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## The Effect of Water Stargrass Removal on Dissolved Oxygen, Temperature, and Water Velocity in the Lower Yakima River



Water Stargrass Yakima River, photo credit: Stephen Ingalls

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February 2024

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2. Benton Conservation District, Kennewick, WA

## Publication Information:

This report was part of work funded by the Yakima Basin Integrated Plan through the Washington State Department of Ecology under grant number: WRYBIP-1921-BentCD-00018. This work was collaborative between Washington State University-Tri-cities and Benton Conservation District. All data generated as part of this work are stored in the Ecology Information Management (EIM) system.

## Suggested citation:

Pelly, A.C., S.S. Roley, M. Appel, 2024. The Effect of water stargrass removal on dissolved oxygen, temperature and water flow in the lower Yakima River.

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## Acknowledgements:

The authors would like to acknowledge the following for their contributions to this work:

- Thomas Sexton, Kristy Pentico, and Marty Sexton with Benton Conservation District for the operation of the harvester and removal of the water stargrass in the pilot treatment areas
- Riley Zionce with Franklin Conservation District for the assembly of the logger casings and support of the water stargrass harvesting operations
- Maryam Akhlaghi Ghanbari, William L. Petersen, and Cristian De Paz (Washington State University), Matt Jasper (Benton Conservation District), and Athena Pelly for data collection field work
- John A. Harrison and Stephen M. Henderson (Washington State University), Matthew H. Kaufman (Worcester State University), and Robert O. Hall (University of Montana) for methodological advice
- State of Washington Water Resource Center and the Northwest Climate Adaptation Center for additional funding

## Abstract

High water temperature and low dissolved oxygen (DO) limit salmon migration in the lower Yakima River. One of the principal drivers of low DO is nighttime respiration by water stargrass (*Heteranthera dubia* (Jacq.) MacMill.), a native aquatic plant. Changes in Yakima River hydrology and river management, including dams and climate change, have facilitated the spread of water stargrass in the lower Yakima River, such that it now grows bank-to-bank in much of the lower Yakima. Plant removal may increase DO concentrations by reducing nighttime oxygen consumption. We measured DO across multiple years (2021-2023) with various flow conditions. In 2023, we experimentally removed patches of water stargrass with a mechanical harvester and examined the effect on DO, temperature, and water depth. We found a detectable increase in DO after plant removal of up to 0.6 mg/L, despite the small size of the removal. We found no change in temperature due to removal and minimal effects on depth. In the higher-flow year (2022), water stargrass and mosquito populations were suppressed, and DO concentrations were higher in the early summer. The detectable increase in DO concentration with plant removal and with higher flow suggests that plant removal is a promising method for improving salmon habitat, especially when coupled with flushing flows, although removal will likely need to be done at a larger scale to meet Washington state DO standards for salmonids.

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## Introduction and Background

Historically, anadromous salmonids (*Oncorhynchus* spp.) migrated and spawned in the Kiona Reach of the Yakima River (Wise et al. 2009, Pickett et al. 2016), but over the last decade, high daytime temperatures and low nighttime dissolved oxygen (DO) have inhibited their movement through the lower Yakima River (Wise et al. 2009, Appel et al. 2011). As cold-water fish, salmonids are unable to migrate when daytime temperatures are high (>21°C), but low DO concentrations at night impede migration when temperatures may drop to tolerable levels (Appel et al. 2011). Warm water can hold less gas than cold water, and so warmer temperatures exacerbate the DO problem.

The low DO concentrations are likely caused by respiration from the dominant native aquatic vegetation known as water stargrass (*Heteranthera dubia* (Jacq.) MacMill.). As a primary producer, water stargrass releases oxygen during the day, via photosynthesis, and consumes oxygen, via respiration, at night. Water stargrass dominates the lower Yakima River below Prosser, WA oftentimes extending bank to bank and emerging through the water surface (Wise et al. 2009). As a result, it accounts for approximately 90% of the total respiration in this reach (Pelly 2020). The volume of water stargrass is shifting the conditions of the flowing river in places so that it mimics that of a marsh environment.

The high temperatures in the lower Yakima River are a consequence of combined natural and human changes. The lower Yakima River is in a semi-arid basin and receives less than 10 inches of rainfall per year. There is minimal shading on the river, with summertime diurnal warming driven by solar radiation. The natural warming of the lower Yakima River at baseflow (summer) conditions has been exacerbated by the alteration in the natural hydrologic regime. The U.S. Bureau of Reclamation regulates the flows on the lower Yakima River with storage control dams to support irrigation. As a result, the timing and magnitude of the spring freshet is greatly altered with ponding and reduced flows below Prosser (Gendaszek et al. 2021). These cumulative impacts increase water temperature by allowing solar radiation to reach more of the water column (May et al. 2018). Climate change models for the Yakima Basin (Malek et al. 2020) show that the basin is sensitive to climate change as the Cascade Mountain snowpack, which feeds the Yakima River, shifts to rainfall thus altering the available summer water supply (Hall et al. 2022). As a result, less water is stored in snow, requiring reservoirs to store more water to meet summertime demands. Additionally, climate change-driven increases in average ambient air temperatures coupled with earlier peak flows will continue to impair summertime water temperatures (Pickett 2016).

The low spring and summer flows on the lower Yakima River can increase aquatic plant abundance due to decreased plant scour - higher flushing flows prevent early plant

establishment and scour existing plants (O'Hare et al. 2018). Changes in flow volume and timing are at least partially responsible for the increased abundance in water stargrass (Wise et al. 2009). Other factors include decreased turbidity (Rinella et al. 1992, Pickett 2016) facilitating light penetration. Plants can expand their range under low-velocity conditions, but their presence also creates conditions that facilitate their continued dominance, bringing the river into a feedback loop. Plants decrease water velocity, which leads to settling of particles and lower turbidity. The resultant low velocity and low turbidity perpetuate plant persistence (Madsen et al. 2001, Hestir et al. 2016).

Plant removal from other rivers reduced reach-scale respiration rates elsewhere (Madsen et al. 1988, Manolaki et al. 2022), and a similar approach might work in the Kiona Reach. Small water stargrass-free patches were ineffective at increasing DO concentrations, likely because upstream respiration influenced DO in these small patches (Pelly 2020). As a result, removal will likely have to be in larger patches to cause a detectable change in DO concentrations, however, the amount of biomass removed from an area to influence a measurable effect is unknown.

Water stargrass removal is likely to increase water velocity and decrease water depth in the removal patches. Water velocity and depth influence many ecosystem properties, including sediment retention, sediment grain size, temperature, and gas exchange. These properties directly or indirectly influence respiration, DO concentrations, and suitability for spawning. Slower river velocities and increasing marsh-like conditions also have a measurable impact on the mosquito densities in the lower Yakima River. Benton County Mosquito Control Board has documented an increase in disease-carrying mosquitos near the river as water stargrass densities increase (*pers. communication; A. Bheeler, mosquito control district*). As a result, understanding the effects of plant removal on flow will better help us predict the indirect consequences of plant removal.

