R @ Kiona (37A090)	29.6	8/3/2015	4:15 PM	25.2	21.0	8.7	8.5	265	9.9	8.0	125%
Horn Rapids Park	18.0	8/3/2015	5:00 PM	25.9	21.0	9.0	8.5	251	10.3	8.0	129%
Twin Bridges Road	13.2	8/3/2015	5:22 PM	25.9	21.0	9.1	8.5	255	10.7	8.0	137%
Rt 224 - Yakima R @ Van Giesen Br (37A060)	8.6	8/3/2015	5:40 PM	26.4	21.0	9.1	8.5	260	9.9	8.0	128%
Above Chandler Power Plant	38.7	8/3/2015	6:22 PM	25.3	21.0	8.7	8.5	279	9.6	8.0	121%
Grant Ave Bridge in Prosser	47.0	8/3/2015	6:55 PM	25.9	21.0	8.0	8.5	248	8.0	8.0	103%
Yakima R at Prosser (37A110) - Wine Cntry Rd	47.4	8/3/2015	7:25 PM	26.0	21.0	8.0	8.5	247	7.9	8.0	102%
Euclid Road (YGVW)	55.1	8/3/2015	8:05 PM	24.7	21.0	7.9	8.5	248	8.0	8.0	101%
Crystal Springs Campground	213.0	8/4/2015	2:14 PM	19.9	12.0	7.5	8.5	45	8.6	9.5	98%
Kachess River - Gage station	203.4	8/4/2015	2:36 PM	19.7	16.0	7.7	8.5	46	8.7	9.5	100%
Yakima R nr Cle Elum (39A090)	191.0	8/4/2015	3:31 PM	20.8	16.0	7.6	8.5	53	8.7	9.5	101%
Cle Elum River - Bull Frog Road	185.9	8/4/2015	3:48 AM	19.8	16.0	7.6	8.5	49	8.7	9.5	101%
South Cle Elum Way	183.1	8/4/2015	4:07 PM	20.1	21.0	7.6	8.5	54	8.8	8.0	101%
Thorp Highway North (39A070) - Boat Launch	165.5	8/4/2015	4:45 PM	21.0	21.0	7.7	8.5	55	8.7	8.0	101%
Umtanum Rd (Yakima R @ Ellensburg, 39A060)	153.1	8/4/2015	5:11 PM	20.5	21.0	7.7	8.5	61	8.8	8.0	102%
Thrall Boat Launch (Datin Rd.)	148.2	8/4/2015	5:30 PM	20.4	21.0	7.7	8.5	63	8.9	8.0	103%
Yakima R @ Umtanum Cr Footbridge (39A055)	139.7	8/4/2015	6:23 PM	20.6	21.0	8.0	8.5	79	9.1	8.0	105%
Roza Recreational Site Boat Launch	129.4	8/4/2015	6:49 PM	21.0	21.0	8.4	8.5	81	9.5	8.0	110%
Yakima R @ Harrison Bridge (39A050) - Rt 823	121.3	8/4/2015	7:09 PM	20.9	21.0	8.6	8.5	83	9.6	8.0	112%
Playland Riverside Park near Selah Road	117.1	8/4/2015	7:30 PM	21.1	21.0	8.6	8.5	82	9.3	8.0	109%
Yakima R @ Nob Hill (37A205) - Rt. 24	111.4	8/4/2015	7:52 AM	21.2	21.0	8.6	8.5	84	9.2	8.0	109%
Century Landing Boat Launch (Union Gap)	107.1	8/4/2015	8:15 PM	21.3	21.0	8.4	8.5	95	8.8	8.0	104%
Parker Bridge Road (PRW)	104.6	8/4/2015	8:26 PM	21.4	21.0	8.5	8.5	93	8.8	8.0	104%
				above		**above**			**below**		**above**
	total			**criteria**		**criteria**			**criteria**		**110%**
Count	23			16		8			6		6
				70%		35%			26%		26%

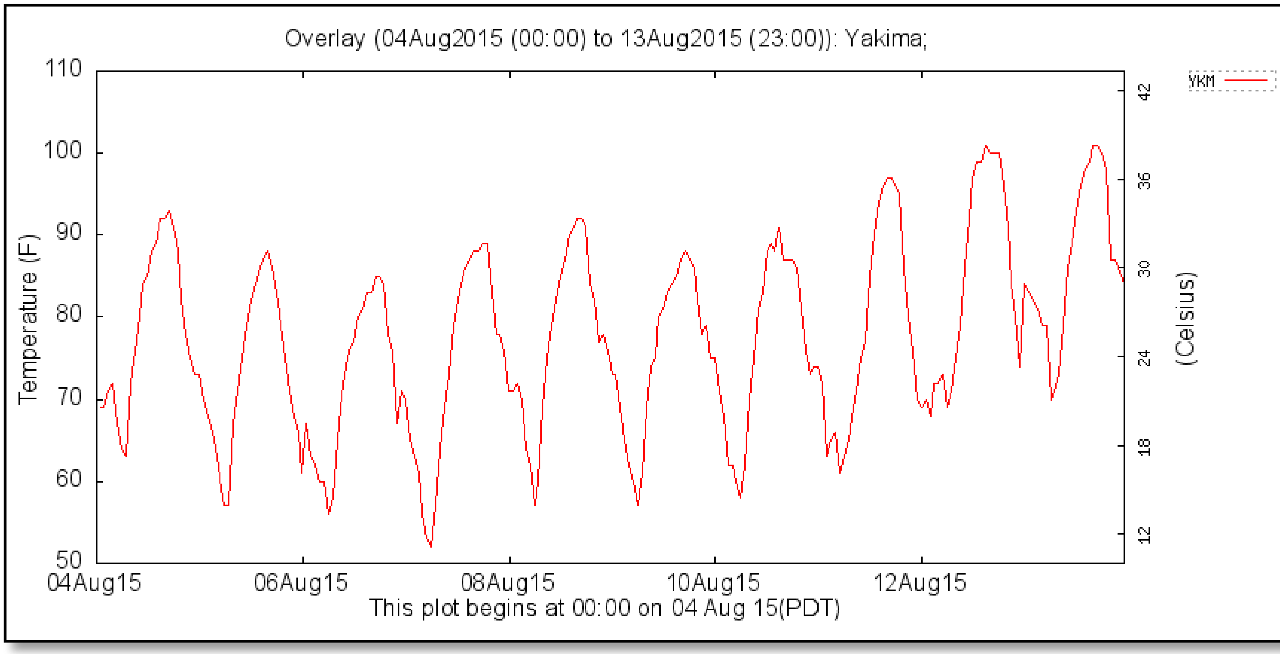
Table A-2. Results for August 12-13, 2015.

