Management and Control Techniques for Water Stargrass in the Lower Yakima River

FINAL Report to the Yakima Basin Fish & Wildlife Recovery Board

Photo: Yakima River, 2019 by Stephen Ingalls, Benton Mosquito Control

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September 17, 2021

Executive Summary

Basin-wide efforts and targeted improvements to reduce sediment loads and toxic chemicals to the lower Yakima River in the late 1990s were a big success, resulting in dramatic improvements to lower Yakima River water quality. While these improvements were vital to the overall health of the lower river, the improvements also led to the unintended consequence of over-abundant macrophyte growth. The years of legacy nutrients in the lower river, coupled with improved water clarity, resulted in the rapid propagation and growth of *Heteranthera dubia* (water stargrass). Although classified as a native plant, water stargrass has consumed river resources to the near exclusion of other beneficial aquatic macrophytes. Consequently, water stargrass has reached nuisance levels, acting similarly to an invasive species. To restore river health and mitigate documented harmful ecological impacts to native fishery populations, the plant requires targeted mitigation and intervention.

While our understanding of the negative impacts of water stargrass on fish, human health, and water quality have expanded over the past twenty years, we have not extensively investigated management techniques for its control in this basin. This report, commissioned by the Yakima Basin Fish and Wildlife Recovery board, addresses this critical data gap and provides a comprehensive review of potential control methods specific to the conditions and beneficial uses of the lower Yakima River.

For this review, we investigated common plant removal techniques including: manual, mechanical, chemical, environmental, and biological manipulation controls. In addition, larger scale watershed control methods were investigated, such as altering flow regimes and creating velocity and bed scour for flushing of plant biomass. These watershed control methods may be more effective at plant control across larger spatial and temporal scales, though they will require more research regarding their potential applications and feasibility, as well as coordinated discussions with basin-wide partners. All investigated management methods were reviewed in the context of water stargrass biological properties as well as the feasibility and applicability of each method within the lower Yakima River. Two technical advisory group (TAG) meetings were held during the development phase of this report in May and June of 2020. The TAG meetings provided review and refinement of the researched methods by plant specialists, freshwater ecologists, fish biologists, and basin stakeholders. The results of this report will support the subsequent development of a Water Stargrass Mitigation Recommendations Report by Benton Conservation District that will identify mitigation goals, top tier recommendations, including those from the TAG, and identify associated targeted techniques for controlling water stargrass as identified within this report.

The findings of this report concluded that targeted control of water stargrass will require the integration of multiple management techniques, likely at different times throughout the plant's life cycle, in order to effectively combat the problem. The selection of appropriate treatment methods will depend on the goals of the removal (fish protection, irrigation, recreation, and/or human health), the spatial extent of area needing to be cleared, location within the river and associated river hydrogeology, and the available cost structure for implementation. Each identified alternative has benefits and constraints, and the selection of removal techniques will require recognition of the trade-offs when selecting a treatment application. For instance, mechanical harvesting and hand-pulling are both demonstrated effective treatment options for aquatic plant removal but will have different suitability in their applications. Mechanical harvesting will likely be effective for clearing large areas of the river quickly, such as in the Yakima Delta or behind dams. Mechanical harvesting, however, can be costly and requires ongoing operation and maintenance with specialized knowledge of machine operation and safety training. This method is also not suited for clearing plants from shallow waters or narrow confined areas, such as those found in side-channels. For these areas, hand-pulling may be better suited. This method is less costly than harvesting if volunteer labor is utilized. While potentially cheaper, hand-pulling is time and labor intensive. Timing of treatment application will also be a critical consideration, as some techniques may have a greater impact when applied earlier in the plant's life cycle. However, this timing may be in conflict with lower river's in-season work window which is protective of the native anadromous species who migrate through the lower river corridor.

Investigated chemical methods highlighted only a few options that show promise for treatments in the lower Yakima River. These candidates included endothall, imazamox, carfentrazone-ethyl, and fluridone. Of these, endothall and imazamox provided the greatest promise for chemical control, though each has potential drawbacks for application in the lower Yakima River. As chemical treatments are designed to target invasive species, its application for native species such as water stargrass is more uncertain. Chemical treatments within a flowing river can be challenging, and may work best when performed with water level draw down or use of a bubble curtain to alter the local river conditions. Prior to implementing chemical control methods, small-scale test pilots or laboratory treatments should be explored.