To evaluate the impacts of the water stargrass on water quality and habitat, we initiated an experimental treatment of water stargrass using an aquatic harvester for larger scale removal coupled with monitoring. We experimentally removed > 1 acre of water stargrass from two treatment areas in the Kiona Reach of the lower Yakima River near Benton City to address the effects of water stargrass removal on DO, temperature, and water flow. We hypothesized that DO, temperature, and velocity would increase in response to water stargrass removal, and that mosquito habitat would decrease. This experimental removal was intended as a pilot project to better understand the relationships of water stargrass and water quality, with the goal of determining the future feasibility of improving lower Yakima River conditions via water stargrass removal at a larger scale.

## Methods

### Experimental Design

This investigation occurred in two phases: in 2021-2022, we investigated the links between water stargrass, water flow, and DO, and in 2023, we investigated the effect of removal on DO and temperature.

In 2022, the Cascade Mountains' snowpack was larger than in previous years, resulting in high spring flows. These conditions created a natural experiment, in which we compared conditions in a high-snowpack year (2022) to a typical snowpack year (2021). The conditions in 2022 were typical of ~pre-2000 snowpack, when the impacts of climate change were not as strong as they are currently, whereas conditions in 2021 represent the “new normal” in Cascades snowpack (Elsner 2010, Hall et al. 2022). During 2021 and 2022, we measured DO and temperature (see “Dissolved oxygen and temperature,” below).

In 2023, we imposed an experiment in which we removed water stargrass from the Yakima River. We employed a BACI (Before-After-Control-Impact) experimental design, which allowed us to detect the effects of an environmental impact (in our case, water stargrass removal) independently of seasonal changes (Stewart-Oaten et al. 1986). In this design, we establish both control and impact reaches, with the control reach upstream and the impact reach downstream of water stargrass removal (Fig. 1). We measured all variables at the control and impact reaches before and after harvest. The methods and work were documented in the Department of Ecology Quality Assurance/Quality Control Plan and Quality Assurance Quality Control Plan Addendum (Appel 2021 and Appel 2022).

In a BACI design, we compare the “before” relationship between the control and impact reaches to their relationship after removal. If that relationship changes, then it indicates that removal had an impact. By comparing to a control, we account for underlying seasonal changes in DO and temperature.

### Site Description

All investigations took place at a site in the lower Yakima River near Benton City, WA, within a stretch of river known as the Kiona Reach (Fig. 1). The upstream boundary for the project was the USGS gaging station near river mile 30, just above the Benton City Bridge. The lower boundary for the project area was upstream of the Benton City railroad bridge at river mile 28.5. Each year, two harvesting areas, termed areas of potential effect (APE), were

located between the upstream and downstream boundaries. Harvest was initially planned in APEs 1 and 2 but was canceled in 2021 due to a delay in harvester delivery and again in 2022 due to a lack of water stargrass. In 2022, water stargrass appeared to have been largely scoured from APE 1 and never grew back, so we designated a new harvesting area (APE 3), and APEs 2 and 3 were used for the 2023 removal experiment (Fig. 1).

We used multiple monitoring locations within the project boundaries to evaluate changes within each harvested APE. For each APE, we designated two monitoring locations near the left bank, one at the upstream boundary (labeled “A”) and one at the downstream boundary (labeled “C”). Each of these locations is hereafter referred to by a 2-character code indicating the APE and boundary location (e.g., 2A refers to the upstream boundary of APE 2). We designated two additional monitoring locations downstream of the main APEs at river mile 28.5. One of these was near the thalweg along the left bank (labeled “DSL”), and the other was near the right bank, in an area of slow-moving water where a dense water stargrass bed grew each year (labeled “DSR”).

During the removal experiment in 2023, locations 2A and 2C both served as upstream monitoring controls. Although 2C was downstream of APE2, APE2 had sparse water stargrass growth and so the magnitude of removal was minimal. Instead, both 2A and 2C served as upstream controls for removal in APE3. Each of the sensors at the control locations (2A, 2C) had periods of missing or otherwise unusable data due to vandalism and damage from the harvester. The missing data did not overlap, though, so data from these two sensors cover the full season.

Locations 3A and 3C provided boundaries for the second APE that was farther downstream. The DSL and DSR locations were the furthest downstream of the impact sites and provided the downstream boundary controls. The multiple downstream sensors allowed us to address if removal effects would differ among locations. Because DO measured at a particular location reflects the net effects of physical and biological processes for some distance upstream, it is possible that we would detect different effects at different distances downstream. Furthermore, although lotic waters are often well-mixed, pockets of slow-moving water may not mix fully. These pockets occur more commonly in wider streams and in places where plants or other obstacles inhibit the margins from mixing with the thalweg.

There was also missing data from one of the APE 3 sensors. The sensor at 3A was damaged by the harvester at the same time as the sensor at 2C and its data are therefore missing from August 11 through September 7.