				degC		s.u.		uS/cm	mg/L		%
Site Description	**RM**	**Date**	**Time**	**Temp**	**crit.**	**pH**	**crit.**	**Cond**	**DO-C**	**crit.**	**DO-sat**
Crystal Springs Campground	213.0	8/12/2015	2:30 PM	20.3	12.0	7.3	8.5	45	8.4	9.5	97%
Kachess River - Gage station	203.4	8/12/2015	2:42 PM	17.6	16.0	7.6	8.5	46	9.2	9.5	101%
Yakima R nr Cle Elum (39A090)	191.0	8/12/2015	3:10 PM	21.3	16.0	7.3	8.5	53	8.7	9.5	102%
Cle Elum River - Bull Frog Road	185.9	8/12/2015	3:50 PM	19.7	16.0	7.6	8.5	52	8.8	9.5	100%
South Cle Elum Way	183.1	8/12/2015	4:18 PM	20.7	21.0	7.6	8.5	56	8.7	8.0	101%
Thorp Highway North (39A070) - Boat Launch	165.5	8/12/2015	4:50 PM	21.3	21.0	7.6	8.5	55	8.6	8.0	102%
Umtanum Rd (Yakima R @ Ellensburg, 39A060)	153.1	8/12/2015	5:15 PM	21.3	21.0	7.7	8.5	60	8.8	8.0	104%
Thrall Boat Launch (Datin Rd.)	148.2	8/12/2015	5:33 PM	21.4	21.0	7.8	8.5	63	8.9	8.0	105%
Yakima R @ Umtanum Cr Footbridge (39A055)	139.7	8/12/2015	6:00 PM	22.0	21.0	8.1	8.5	76	9.3	8.0	110%
Roza Recreational Site Boat Launch	129.4	8/12/2015	6:41 PM	22.1	21.0	8.4	8.5	78	9.5	8.0	113%
Yakima R @ Harrison Bridge (39A050) - Rt 823	121.3	8/12/2015	6:58 PM	22.1	21.0	8.5	8.5	80	9.4	8.0	113%
Playland Riverside Park near Selah Road	117.1	8/12/2015	7:15 PM	22.3	21.0	8.3	8.5	80	9.2	8.0	110%
Yakima R @ Nob Hill (37A205) - Rt. 24	111.4	8/13/2015	12:49 PM	21.9	21.0	8.1	8.5	8	9.6	8.0	114%
Century Landing Boat Launch (Union Gap)	107.1	8/13/2015	4:45 PM	22.3	21.0	8.3	8.5	92	10.0	8.0	121%
Parker Bridge Road (PRW)	104.6	8/13/2015	1:30 PM	22.6	21.0	8.5	8.5	91	9.9	8.0	119%
Donald Wapato Road	100.3	8/13/2015	1:48 PM	23.9	21.0	9.1	8.5	93	12.1	8.0	149%
Rt 223 at Granger WWTP	83.0	8/13/2015	2:24 PM	23.7	21.0	8.1	8.5	180	9.8	8.0	121%
Rt 241 Boat Launch (Mabton - 37A130)	59.8	8/13/2015	3:07 PM	25.1	21.0	8.5	8.5	215	11.3	8.0	144%
Euclid Road (YGVW)	59.8	8/13/2015	3:40 PM	26.4	21.0	8.6	8.5	229	11.5	8.0	149%
Yakima R at Prosser (37A110) - Wine Cntry Rd	47.4	8/13/2015	4:15 PM	26.1	21.0	8.3	8.5	220	10.2	8.0	131%
Grant Ave Bridge in Prosser	47.0	8/13/2015	4:32 PM	26.0	21.0	8.3	8.5	222	8.8	8.0	113%
Above Chandler Power Plant	38.7	8/13/2015	5:05 PM	27.5	21.0	9.0	8.5	257	12.8	8.0	169%
Benton City Boat Launch	29.6	8/13/2015	5:28 PM	27.0	21.0	9.0	8.5	242	12.4	8.0	163%
Horn Rapids Park	18.8	8/13/2015	6:15 PM	26.9	21.0	8.8	8.5	257	10.1	8.0	132%
Twin Bridges Road	13.2	8/13/2015	6:36 PM	27.9	21.0	9.1	8.5	258	12.9	8.0	172%
Rt 224 - Yakima R @ Van Giesen Br (37A060)	8.6	8/13/2015	6:55 PM	27.6	21.0	9.1	8.5	263	12.4	8.0	164%
				above		**above**			**below**		**above**
	total			**criteria**		**criteria**			**criteria**		**110%**
Count	26			25		7			4		18
				96%		27%			15%		69%

Table A-3. Results for September 1-3, 2015.

				degC		s.u.		uS/cm	mg/L		%
Site Description	**RM**	**Date**	**Time**	**Temp**	**crit.**	**pH**	**crit.**	**Cond**	**DO-C**	**crit.**	**DO-%**
Yakima R @ Kiona (37A090)	29.6	9/1/2015	9:55 AM	19.1	21.0	7.6	8.5	249	7.2	8.0	81%
Euclid Road (YGVW)	55.1	9/1/2015	11:48 AM	19.3	21.0	7.8	8.5	177	9.2	8.0	104%
Crystal Springs Campground	213.0	9/1/2015	2:20 PM	15.5	12.0	7.5	8.5	45	9.1	9.5	96%
Kachess River - Gage station	203.4	9/1/2015	2:37 PM	17.5	16.0	7.6	8.5	46	8.9	9.5	98%
Yakima R nr Cle Elum (39A090)	191.0	9/1/2015	3:20 PM	17.2	16.0	7.3	8.5	51	8.8	9.5	96%
Cle Elum River - Bull Frog Road	185.9	9/1/2015	3:35 PM	17.3	16.0	7.5	8.5	59	9.1	9.5	99%
South Cle Elum Way	183.1	9/1/2015	4:04 PM	17.3	21.0	7.5	8.5	60	9.1	8.0	100%
Thorp Highway North (39A070) - Boat Launch	165.5	9/1/2015	4:35 PM	17.7	21.0	7.6	8.5	58	9.2	8.0	101%
Umtanum Rd (Yakima R @ Ellensburg, 39A060)	153.1	9/1/2015	5:00 PM	18.0	21.0	7.8	8.5	67	9.5	8.0	105%
Thrall Boat Launch (Datin Rd.)	148.2	9/1/2015	5:18 PM	18.0	21.0	7.8	8.5	70	9.6	8.0	106%
Yakima R @ Umtanum Cr Footbridge (39A055)	139.7	9/1/2015	6:09 PM	18.0	21.0	8.1	8.5	88	9.9	8.0	109%
Roza Recreational Site Boat Launch	129.4	9/1/2015	6:33 PM	18.2	21.0	8.6	8.5	88	10.5	8.0	117%
Yakima R @ Harrison Bridge (39A050) - Rt 823	121.3	9/1/2015	6:50 PM	18.2	21.0	8.6	8.5	93	10.2	8.0	113%
Playland Riverside Park near Selah Road	117.1	9/1/2015	7:08 PM	18.8	21.0	8.6	8.5	92	9.9	8.0	111%
Yakima R @ Nob Hill (37A205) - Rt. 24	111.4	9/2/2015	12:57 PM	17.2	21.0	7.9	8.5	92	10.1	8.0	109%
Century Landing Boat Launch (Union Gap)	107.1	9/2/2015	1:20 PM	17.8	21.0	8.0	8.5	104	10.2	8.0	112%
Parker Bridge Road (PRW)	104.6	9/2/2015	1:34 PM	18.1	21.0	8.1	8.5	102	10.3	8.0	114%
Donald Wapato Road	100.3	9/2/2015	1:50 PM	19.2	21.0	8.7	8.5	101	11.8	8.0	133%
Rt 223 at Granger WWTP*	83.0	9/2/2015	2:29 PM	19.4	21.0	8.0	8.5	190	10.1	8.0	114%
Rt 241 Boat Launch (Mabton - 37A130)	59.8	9/2/2015	3:08 PM	19.9	21.0	8.0	8.5	169	9.8	8.0	113%
Euclid Road (YGVW)	59.8	9/2/2015	3:26 PM	20.4	21.0	8.0	8.5	184	9.8	8.0	113%
Yakima R at Prosser (37A110) - Wine Cntry Rd	47.4	9/2/2015	3:51 PM	19.8	21.0	7.6	8.5	168	8.3	8.0	95%
Grant Ave Bridge in Prosser	47.0	9/2/2015	4:07 PM	19.9	21.0	7.7	8.5	170	8.9	8.0	102%
Above Chandler Power Plant	38.7	9/2/2015	4:34 PM	21.0	21.0	8.4	8.5	192	10.6	8.0	124%
Benton City Boat Launch	29.6	9/2/2015	5:06 PM	20.8	21.0	8.4	8.5	186	10.6	8.0	123%
Horn Rapids Park	18.0	9/2/2015	5:36 PM	21.2	21.0	8.3	8.5	205	9.7	8.0	113%
Twin Bridges Road	13.2	9/2/2015	6:00 PM	21.3	21.0	8.4	8.5	226	10.4	8.0	123%
Rt 224 - Yakima R @ Van Giesen Br (37A060)	8.6	9/2/2015	6:21 PM	21.2	21.0	8.3	8.5	246	10.3	8.0	121%
Yakima R nr Cle Elum (39A090)	191.0	9/3/2015	1:53 PM	17.1	16.0	7.1	8.5	54	8.9	9.5	96%
Cle Elum River - Bull Frog Road	185.9	9/3/2015	2:25 PM	17.7	16.0	7.5	8.5	60	9.2	9.5	101%
South Cle Elum Way	183.1	9/3/2015	2:50 PM	17.2	21.0	7.4	8.5	65	9.3	8.0	101%
Yakima R @ Umtanum Cr Footbridge (39A055)	139.7	9/3/2015	3:38 PM	17.1	21.0	8.4	8.5	98	11.3	8.0	122%
Roza Recreational Site Boat Launch	129.4	9/3/2015	4:10 PM	18.7	21.0	8.6	8.5	103	11.0	8.0	123%
Playland Riverside Park near Selah Road	117.1	9/3/2015	4:38 PM	18.7	21.0	8.6	8.5	103	11.0	8.0	123%
Donald Wapato Road	100.3	9/3/2015	5:03 PM	17.7	21.0	8.7	8.5	103	11.8	8.0	129%
Euclid Road (YGVW)	59.8	9/3/2015	5:58 PM	20.6	21.0	8.2	8.5	213	10.5	8.0	122%
Benton City Boat Launch	29.6	9/3/2015	6:46 PM	20.0	21.0	8.6	8.5	188	11.4	8.0	131%
*Maybe influenced by plume from Granger Drain											
				above		**above**			**below**		**above**
	total			**criteria**		**criteria**			**criteria**		**110%**
Count	37			9		8			7		20
				24%		22%			19%		54%