While the scope and impact of water stargrass on native migratory fish species and human health is multi-faceted and complex, as a native plant we do not need to strive for one hundred percent containment as seen with typical invasive species management. Instead, the smarter approach is to target key areas that will provide the greatest level of impact with a combination of effective and available techniques suited to the treatment application area. Remaining uncertainties regarding the plant's life cycle, propagation, and role in nutrient cycling within the lower Yakima River should be further investigated to help identify critical timings for treatment, as well as methods that will most effectively mitigate and manage its growth to healthier population levels. Lastly, monitoring and evaluation plans to study the effectiveness of the implemented techniques for improvement of the beneficial uses of the lower Yakima River should be considered in parallel with any treatment actions so that treatment operations can be better understood and refined.

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1.0 INTRODUCTION

1.1 Water stargrass history in the lower Yakima River

The lower Yakima River in eastern Washington State is dominated by water stargrass (*Heteranthera dubia* (Jacq.) MacMill.). Though native to the region, this macrophyte (i.e., aquatic plant) functions like a non-native invasive species in this section of the river by outcompeting other plants and colonizing the majority of the river from bank to bank (Wise et al. 2009, Appel et al. 2011).

Prior to dam construction on the Yakima River, peak spring flows (i.e., freshets) tended to be higher and faster than they are now. Due to these scouring flows, water stargrass was most likely low in abundance. After dam construction from the 1890s–1940s, much of the spring freshet was reserved for irrigation uses in reservoirs, while sediment and nutrient runoff from agricultural operations increased. Water stargrass abundance remained low, most likely due to high turbidity, even though it now had an ample nutrient source (Rinella et al. 1992, Wise et al. 2009, Pickett 2016).

In the late 1990s, a water quality improvement plan was put in place, leading to improvements in irrigation practices in the lower Yakima Valley. Sediment runoff dramatically decreased, leading to much greater light penetration in the river. Water stargrass has a very high light requirement (Blackburn et al. 1961, Zhu et al. 2008), so the reduced turbidity in combination with low flows and historical sediment nutrient load likely provided ideal conditions for its growth. The plant began rapidly spreading, and by 2005 water stargrass dominated the majority of the lower river from Prosser to the confluence with the Columbia River (Wise et al. 2009).

1.2 Consequences of water stargrass colonization

The lower Yakima River is a migration corridor for multiple salmonid species, which already face several barriers to their movement. During the summer months, the Kiona reach is the warmest stretch of the Yakima River, with most of its 47 river miles inhospitable for adult salmonid migration at baseflow (summer) conditions. Specifically, in-stream water temperatures often exceed 21 °C during baseflow conditions, which is limiting for adult migration of Chinook salmon (*Oncorhynchus tshawytscha*), steelhead (*O. mykiss*), sockeye salmon (*O. nerka*), coho salmon (*O. kisutch*), as well as Pacific lamprey (*Entosphenus tridentatus*). Rapidly warming spring/summer waters can also limit success of late season juvenile out-migration. These challenges are compounded by the fact that warmer water temperatures provide more favorable conditions for invasive predator populations over native salmon stocks (McCullough et al. 2001, Carter 2008).

The abundant growth of water stargrass adds multiple water quality and habitat challenges for salmonid migration, adding to the barriers they already face from warm temperatures. Water stargrass physically displaces the river and increases sedimentation. Fall Chinook spawning, once prevalent in the lower Yakima, has shifted above Prosser Dam as a result of decreased spawning gravel quality (Appel et al. 2011), forcing the thermally stressed fish to migrate even further. Comparison of fall Chinook populations in the Yakima River and the neighboring Columbia River Hanford Reach over the last 20 years shows the Yakima River run remained stagnant, while the Hanford Reach run has multiplied five times. WDFW attributes this difference to the spread of water stargrass on the Yakima River spawning grounds (P. Hoffarth, WDFW, personal communication). During base flow conditions, nighttime dissolved oxygen levels typically drop well below the Washington State water quality standard for salmon-bearing waterways of 8 mg/L, most likely as a result of water stargrass respiration (Wise et al. 2009, Pelly 2020). McMichael (2017) noted that high summer river temperatures, lower DO levels, increased pH levels, and dense water stargrass stands might provide favorable conditions for the recruitment and refuge of non-native piscine predator species to the detriment of native salmon species. Predation on out-migrating juvenile salmonids has been identified as a significant limiting factor threatening salmon recovery efforts.