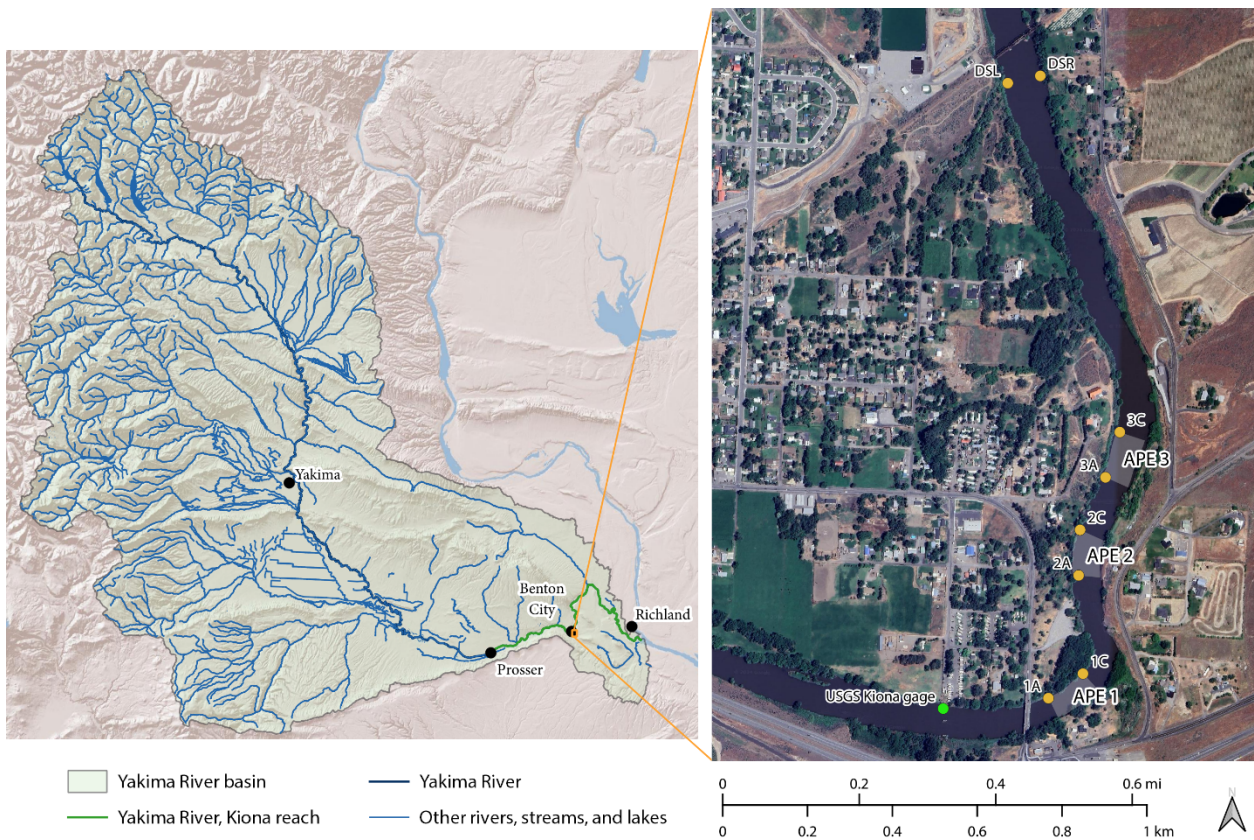


FIGURE 2. MAP OF YAKIMA RIVER BASIN WITH KIONA REACH HIGHLIGHTED, AND DETAILED STUDY SITE MAP SHOWING MONITORING LOCATIONS (POINTS) AND HARVEST AREAS (POLYGONS). YAKIMA RIVER BASIN BASE MAP COURTESY OF ESRI; STUDY SITE BASE MAP COURTESY OF GOOGLE; DATA SOURCES FOR OTHER LAYERS: WSDOT (2010), USGS (2018).

## Water stargrass removal

Water stargrass removal occurred in 2023 with a commercial aquatic plant “EcoHarvester” (Lake Weeders Digest LLC, Minnesota). Removal occurred at the Benton City site (Fig. 1) on the left bank during 8/8/2023 and 8/9/2023, and the right bank was harvested from 8/22/2023 through 8/25/2023. Removal was originally planned to be confined to APEs 2 and 3; however, due to less water stargrass growth than expected throughout APE 2, removal occurred throughout both APEs, as well as the space between them and approximately 50 yards downstream of APE 3 to maximize the amount of water stargrass removal.



Figure 3. EcoHarvester with roller head on the lower Yakima River.

The harvester is powered by a diesel engine that turns two paddle wheels (Fig. 2). Plant material is pulled from the water via a roller head that pinches plant material between the head and a second smaller roller that allows entire plants to be pulled. In conditions with soft sediment, roots are also removed. Vegetation is pulled onto a conveyor where it is moved into the 3 cubic yard bunk. A full bunk load of vegetation weighs approximately 2,000 lbs. Once the bunk is full, the conveyor is flipped, and vegetation can be offloaded by running the conveyor backward. At this site, vegetation was offloaded onto the shore of a private landowner. The treatment area totaled 5.7 acres with 210 cubic yards of harvested plant material removed from the Kiona Reach.

### Dissolved oxygen and temperature

To determine the effect of removal on DO and temperature, we deployed miniDOT DO and temperature sensors (PME, Vista, CA) at each monitoring location. Each sensor was placed as close as feasible to the main flow of the river, except the sensor at DSR, which was intentionally located in an area of slow-moving water. We attached each sensor to a housing: either a “fake rock” (a U-shaped piece of concrete), or to a rectangular steel pipe. The sensor was attached to the underside of the housing, such that it was raised off the surface of the river, protected from floating debris, and not readily visible to swimmers and boaters. All DO and temperature sensors had wipers that removed algal or sediment build-up every six hours. We periodically spot-checked their measurements with a YSI ProODO (YSI, Yellow Springs, OH) and all miniDOTs underwent calibration checks as described in the Project’s Quality Assurance Project Plan (QAPP); (Appel and Pelly 2023).

## Water flow

To determine the effect of water stargrass on water depth and velocity, we used continuous depth measurements, discharge at the USGS gauge, channel dimensions and periodic velocity measurements. We established four transects along the Kiona Reach, upstream and downstream of each of two removal sites. We traversed each transect in a kayak and measured depth with a pressure transducer attached to a GPS unit. We could then calculate stream area for that transect and date.

The upstream USGS gauge reports continuous discharge (Q). Because there are no significant inputs or outputs of surface or groundwater between the gauge and our study site, Q at the gauge is accurate for use in our study. To determine velocity, we algebraically rearranged the equation:  $Q = \text{area} \times \text{channel velocity}$  to  $\text{velocity} = Q/\text{area}$ .

To determine the effect of plant removal on depth and velocity, we calculated the ratio of depth: discharge. We calculated it as a ratio with discharge to account for seasonal fluctuations in flow. A higher depth: discharge ratio indicates that for a given discharge, the water is deeper, typically indicating that the water has slowed. We expect water stargrass removal to decrease the depth: discharge ratio.

## Results

### Inter-annual variation in DO concentration

Our 3 years of DO data span a high snowpack year (2022) and two “typical” years (2021 and 2023). In the high snowpack year, water stargrass abundance was also lower in early and mid-summer, likely because high flows scoured and removed water stargrass in places with high velocity and delayed the growth of plants elsewhere. Later in the season, the water stargrass recovered in places, although not everywhere.

In the high snowpack/low water stargrass year (2022), minimum daily DO was initially higher, sometimes >1 mg/L higher, than in the typical snowpack years (Fig. 3). In late summer (after ~Aug 15), all 3 years had similar minimum DO concentrations, likely because both flow conditions and water stargrass abundance were similar by late summer. Except for a few days in autumn, daily DO minimum remained below the Washington state standard. At the USGS Kiona gauge, DO data exhibited a similar pattern, with 2022 DO higher than other years in June and July. By late summer, as water stargrass biomass recovered, DO concentrations were similar to other years (Fig. 4).