Appendix Figures



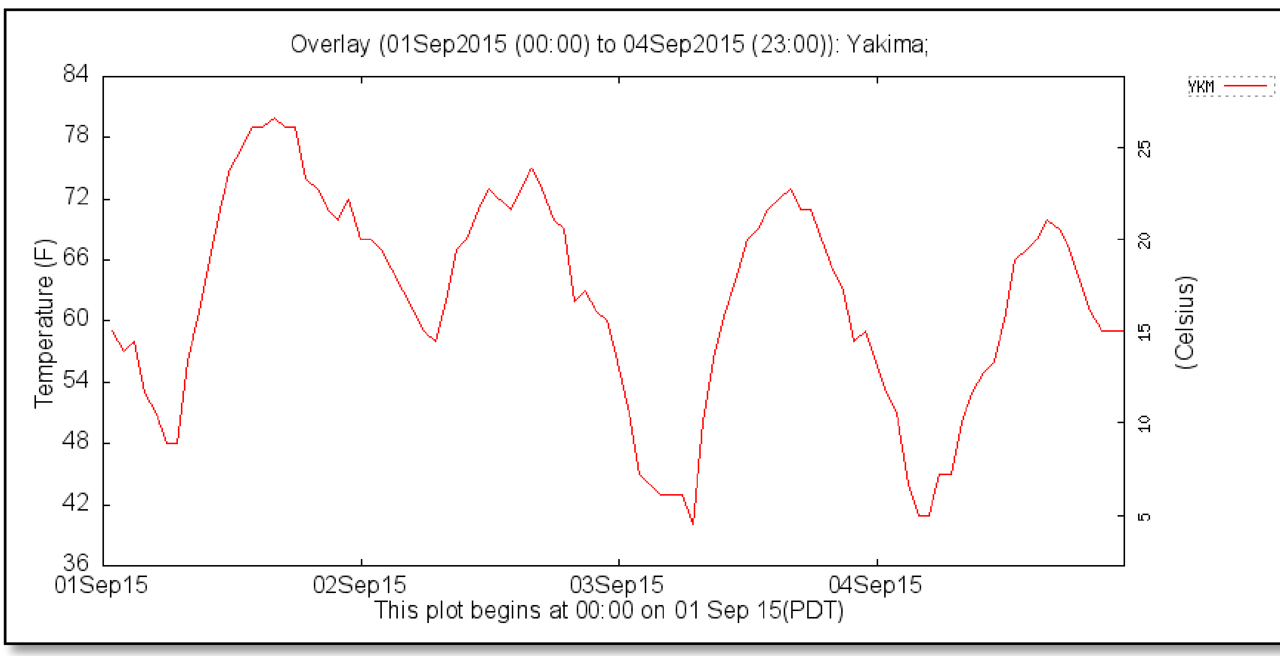


Figure A-2. Air temperatures at Yakima Airport during reconnaissance dates.