Water stargrass also poses problems for people who rely upon the Yakima River for their livelihood and recreation. The plant can plug irrigation intake screens and dense stands can interfere with fishing and impede recreational benefits of the river (Appel et al. 2011). Finally, water stargrass may increase risks to human health, as when the plant reaches the top of the water column in slack-water areas, it provides breeding habitat for mosquitoes carrying West Nile virus (A. Bheeler, Benton County Mosquito Control Board, personal communication).

Water stargrass may also have some beneficial effects for the river ecosystem such as limiting other noxious plant growth. Small patches of invasive submersed macrophytes, including Eurasian watermilfoil (*Myriophyllum spicatum*), grow within water stargrass beds. It may be that water stargrass is outcompeting some noxious weeds and preventing them from spreading further in the Yakima.

The Yakima River Basin is considered one of the most vulnerable watersheds in Washington State for climate change impacts. Historically, flows in the Yakima have been dependent on a mix of spring snowmelt and winter rains, but as average temperatures warm, the basin is shifting to one dominated by rain. With summers predicted to become warmer and dryer, peak flows are shifting earlier while summer flows are decreasing (Elsner et al. 2010, Pickett 2016). As water demands in the basin increase, it is imperative that the question of how to improve lower Yakima water quality, support migration, and mitigate water stargrass growth are addressed.

1.3 Status as a native plant

Water stargrass is native to Washington State, so it is not classified as an invasive plant or noxious weed, even though it dominates its ecosystem, outcompeting other plants to the detriment of the aquatic community. Notably, although native species tend to be excluded from the category of invasives, they may be scientifically classified as such when barriers to their growth are suddenly removed, allowing them to dominate their habitat and harm other species (Schultz and Dibble 2012). Though water stargrass in the lower Yakima River meets this definition, in the State of Washington it falls under the category of native nuisance plants.

Due to its status as a native plant, management options and funding available for water stargrass control are limited. For manual or mechanical methods of plant management, governed by the Washington Department of Fish and Wildlife (WDFW), water stargrass is classified as an aquatic beneficial plant. Compared to removal and control regulations for aquatic noxious weeds (i.e., the legal category of invasive plants), control of aquatic beneficial plants faces additional area size and permitting restrictions (WDFW 2015). For chemical methods of plant management, which are regulated by the Washington State Department of Ecology (Ecology), water stargrass is included in the category of aquatic nuisance plants. Compared to noxious weed management, control projects for aquatic nuisance plants face restrictions on which herbicides may be used and the percentage of the waterbody that may be treated (Ecology 2021a).

Finally, since water stargrass is a native part of the Yakima River ecosystem, management goals will not include eradication, as they might if it was a nonnative invasive plant. Instead, its native status should inform management strategies that aim to restore it to a useful and healthy part of its ecosystem.

1.4 Water stargrass life cycle and management

Water stargrass life cycle patterns (i.e., plant phenology) have implications for potential management strategies. For instance, some herbicides are most effective when plants are actively translocating materials (e.g., carbohydrates and nutrients) to and from their roots. Methods that remove entire plants including roots from the sediment may be most effective when growth is at its peak, as this may help deplete the sediment nutrient supply. Methods that rely on shading may be most effective when plant biomass is minimal, as they may help keep plants—and thus their effect on the river ecosystem—small. Careful selection of management strategies based on water stargrass phenology may enhance the effectiveness of control that is achieved.

Only some aspects of water stargrass phenology are known. Based on observations in an Ohio stream, water stargrass growth ceases in the autumn or early winter when water temperatures fall to 10 °C and resumes in the late winter or early spring when water temperatures reach 8 °C (Horn 1983).