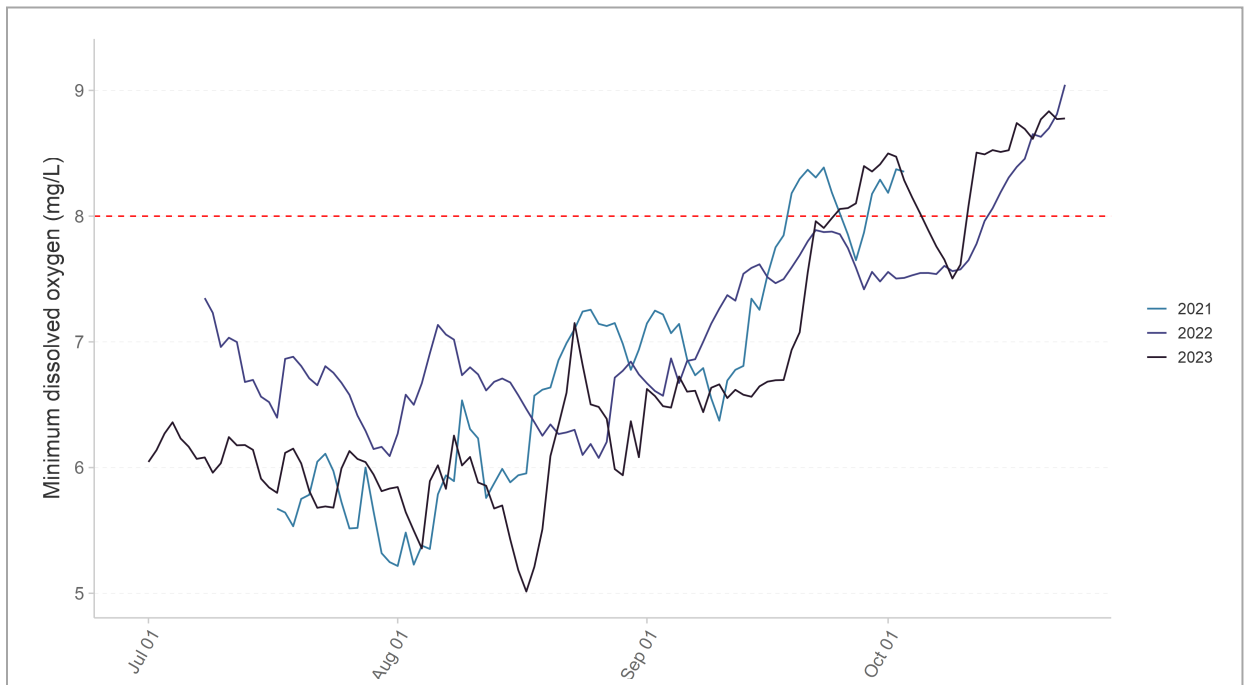


Figure 4. Daily minimum dissolved oxygen concentration (mg/L), averaged across sensors deployed in the Kiona Reach (see Fig. 1 for deployment locations). The red line is the state standard for salmonids.

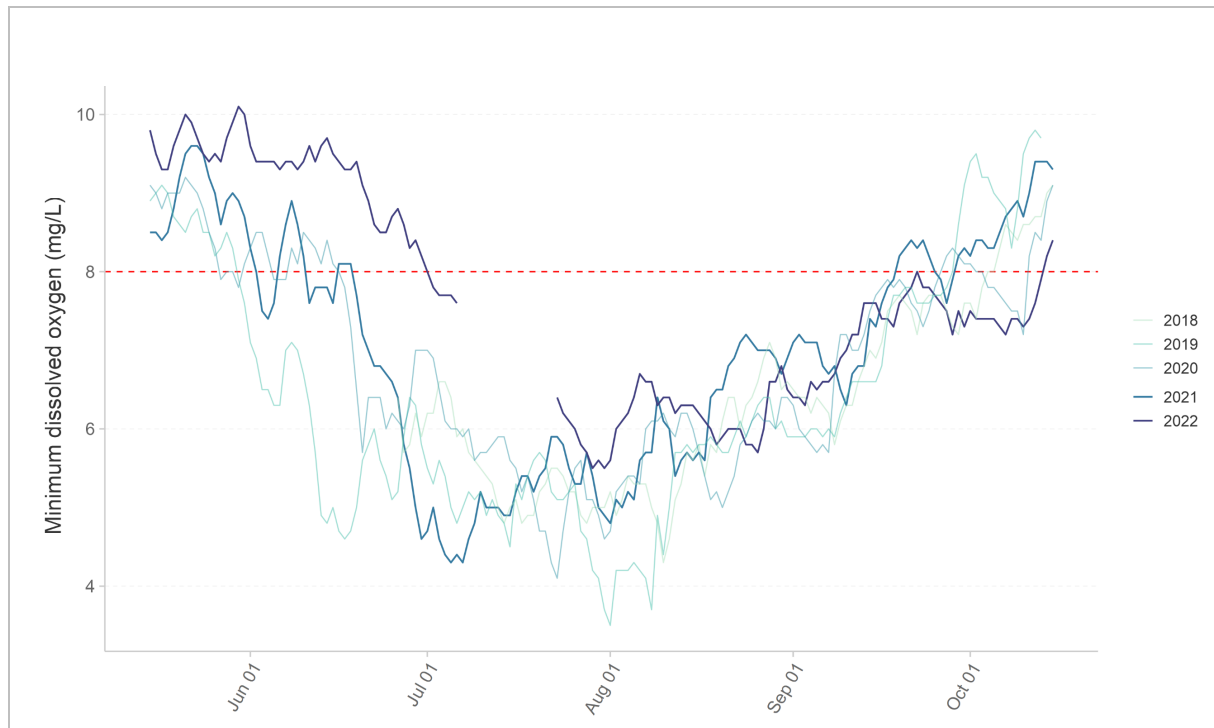


Figure 5. Daily minimum dissolved oxygen (DO) concentration at the USGS Kiona gauge, from 2018-2022.

### Seasonal patterns in temperature and DO, 2023

Seasonal patterns in DO minima were consistent among logger sites. All loggers exhibited lower minimums in summer, with DO gradually rising through the fall. All sites were below the Washington State DO standard for salmonids for the entire summer. Prior to water stargrass removal, the most-downstream loggers (DSL and DSR) had consistently lower DO than the others. Starting just before the first removal, DSR minima were close to other loggers', and after removal, DSR had the highest or second-highest minimum DO (Fig. 5).

The seasonal patterns are as expected. Metabolic activity typically peaks in summer, which means that ecosystem respiration (i.e., the combined respiration of all organisms in the reach) is usually highest in summer. Aerobic respiration removes oxygen from the water, resulting in lower DO minima in the summer. Furthermore, warmer water can hold less oxygen than cold water.

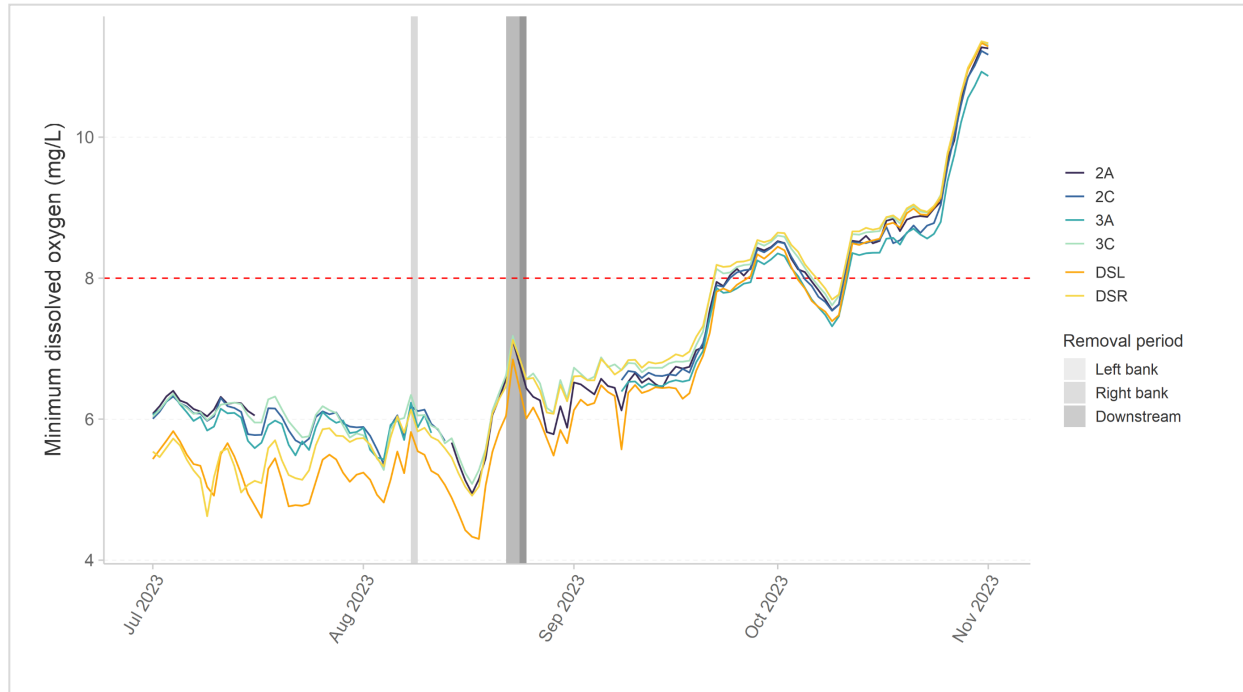


Figure 6. Daily minimum DO concentration at various sites in the lower Yakima River. In order from upstream to downstream: 2A, 2C, 3A, 3C, DSL and DSR. See map (Fig. 1) for exact locations. The solid vertical bars represent water stargrass removal: respectively, removal from the left bank, right bank, and between 3C and DSL (downstream). The red dashed line represents the Washington State DO standard for salmonids.