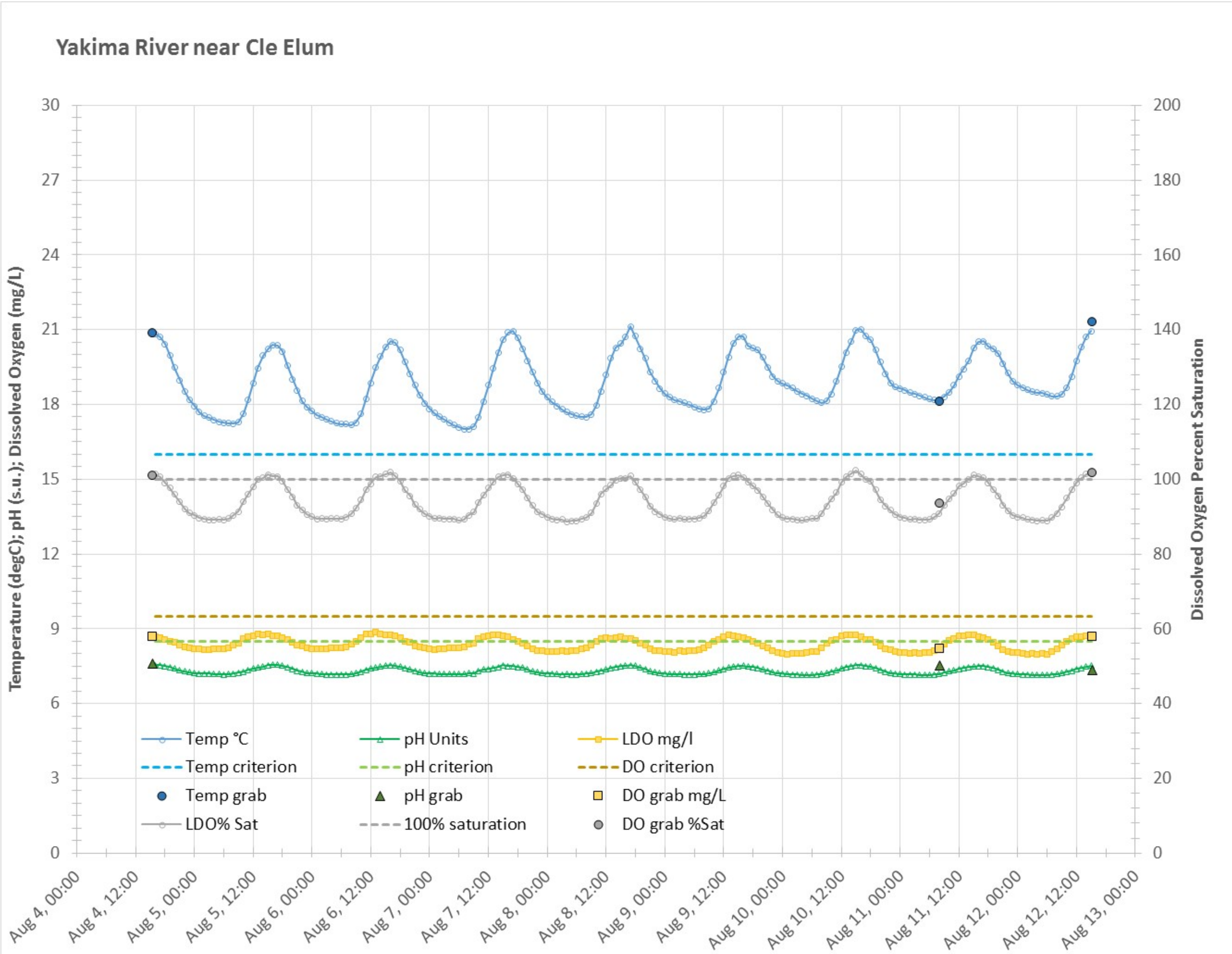


Figure A-3. Continuous monitoring results during August at the site near Cle Elum.

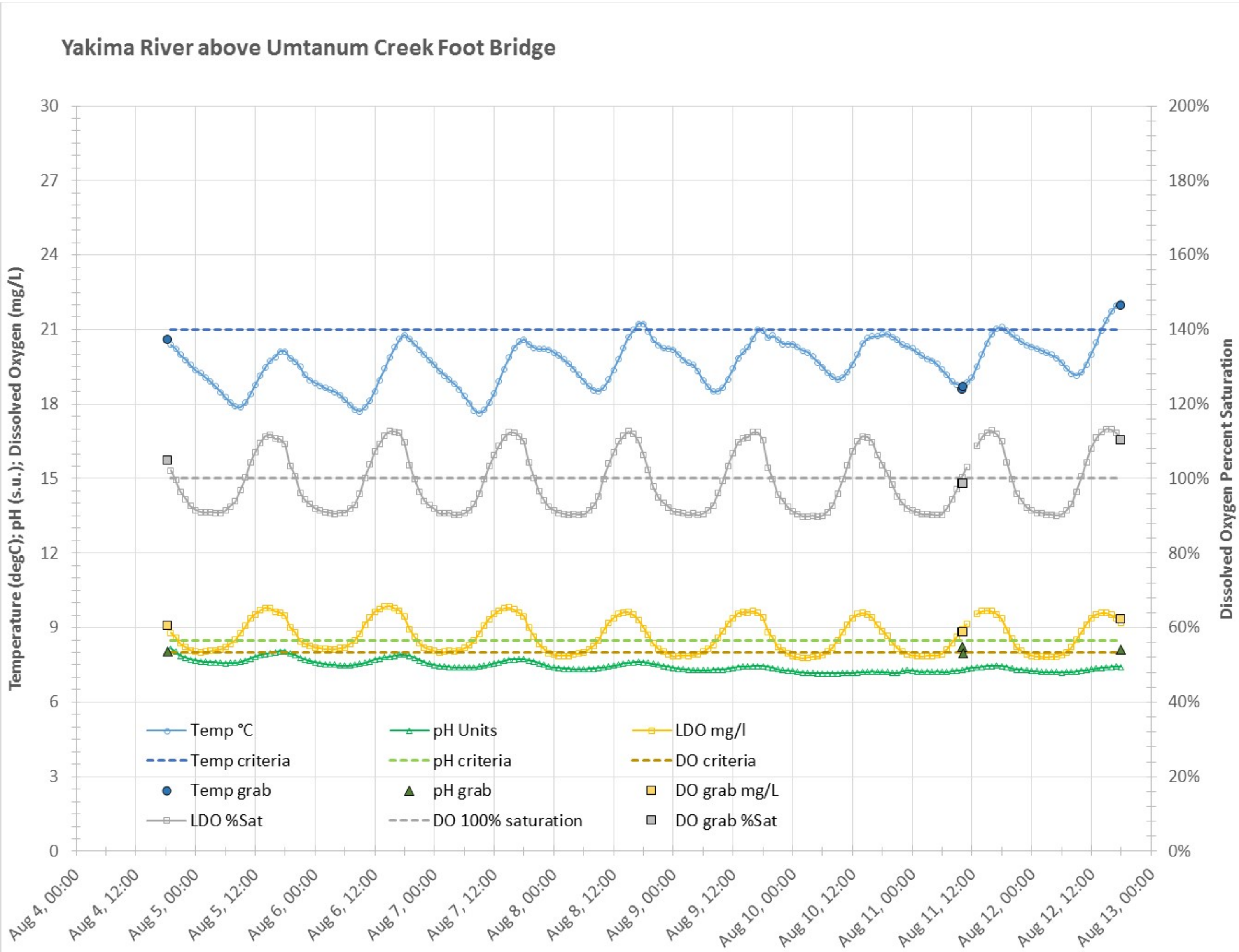


Figure A-4. Continuous monitoring results during August at the site near the Umtanum Creek Foot Bridge.