One important question for plant management is how water stargrass overwinters, as in some systems only belowground rhizomes and roots persist through the winter, making it vulnerable to sedimentation events before growth begins in the spring (N. Rybicki, USGS, personal communication). In other locations, entire plants persist through the winter, though many leaves may be lost (Horn 1983). In the early spring of 2021, the Benton Conservation District (Benton CD) documented water stargrass growth in the lower Yakima and found that the population overwinters at least partially as entire plants. The plants do appear to lose some biomass during the winter, but they also retain a considerable amount. Many leaves are lost but the stems appear to stay, ready for new leaves to bud out the following growing season (M. Nielson, Benton CD, personal communication). This may provide it with a head start on growth in the spring compared to plants that overwinter mainly as rhizomes.

Other questions remain to be answered, including when during the season water stargrass plants have lost the majority of the biomass they will lose, or whether spring growth begins when daytime maximum temperatures reach 8 °C or when temperatures consistently stay above that point. Experimentally growing water stargrass in aquariums or tanks to observe its life cycle over the course of the year may be a worthwhile strategy to inform management methods.

1.5 System uncertainties

In addition to questions regarding phenology (see Section 1.4), several questions remain regarding water stargrass in the lower Yakima River, the answers to which may inform effective management strategies. One important question that has remained unanswered is from where water stargrass obtains its nutrients, since rooted macrophytes are capable of absorbing nutrients from the sediments through their roots and from the water column through their foliage. Plants most commonly draw macronutrients (e.g., nitrogen and phosphorus) from the sediments, where concentrations tend to be higher, though in waterbodies with excessively high nutrient loads in the water column (i.e., eutrophic waters), they may absorb them through their leaves (Sand-Jensen and Borum 1991, Barko et al. 1991, Madsen and Cedergreen 2002). In the Yakima River, where water column nutrient levels are relatively low (USGS 2021), water stargrass is most likely drawing nutrients from the sediments, where there may be a large historical supply (Wise et al. 2009). Therefore, management methods that rely on reducing water column nutrient loads may prove ineffective at controlling water stargrass. However, this remains an untested hypothesis.

Management methods that remove plant biomass from the river may help deplete nutrient loads in the sediments, as nutrients are incorporated into the plant tissues that are removed from the system. If water stargrass is indeed drawing its nutrient supply from the sediments, regular removal of plant aboveground biomass may be effective at preventing future growth, as nutrients would be gradually depleted from the sediments. However, the nutrient level in the sediments is unknown, so it is uncertain whether this could be an effective long-term management strategy.

Though water stargrass is most likely not drawing nutrients from the water column, at least not as a primary source, the plant population may have an effect on nutrient concentrations in the water. If plants obtain at least some of their nutrient supply from the water column, they may be helping to keep nutrient levels low. If this is the case, large-scale plant removal could have the unintended consequence of increasing nutrient concentrations in the lower Yakima. Alternatively, if water stargrass obtains its supply entirely from the sediments, nutrient concentrations may be entirely unaffected by plant removal. The U.S. Geological Survey (USGS) is currently investigating questions related to water stargrass and nutrients (R. Sheibley, USGS, personal communication), and their research may help address some of these questions.

The required size of removal area to see an improvement in dissolved oxygen conditions is presently unknown. Joint research between the Benton CD and Washington State University Tri-Cities is planned for the summer and fall of 2021 to investigate this question. It will be important to determine the minimum treatment area for plant removal that will positively benefit dissolved oxygen levels in the lower river for the benefit of salmon survival and migration. Additional uncertainties as mentioned above include the phenology and life cycle of water stargrass in the lower Yakima River. Developing a life cycle model for water stargrass in the lower Yakima River that helps improve our understanding of how the plant overwinters, spreads, timing of senescence and the abiotic and biotic factors that influence its development and growth will be critical in helping to develop impactful management strategies. The uncertainties surrounding water stargrass in the lower Yakima River can affect management decision-making, however, carefully designed studies coupled with pilot tests of management methods could be used to answer many of these unknowns.