Similarly, temperature patterns followed the expected seasonal pattern, with highest temperatures during the summer and a gradual decline through the fall. The loggers recorded remarkably similar temperatures, despite their varied locations (Fig. 6).

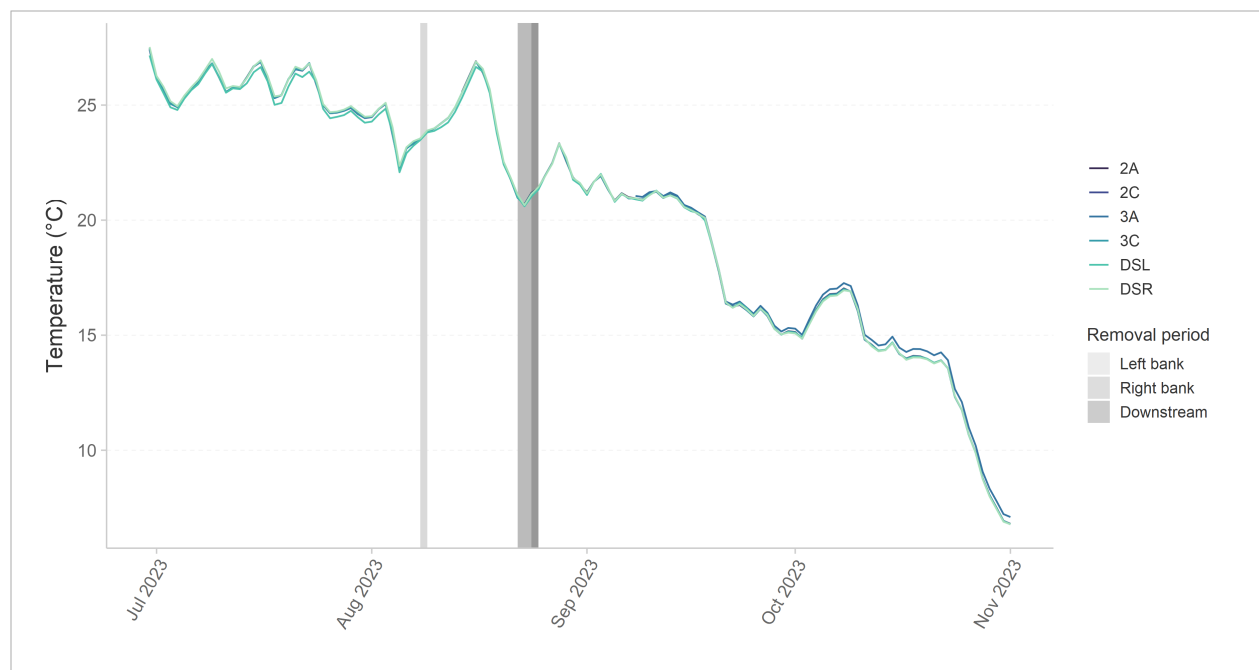


Figure 7. Daily average temperature at various sites in the lower Yakima River. In order from upstream to downstream: 2A, 2C, 3A, 3C, DSL and DSR. See map (Fig. 1) for exact locations. The solid vertical bars represent water stargrass removal: respectively, removal from the left bank, right bank, and between 3C and DSL (downstream).

### Effect of water stargrass removal on DO and temperature

Overall, water stargrass removal had a small but detectable effect on DO, and the magnitude of that effect varied with location and time (Fig. 7, Table 1). The most dramatic change occurred at DSL, the logger furthest downstream. Prior to removal, DO was lower at DSL than at either of the control loggers. In the weeks immediately after removal (Aug 26-Sep 18), DSL DO increased by 0.6 mg/L relative to control 2A (i.e., from -0.82 to -0.22 mg/L), and increased by an average of 0.4 mg/L relative to control 2C (i.e., from -0.74 to -0.31 mg/L). The effect of removal was smaller at the logger directly downstream of the removal area (3C). There, DO increased by an average of 0.3 mg/L (i.e., from -0.049 to 0.244 mg/L) in comparison to control 2A and by an average of 0.09 mg/L (i.e., from 0.04 to 0.13) in comparison to control 2C. The effect of removal attenuated later in the season but was still evident at all downstream loggers, regardless of the control logger (Fig. 7, Table 1). Water stargrass removal had no effect on daily mean temperature, with all loggers recording essentially the same values through the entire study period (Fig. 6).