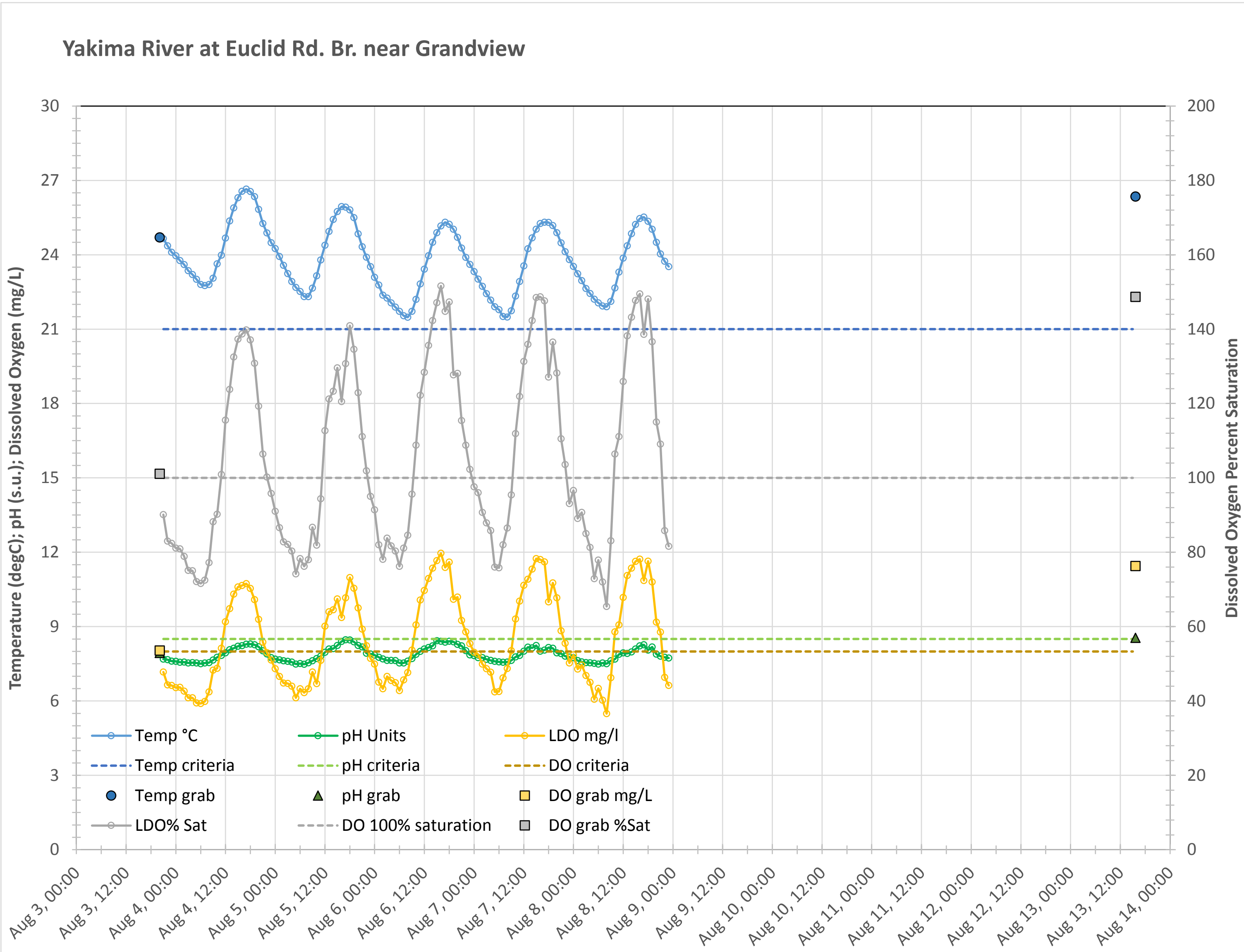


Figure A-5. Continuous monitoring results during August at the site at the Euclid Road bridge near Grandview.

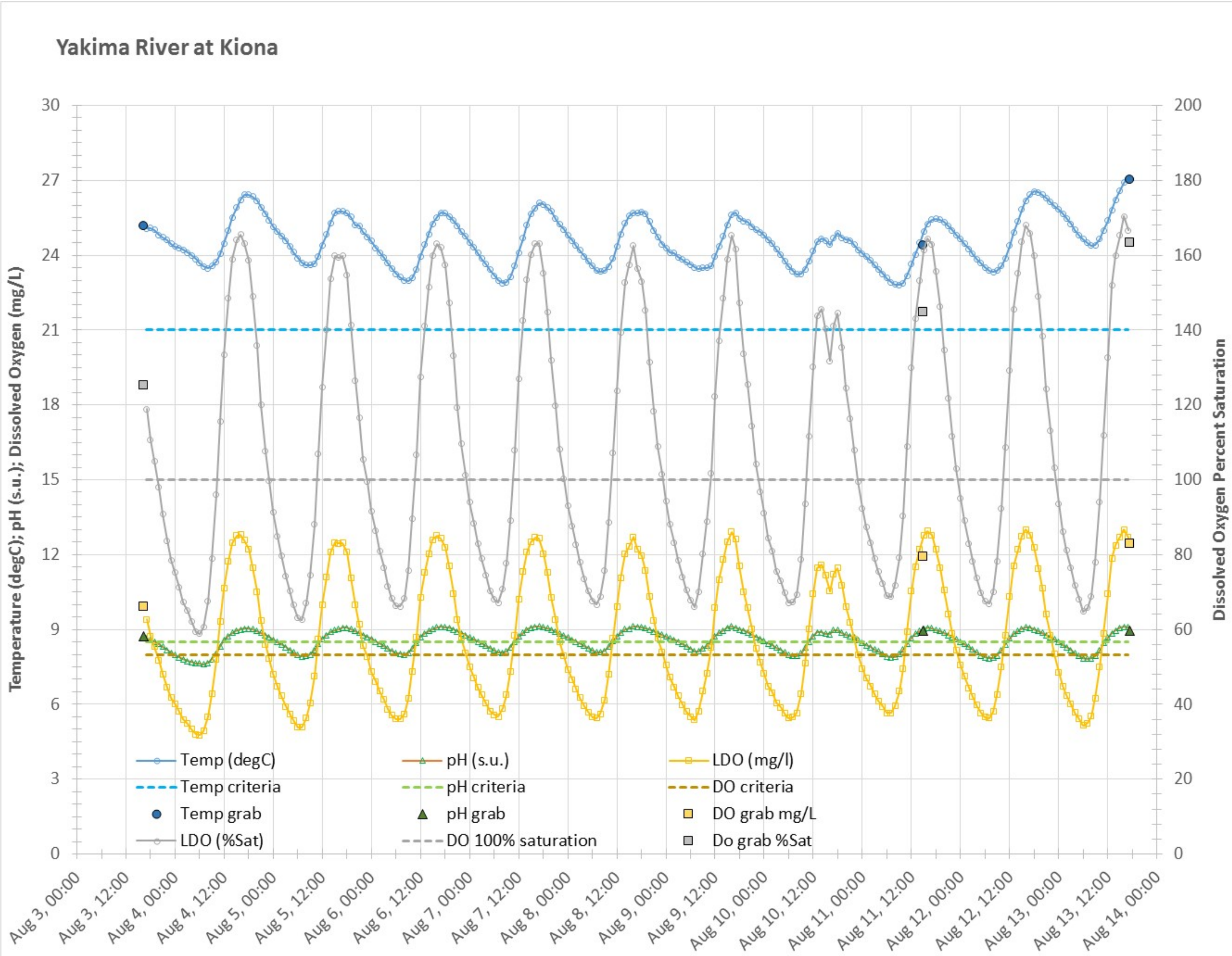


Figure A-6. Continuous monitoring results during August at the site at the Kiona USGS gage.