2.0 PROJECT GOALS

The primary goal of this project is to research treatment methods specific to the removal of water stargrass biomass in the lower Yakima River with a direct benefit to salmonids and the beneficial uses of the river. In the lower Yakima, these uses include recreation, water supply uses (i.e., domestic, industrial, agricultural, and stock water), wildlife habitat, commerce and navigation, boating, aesthetics, and aquatic life (Ecology 2011). The aquatic life requiring protection are federal- and state-listed and other sensitive and vulnerable species, designated as priority species by the Washington Department of Fish and Wildlife (WDFW 2008). The priority species that are known to use the lower Yakima River are all anadromous salmonids: spring Chinook salmon, summer steelhead, sockeye salmon, coho salmon, and fall Chinook salmon (WDFW 2016). To avoid adverse impact to these species, water stargrass management work may need to be confined to the times when spawning and incubating salmonids are least likely to be present.

Our goal is not to eradicate water stargrass, as it is a useful, healthy, and native part of the Yakima River ecosystem. Instead, the goal of this project is to mitigate and control water stargrass abundance, thus opening up channels for fish passage and habitat, reducing its contribution to physical and chemical barriers to fish migration (i.e., high temperatures, altered flows, and low dissolved oxygen concentrations), and minimizing its negative impacts on recreation and irrigation water withdrawals.

The goal of this document is to aid in the development of a “Water Stargrass Recommendations Report” for the mitigation of water stargrass in the lower Yakima. This will rely on principles of integrated pest management (IPM), a strategy that in the context of native aquatic plant management considers each individual plant problem independently and evaluates a range of chemical and non-chemical alternatives available for control. For each problem, the management scenarios that are developed should be highly individualized, recognizing that no single control method will by itself be completely effective. Instead, a variety of biological, physical, mechanical, and/or chemical methods are integrated into a cohesive plan developed to provide long-term control of problematic aquatic plants (Chartrand et al. 2017).

3.0 MANAGEMENT AND CONTROL ALTERNATIVES

3.1 Summary of alternatives

An exhaustive list of standard aquatic plant management options has been considered and evaluated for water stargrass and the characteristics of the lower Yakima River (Table 1). This table separates potential mitigation methods into those that merit further consideration and those that are not realistically applicable to water stargrass and/or the lower Yakima River.

A list of potential water stargrass management methods was compiled from all those listed in Ecology’s Aquatic Plant and Algae Management (APAM) permit (Ecology 2021b), those investigated in the Environmental Impact Statement for the APAM permit (Chartrand et al. 2017), as well as other methods investigated in various scientific journal articles. In addition, the Benton CD convened a Technical Advisory Group (TAG) to review and provide feedback on these methods. Several additional methods were added to the list of possible methods based on recommendations from TAG members.

Potential methods were reviewed for their permissibility under Ecology and WDFW permits, potential effects on aquatic ecosystems, human health, and beneficial uses of the river (e.g., irrigation), and documented success or failure at controlling water stargrass. Several management methods were almost immediately discarded from consideration due to their toxicity to salmonids or humans, or due to regulations that prohibit their use in rivers. These methods were only briefly researched and are listed in this document with a brief explanation of why they are unacceptable for water stargrass management. Potential management methods that were not immediately discarded were extensively researched to determine their advantages and disadvantages, including potential effects to ecosystem or human health, logistical challenges (e.g., required irrigation restrictions), and effectiveness (or, for methods that have not been tested, potential effectiveness) against water stargrass.

Table 1. Summary of management and control alternatives for water stargrass in the lower Yakima River

Method	Likely Work Window	Effectiveness for Water Stargrass	Advantages	Disadvantages	Permit Required	Notes
No action **Scale: Reach** **Duration: N/A**	N/A	Not effective	• WSG may be outcompeting invasive plants slowing their spread, mitigation may create other remediation issues • No direct cost • May aid in nutrient cycling and sequestration for the lower river	• WSG allowed to spread further • Dissolved oxygen impacts • Spawning gravel covered • Irrigation and recreational use harmed • Continuing public health threat with mosquito habitat • Reduction in flow velocity, unknown effects on established rating curves	None	Disadvantages of doing nothing outweigh the advantages
Manual Methods						
Hand-pulling **Scale: Small, local** **Duration: Longer term if roots removed (multiple seasons)**	Jun 1–Sep 15	Very effective if roots are removed	• No requirements for specialized skills, training, or equipment • Can be implemented quickly, no lengthy permitting process • Minimal environmental impacts • Useful in shallow or hard to reach areas (e.g., side channels)	• Very labor-intensive; most appropriate for localized areas • May lead to further plant colonization if stem fragments are not captured • Requires disposal of plant biomass • Requires low-flow conditions	2015 pamphlet (WDFW)	Most effective in combination with digging to enable easier removal of roots