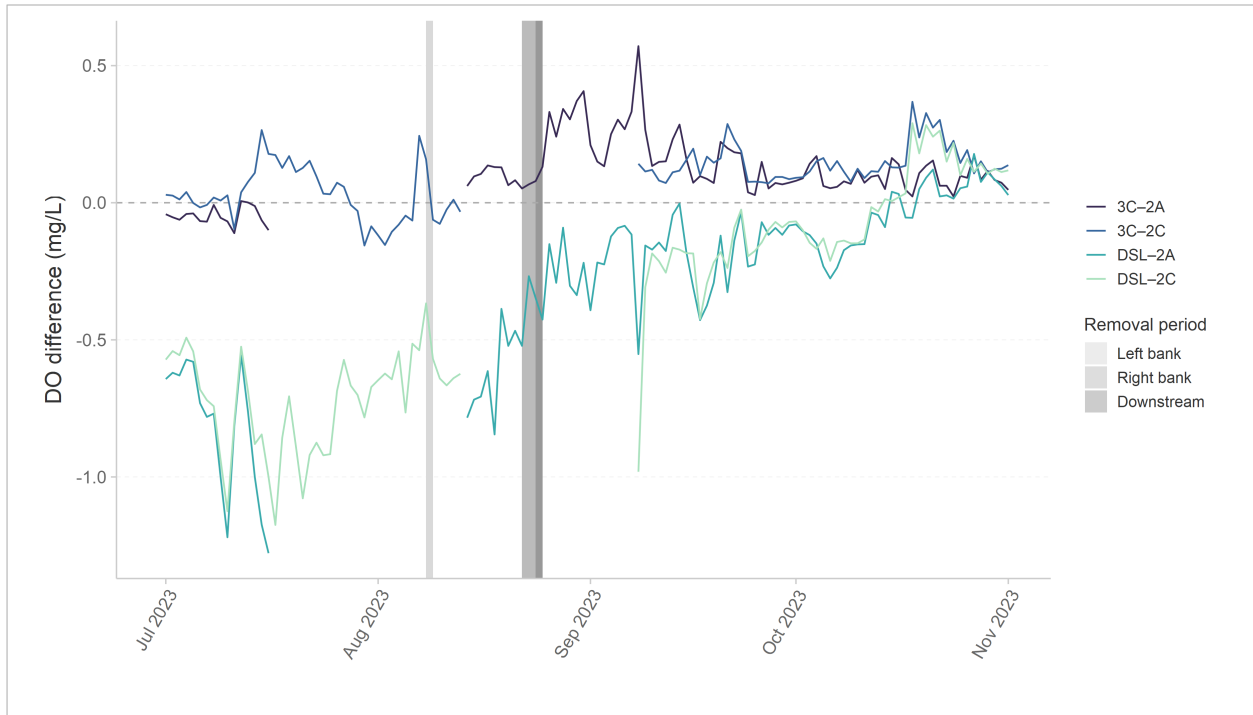


FIGURE 8. THE DIFFERENCE IN MINIMUM DO (DELTA DO) BETWEEN DOWNSTREAM (IMPACT) AND UPSTREAM (CONTROL) DO, BEFORE AND AFTER REMOVAL.

NOTE: A POSITIVE VALUE MEANS THAT IMPACT SITE HAS HIGHER DO THAN THE CONTROL AND VICE VERSA. PURPLE IS THE DIFFERENCE BETWEEN THE CONTROL (2A) AND THE LOGGER IMMEDIATELY DOWNSTREAM OF REMOVAL (3C), DARK BLUE IS THE DIFFERENCE BETWEEN THE CONTROL (2C) AND THE LOGGER IMMEDIATELY DOWNSTREAM OF REMOVAL (3C), BLUE-GREEN IS THE DIFFERENCE BETWEEN THE CONTROL (2A) AND THE LOGGER FAR DOWNSTREAM (DSL), AND PALE GREEN IS THE DIFFERENCE BETWEEN THE CONTROL (2C) AND THE LOGGER FAR DOWNSTREAM (DSL). THE SOLID VERTICAL BARS REPRESENT WATER STARGRASS REMOVAL: RESPECTIVELY, REMOVAL FROM THE LEFT BANK, RIGHT BANK, AND BETWEEN 3C AND DSL (DOWNSTREAM).

TABLE 1. AVERAGE CHANGE IN DO (RANGE IN PARENTHESES), CALCULATED AS DO AT THE IMPACT SITE MINUS DO AT THE UPSTREAM CONTROL.

Control	Impact Site	Pre-removal change DO	During-removal change DO	Immediate post-removal change DO	Late post-removal change DO
<b>2A</b>	3C (directly downstream)	-0.05 (-0.11 to 0.01)	0.10 (0.05 to 0.14)	0.24 (0.07 to 0.57)	0.10 (0.02 to 0.22)
<b>2C</b>	3C (directly downstream)	0.04 (-0.16 to 0.27)	-0.03 (-0.08 to 0.01)	0.13 (0.07 to 0.20)	0.15 (0.07 to 0.37)
<b>2A</b>	DSL (most downstream)	-0.82 (-1.28 to -0.56)	-0.62 (-0.85 to -0.39)	-0.22 (-0.55 to 0)	-0.07 (-0.33 to 0.18)
<b>2C</b>	DSL (most downstream)	-0.74 (-1.18 to -0.37)	-0.64 (-0.67 to -0.62)	-0.31 (-0.98 to -0.16)	-0.01 (-0.24 to 0.29)

A POSITIVE NUMBER INDICATES HIGHER DO DOWNSTREAM OF PLANT REMOVAL AND VICE VERSA. TO DETERMINE THE EFFECT OF REMOVAL, COMPARE THE PRE-REMOVAL CHANGE DO TO THE POST-REMOVAL DO. PRE-REMOVAL IS THE PERIOD PRIOR TO AUG 8, BETWEEN REMOVAL IS THE PERIOD OF AUG 10-AUG 22, DURING WHICH REMOVAL OCCURRED, IMMEDIATE POST-REMOVAL IS AUG 26-SEP 18, AND LATE POST-REMOVAL IS SEP 19-NOV 1.

### Longitudinal patterns in dissolved oxygen

Water stargrass is highly abundant within the 17 river miles upstream of our removal site. The Prosser USGS gauge, which is located near river mile 47, is directly downstream of an irrigation diversion dam. That dam provides an upstream boundary for the lower Yakima River within Benton County. At the upstream Prosser gaging station, DO levels were below the Washington standard of 8.0 mg/L in the summertime until early fall, with seasonal changes closely mirroring those downstream as measured by our sensors (Fig. 8). However, DO levels were not as suppressed as those measured within the Kiona Reach and DO levels rose above the state standard a few weeks earlier than at the downstream Kiona reach.

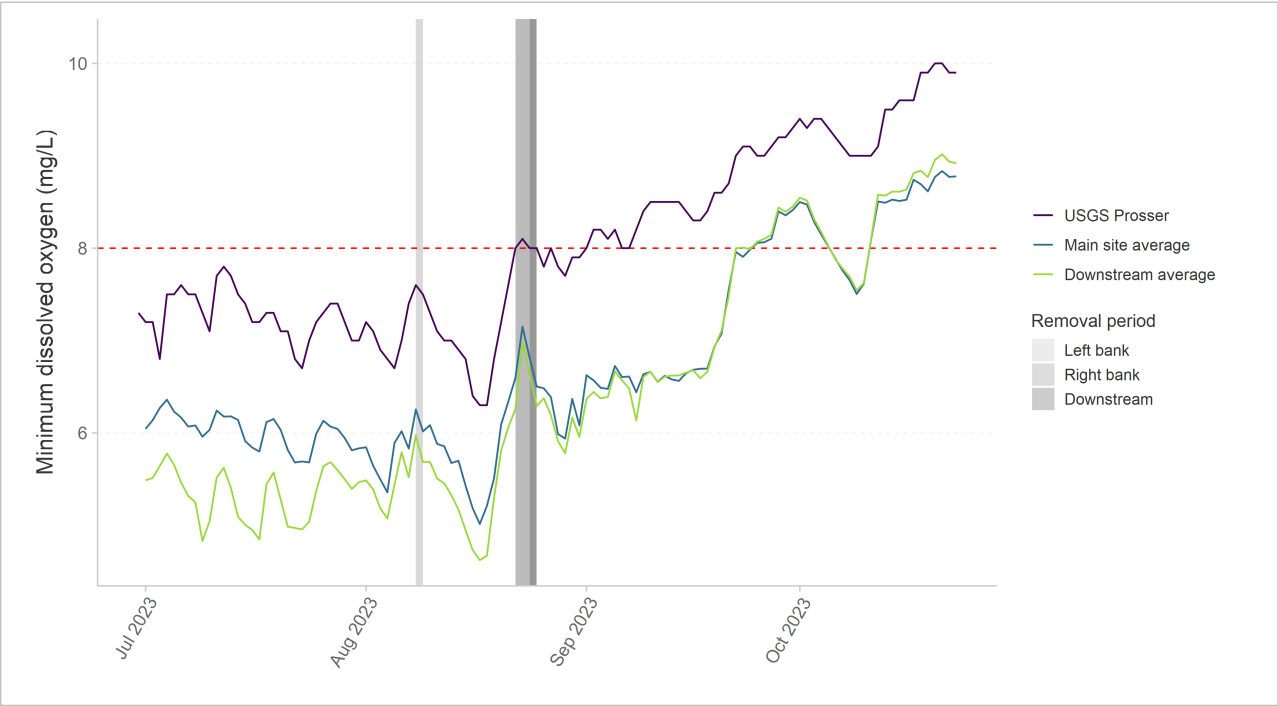


Figure 9. Daily minimum dissolved oxygen (DO) at the USGS Prosser gauge and the average minimum DO at main sites (2A, 2C, 3A, and 3C) and at the downstream sites (DSL and DSR). See Fig. 1 for locations.