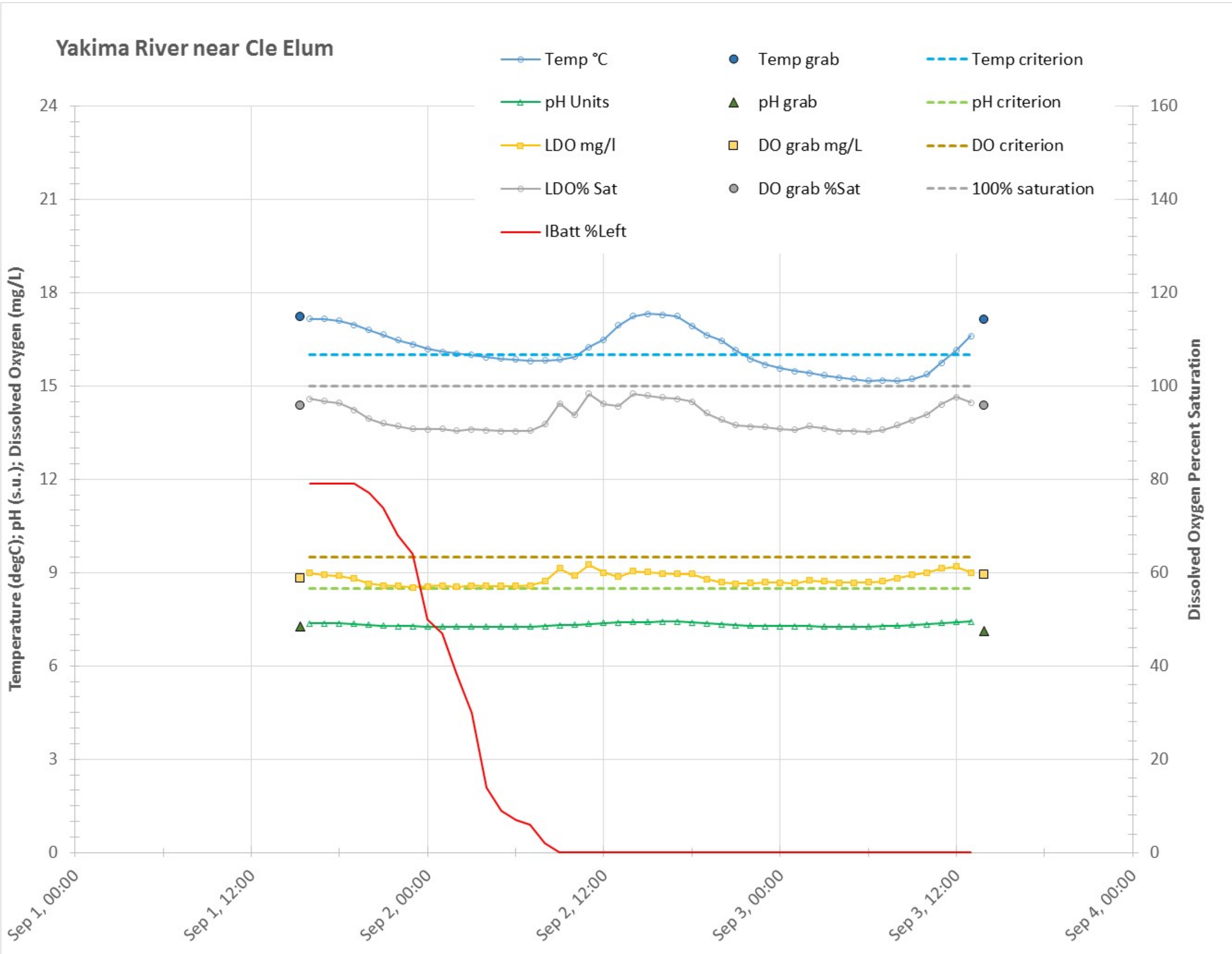


Figure A-7. Continuous monitoring results during September at the site near Cle Elum.

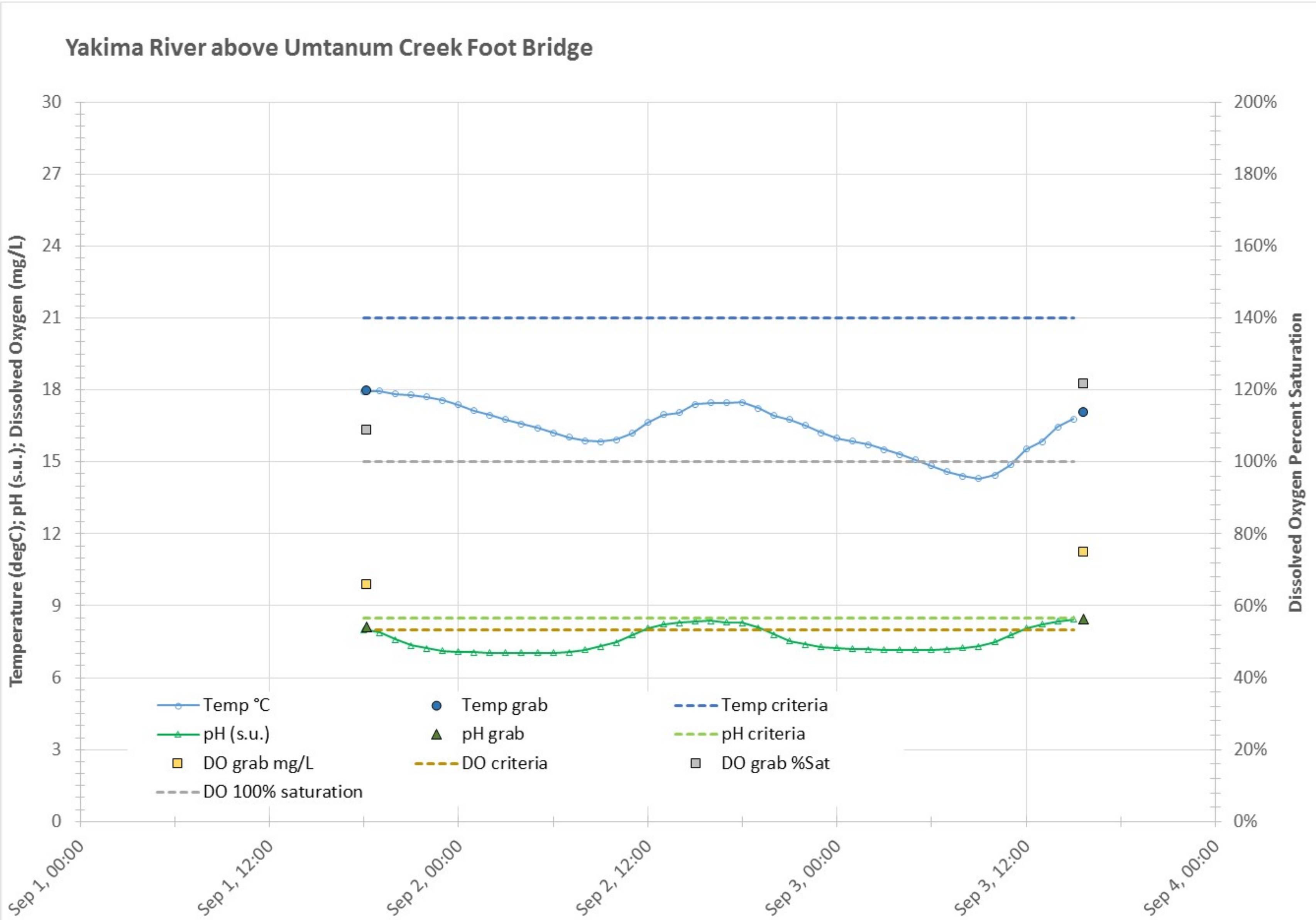


Figure A-8. Continuous monitoring results during September at the site near the Umtanum Creek Foot Bridge.

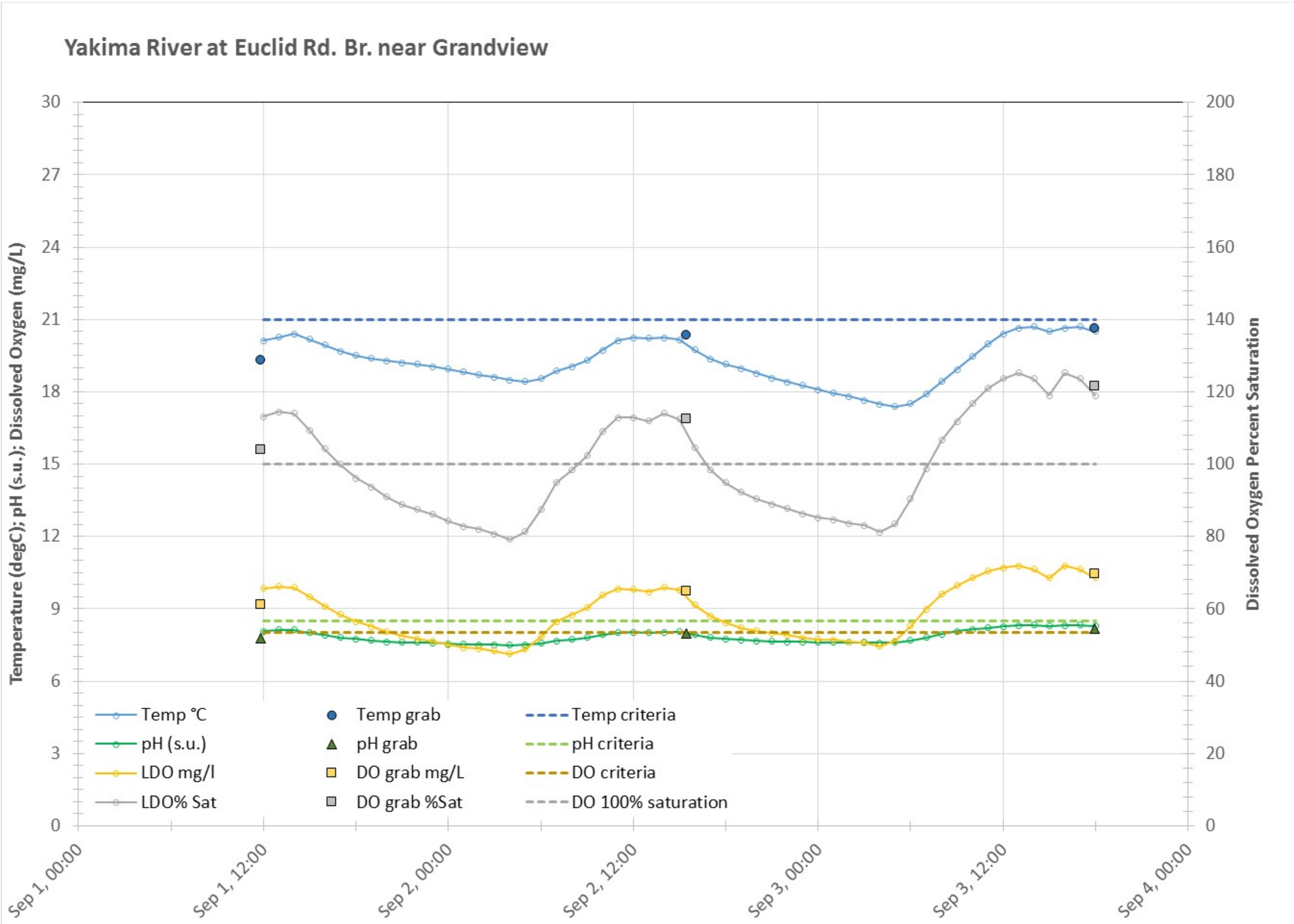


Figure A-9. Continuous monitoring results during September at the site at the Euclid Road bridge near Grandview.