## Effect of water stargrass removal on water depth and velocity

The effects of removal on depth will require further analysis and investigation. The average depth:discharge ratio was nearly identical pre-removal and post-removal (Fig. 10), but the ratio decreased from the peak value calculated during harvesting. Given the natural variation in depth:discharge with seasonal changes (Fig. 11) and that the ratio falls within small range, it is not possible to ascertain if it is the influence of the harvest or natural changes resulting in alterations of flow. Additional analysis will be required to evaluate if the decrease in the ratio observed in the data are the result of harvesting or changes in flow.

Anecdotally, the harvester team encountered immediate changes in current while navigating the equipment during harvest. Swifter flows (increased velocity) in the harvested areas impacted upstream navigation post-harvest with the increased flows. Capturing the change in flow and velocity data may require use of more sophisticated and costly equipment such as an Acoustic Doppler Current Profiler (ADCP) – with data collected immediately before, during and after harvest. Future work should also compare differences in the calculated ratio at the Kiona Gage between the high flow/low biomass water year in 2022 and the more moderate flow/higher biomass year in 2023, to evaluate year to year variations in the average depth:discharge ratio.

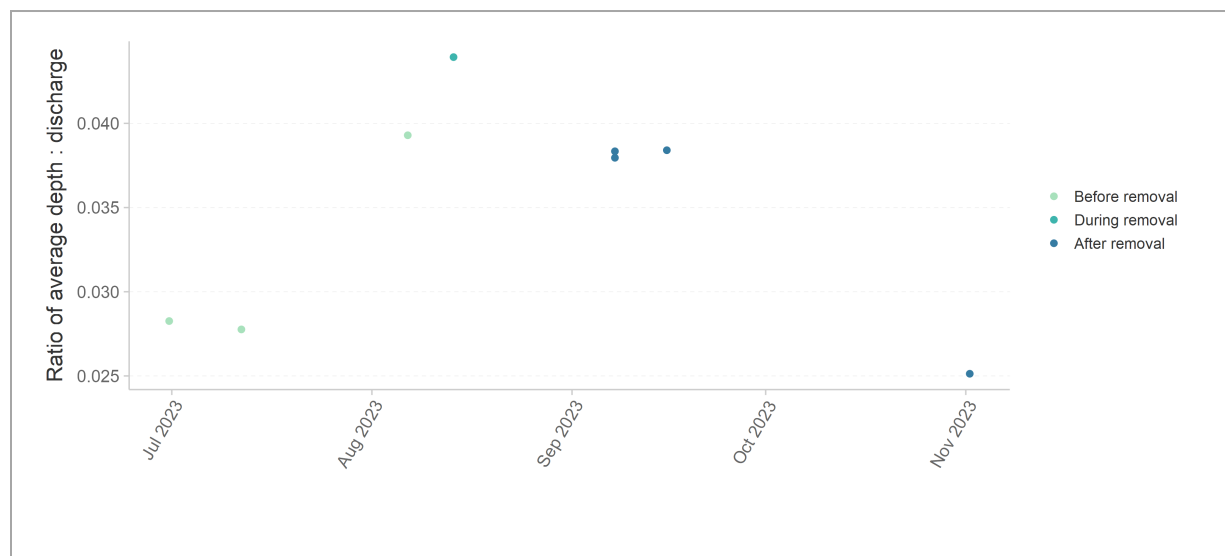
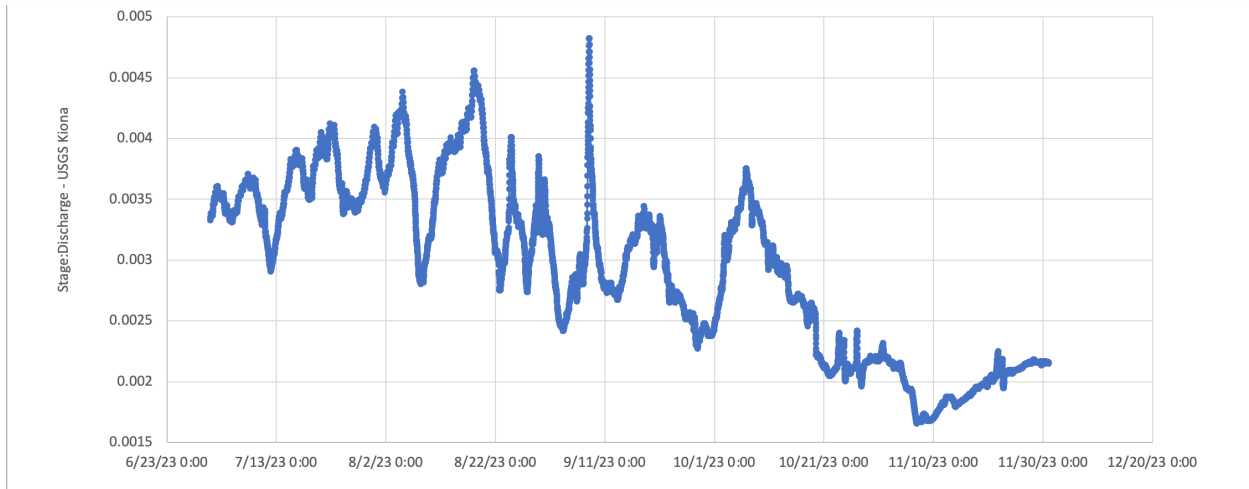


Figure 10. The depth: discharge ratio at site 3C. Discharge is measured at the USGS, Kiona Gauge upstream of harvest.



**Figure 11.** The stage:discharge ratio at USGS Kiona Gage upstream of harvest locations – showing variations in the ratio with seasonal changes.

### Effect of water stargrass removal on mosquito populations

Benton County Mosquito Control Board maintains traps at several locations on the lower Yakima, including Benton City, to track populations and types of mosquitos. Mosquito traps were monitored from April – mid August in 2022 and April – September in 2023 by the mosquito control district and data are provided in Figure 12.

While trends in mosquito data can be difficult to accurately quantify between seasons and years there are interesting comparisons between the 2022 and 2023 mosquito trap data for Benton City. Mosquito counts in 2022 were lower than those in 2023. While many factors influence the yearly mosquito population, it is likely that the sustained higher river flows in 2022, which resulted in swifter velocities and diminished water stargrass mats positively impacted the total mosquito counts that year.

The 2023 mosquito counts are not likely to be impacted by the August harvesting efforts given the timing of the larvae/mosquito life cycle. Tracking mosquito counts along with water stargrass return rates for subsequent years will be important indicators to determine the impact of harvesting efforts on total mosquito populations.