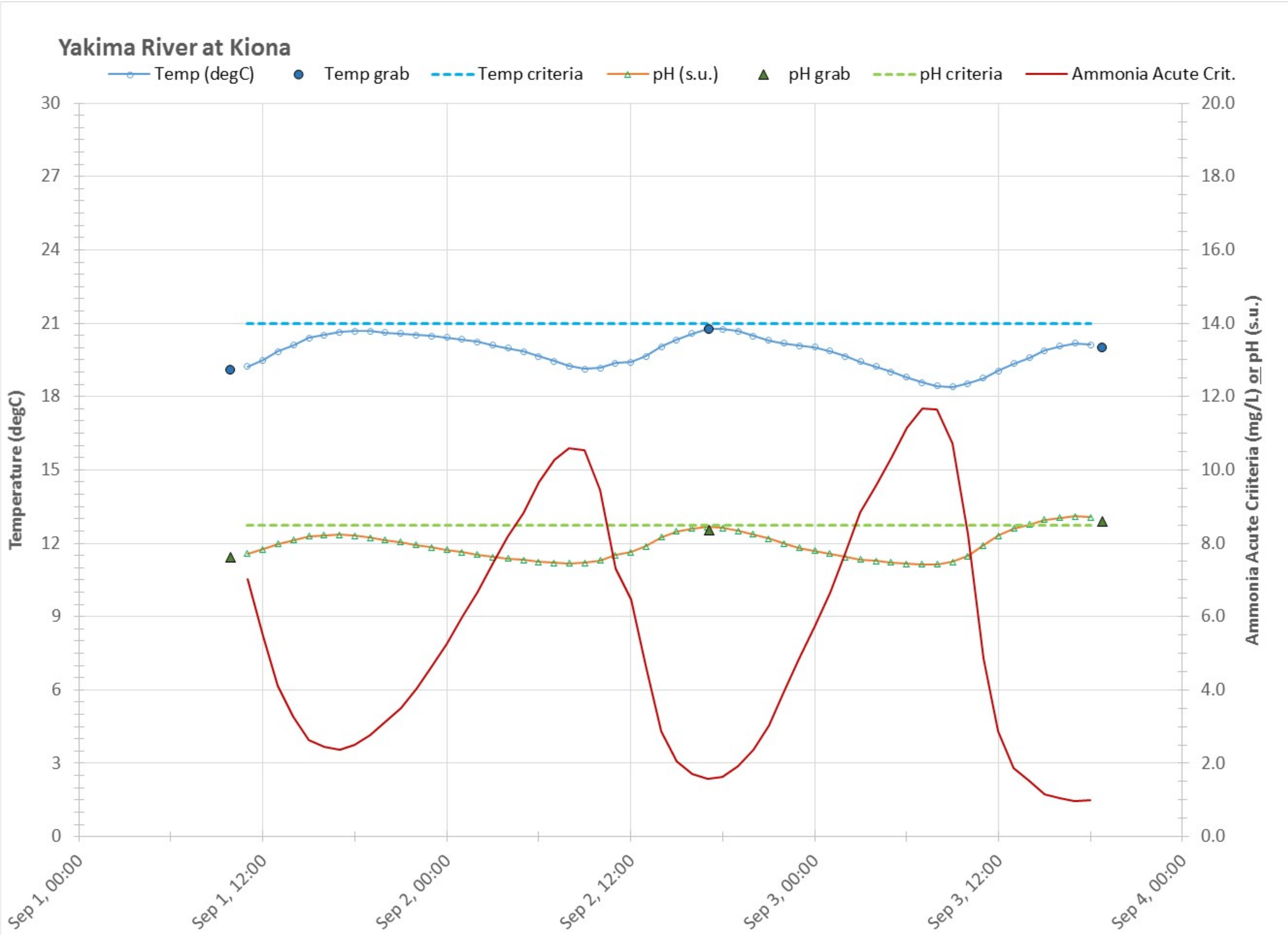


Figure A-10. Continuous monitoring results during September at the site at the Kiona USGS gage.

Appendix B. Glossary, Acronyms, and Abbreviations

Glossary

Anthropogenic: Human-caused.

Clean Water Act (CWA): A federal act passed in 1972 that contains provisions to restore and maintain the quality of the nation's waters. Section 303(d) of the Clean Water Act establishes the TMDL program.

Conductivity: A measure of water's ability to conduct an electrical current. Conductivity is related to the concentration and charge of dissolved ions in water.

Diel: Of, or pertaining to, a 24-hour period.

Dissolved oxygen (DO): A measure of the amount of oxygen dissolved in water.

Hyporheic: The area beneath and adjacent to a stream where surface water and groundwater intermix.

National Pollutant Discharge Elimination System (NPDES): National program for issuing, modifying, revoking and reissuing, terminating, monitoring, and enforcing permits, and imposing and enforcing pretreatment requirements under the Clean Water Act. The NPDES program regulates discharges from wastewater treatment plants, large factories, and other facilities that use, process, and discharge water back into lakes, streams, rivers, bays, and oceans.

Nonpoint source: Pollution that enters any waters of the state from any dispersed land-based or water-based activities, including but not limited to atmospheric deposition, surface-water runoff from agricultural lands, urban areas, or forest lands, subsurface or underground sources, or discharges from boats or marine vessels not otherwise regulated under the NPDES program. Generally, any unconfined and diffuse source of contamination. Legally, any source of water pollution that does not meet the legal definition of "point source" in section 502(14) of the Clean Water Act.

Parameter: Water quality constituent being measured (analyte). A physical, chemical, or biological property whose values determine environmental characteristics or behavior.

Pathogen: Disease-causing microorganisms such as bacteria, protozoa, viruses.

pH: A measure of the acidity or alkalinity of water. A low pH value (0 to 7) indicates that an acidic condition is present, while a high pH (7 to 14) indicates a basic or alkaline condition. A pH of 7 is considered to be neutral. Since the pH scale is logarithmic, a water sample with a pH of 8 is ten times more basic than one with a pH of 7.

Point source: Sources of pollution that discharge at a specific location from pipes, outfalls, and conveyance channels to a surface water. Examples of point source discharges include municipal wastewater treatment plants, municipal stormwater systems, industrial waste treatment facilities, and construction sites where more than 5 acres of land have been cleared.

Pollution: Contamination or other alteration of the physical, chemical, or biological properties of any waters of the state. This includes change in temperature, taste, color, turbidity, or odor of the waters. It also includes discharge of any liquid, gaseous, solid, radioactive, or other substance into any waters of the state. This definition assumes that these changes will, or are likely to, create a nuisance or render such waters harmful, detrimental, or injurious to (1) public health, safety, or welfare, or (2) domestic, commercial, industrial, agricultural, recreational, or other legitimate beneficial uses, or (3) livestock, wild animals, birds, fish, or other aquatic life.

Riparian: Relating to the banks along a natural course of water.

Salmonid: Fish that belong to the family *Salmonidae*. Species of salmon, trout, or char.

Stormwater: The portion of precipitation that does not naturally percolate into the ground or evaporate but instead runs off roads, pavement, and roofs during rainfall or snow melt. Stormwater can also come from hard or saturated grass surfaces such as lawns, pastures, playfields, and from gravel roads and parking lots.

Surface waters of the state: Lakes, rivers, ponds, streams, inland waters, salt waters, wetlands and all other surface waters and water courses within the jurisdiction of Washington State.

Total Maximum Daily Load (TMDL): Water cleanup plan. A distribution of a substance in a waterbody designed to protect it from not meeting (exceeding) water quality standards. A TMDL is equal to the sum of all of the following: (1) individual wasteload allocations for point sources, (2) the load allocations for nonpoint sources, (3) the contribution of natural sources, and (4) a Margin of Safety to allow for uncertainty in the wasteload determination. A reserve for future growth is also generally provided.

Watershed: A drainage area or basin in which all land and water areas drain or flow toward a central collector such as a stream, river, or lake at a lower elevation.

303(d) list: Section 303(d) of the federal Clean Water Act requires Washington State to periodically prepare a list of all surface waters in the state for which beneficial uses of the water – such as for drinking, recreation, aquatic habitat, and industrial use – are impaired by pollutants. These are water quality-limited estuaries, lakes, and streams that fall short of state surface water quality standards and are not expected to improve within the next two years.

Acronyms and Abbreviations

303(d)	Section 303(d) of the federal Clean Water Act
BOD	Biochemical oxygen demand
CWA	(See Glossary above)
degC	Degrees Celsius
DO	(See Glossary above)
Ecology	Washington State Department of Ecology
EIM	Environmental Information Management database
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency

HEC-RAS	A hydraulic model developed by the U.S. Army Corps of Engineers
K-K	Keechelus Reservoir-to-Kachess Reservoir Conveyance project
NAWQA	USGS National Water Quality Assessment program
NMFS	National Marine Fisheries Service (now NOAA Fisheries)
NOAA	National Oceanic and Atmospheric Administration
NPDES	(See Glossary above)
PDT	Pacific Daylight Time
pH	(See Glossary above)
QA	Quality assurance
Reclamation	U.S. Bureau of Reclamation
RM	River mile
SNTEMP	A water temperature computer model
SOD	Sediment oxygen demand
SOP	Standard operating procedures
SWDP	State Waste Discharge Permit
TMDL	(See Glossary above)
TN	Total nitrogen
TNVSS	Total nonvolatile suspended solids
TP	Total phosphorus
TSS	Total suspended solids
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WAC	Washington Administrative Code
WQ-CRO	Water Quality Program, Central Regional Office Section
WQA	Water Quality Assessment
WRIA	Water Resource Inventory Area
WWTP	Wastewater treatment plant
Yak-RW	Yakima Project RiverWare model
YBIP	Yakima Basin Integrated Water Resource Management Plan

Units of Measurement

°C	degrees centigrade
cfs	cubic feet per second
g	gram, a unit of mass
m	meter
mg	milligram
mg/L	milligrams per liter (parts per million)
s.u.	standard units
uS/cm	microSiemens per centimeter (units for conductivity)