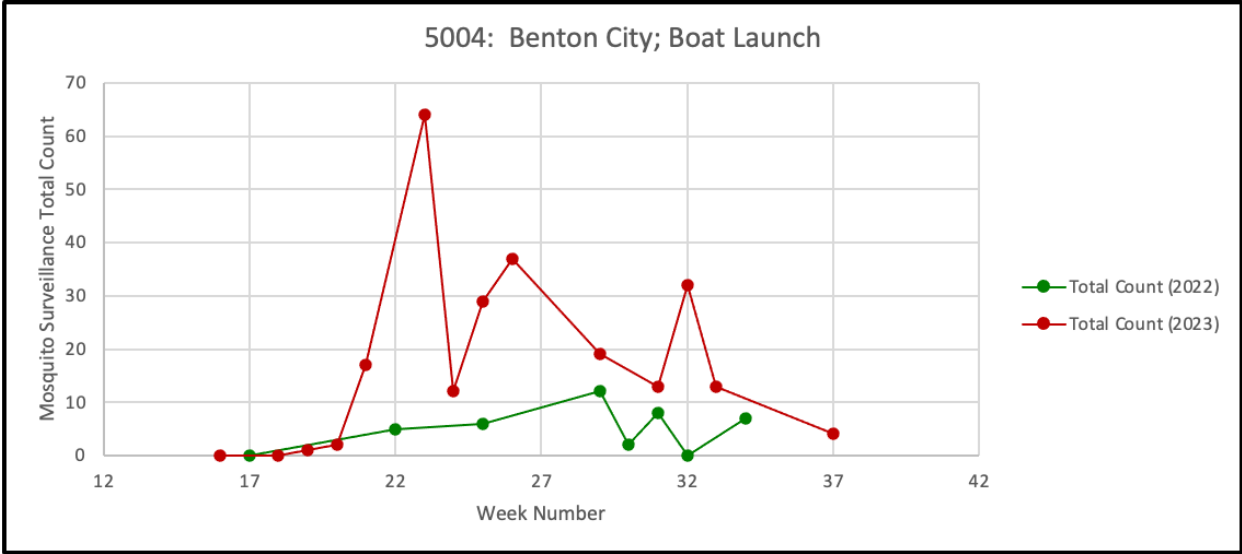


Figure 12. Total Mosquito Count Data from the Benton City Boat Launch Trap. Data provided by Benton County Mosquito Control Board.

## Discussion

This pilot study demonstrated that DO in the lower Yakima River is closely linked to water stargrass biomass. Both flushing flows and mechanical removal reduce water stargrass biomass and increase DO, suggesting that larger-scale removal and strategic flow management could further increase DO, improving conditions for migrating salmon.

### Flow effects on water stargrass and dissolved oxygen

In 2022, the high spring river flows temporarily increased DO concentrations compared to years with typical flow. We hypothesize that the improvement in DO was a result of suppressed water stargrass abundance, leading to lower reach-scale respiration. Higher flows lead to lower plant abundance because of the physical abrasion and removal of plants and rhizomes (Bunn and Arthington 2002). BCD, in collaboration with USGS, measured biomass at Kiona in 2022 continuing a record of measurement from 2018. The biomass analysis highlighted a significant decrease in biomass throughout the growing season as compared to previous years. While the high flows decreased water stargrass abundance and increased minimum DO levels, the reach still failed to meet water quality standards during the summer months. This is likely due to the insufficient removal of rhizomes, such that water stargrass was able to return by late summer, when flow conditions were conducive to its establishment and growth.

### Plant removal and dissolved oxygen

Pilot-scale plant removal increased downstream DO concentration. The increase was not sufficient to meet the Washington state water quality standard for salmonids, but the increase in DO does suggest that a larger-scale removal could further improve DO concentrations. Upstream conditions are a key consideration for future, larger-scale removal.

In rivers, DO concentration reflects DO production and consumption at the sensor and some distance upstream; because water is flowing, the sensor data effectively integrates processes over some distance. That distance is called the reach length. Reach length decreases with gas exchange rate (i.e., the rate at which gases diffuse into and out of the river) and increases with water velocity (Chapra and diToro 1991). We do not have estimates of gas exchange for the Yakima River, but it likely has relatively low gas exchange, because it is a low-gradient river with extensive plant coverage (Ulseth et al. 2019). At the same time, summer water velocity is not particularly high, leading to a long reach length. As a result, DO concentration in the Kiona reach are likely influenced by water stargrass metabolism for several kilometers upstream.

Water typically enters the Kiona Reach with low DO. The Prosser Dam, 17 river miles (27 river kilometers) upstream of the removal area, harbors a large water stargrass population in its reservoir, where low flows and a deeper channel facilitate its growth. Just downstream of the dam, DO is typically below the water quality standard, albeit higher than concentrations in the Kiona Reach (Fig. 8). The cumulative effects of water stargrass respiration between the Prosser Dam and our downstream removal sites likely cause the lower DO concentrations at our removal sites. To raise DO sufficiently to meet the standard, plant removal in the Kiona Reach would have to be extensive enough to overcome respiration along the entire stretch to the Prosser Dam and overcome the effects of the respiration in the Prosser Dam reservoir. Instead, future efforts could consider removing plants in the reservoir itself, so that water entering the Kiona Reach has a higher DO concentration.

### Potential management strategy for dissolved oxygen

Flushing flows and mechanical water stargrass removal could be employed together to achieve higher DO in the Kiona Reach and potentially approach state standards for DO. Flushing flows remove water stargrass biomass early in the season, with higher early-season DO concentration, as a result. Later in the season, as water stargrass returns, mechanical removal could maintain DO concentrations. As the system is highly regulated, considerations could be made to where timed flow releases help with plant scour and delayed plant growth. The U.S. Bureau of Reclamation releases water flows in the late spring to aid in salmonid migrations. These timed releases could potentially be optimized to also attenuate biomass growth and improve early spring dissolved oxygen levels.

Because DO concentrations are influenced by a long reach length, plant removal likely needs to be done on a large scale and at strategic locations to achieve water quality standards. To efficiently operate on a large scale, future removal efforts could target areas of the river with slower flow, where the harvester is easier to operate and so more likely to remove a higher percentage of the biomass. Scaling-up harvesting efforts with increased staff resources and additional equipment may be needed to achieve reach scale improvements in minimum dissolved oxygen levels. In addition, removal at the Prosser Dam may increase the DO concentration of water coming into the Kiona Reach, narrowing the DO deficit from the state standard, and increasing the likelihood that DO concentrations approach the state standard.

## Conclusions

Although water stargrass removal did not raise DO sufficiently to meet water quality standards, removal did increase DO concentrations, by up to an average of 0.6 mg/L. In These results indicate that biomass influences DO concentrations, but large-scale removal will be required to influence DO within a larger reach. In addition, the year with a higher spring flow (2022) had lower water stargrass biomass and higher DO concentration earlier in the season, suggesting that flushing flows can also have a positive influence on DO concentration. Higher spring flows also coincided with a smaller mosquito population. The effects on temperature and depth were minimal. The results of this pilot project suggest that more extensive removal, in a location further upstream, might be necessary for influencing downstream DO at critical locations for salmonids.

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