Method	Likely Work Window	Effectiveness for Water Stargrass	Advantages	Disadvantages	Permit Required	Notes
Hand-digging ***Scale:*** **Small, local** ***Duration:*** **Longer term if roots removed (multiple seasons)**	Jun 1–Sep 15	Very effective	● No requirements for specialized skills, training, or equipment; only cost is for labor and inexpensive tools ● Can be implemented quickly, without a lengthy permitting process ● Expected to cause minimal environmental impacts ● May be useful in areas not accessible to other methods (e.g., shallows, side channels)	● Very labor-intensive; most appropriate for localized areas ● May lead to further plant colonization if stem fragments are not captured ● Requires disposal of plant biomass ● Requires low-flow conditions	2015 pamphlet (WDFW); possible cultural resource concerns	Most effective in combination with hand-pulling A combination of hand-pulling and digging with hand cultivators has been shown to be very effective at clearing water stargrass from localized areas
Hand-cutting ***Scale:*** **Small, local** ***Duration:*** **Short-term**	Jun 1–Sep 15	Not effective	● Faster than other manual methods ● May cause less sediment disturbance than other manual methods	● Very labor-intensive; most appropriate for localized areas ● Roots and rhizomes remain in the sediment and plants quickly regrow ● Belowground plant biomass remains in the sediment and will contribute to ecosystem respiration, so not likely effective at alleviating low DO ● Requires disposal of plant biomass	2015 pamphlet (WDFW)	Not considered further
Raking ***Scale:*** **Small, local** ***Duration:*** **Long-term**	Jun 1–Sep 15	Likely not effective in LYR	● No requirements for specialized skills, training, or equipment; very low equipment cost ● Can be implemented quickly, without a lengthy permitting process ● Expected to cause minimal environmental impacts	● Very labor-intensive; most appropriate for localized areas ● Additional method required to capture removed plants before they float downstream ● Requires disposal of plant biomass ● Most likely ineffective among hard-packed cobble substrate and dense root mats	2015 pamphlet (WDFW)	Most likely a poor choice for water stargrass removal

Method	Likely Work Window	Effectiveness for Water Stargrass	Advantages	Disadvantages	Permit Required	Notes
Mechanical Methods						
Harvesting ***Scale:*** **Large areas** ***Duration:*** **Long-term**	Jun 1–Sep 15	Possibly effective long-term (pulling type); likely short-term effective (cutting type)	● Pulling-type harvesters remove plant roots from sediment (though effectiveness in hard-packed cobble substrate is unknown) ● Can remove plants across a large area ● Removed plants are automatically captured and prevented from floating downstream ● Less expensive than other mechanical methods like rotovation	● Plants may quickly regrow if roots left ● Effectiveness of pulling-type harvesters untested on WSG ● May be inoperable during periods of low or high flows ● Areas of the river with large boulders may be inaccessible ● Possible environmental impact of by-catch depending on season of operation ● Requires disposal of plant biomass ● Expensive equipment & maintenance	Hydraulic Project Approval (WDFW)	Benton CD purchased a pulling-type harvester for pilot study summer 2021 to determine effectiveness
Rotovation ***Scale:*** **Large areas** ***Duration:*** **Long-term**	Jun 1–Sep 15	Likely not effective in LYR	● Fast treatment rate ● Large treatment areas possible	● Significant environmental impacts: turbidity increases, release of nutrients, disruption of benthic communities ● Non-selective, so areas with desirable species need to be avoided ● Likely to be ineffective among cobbles and areas with large boulders will be inaccessible ● Requires disposal of plant biomass ● Extremely expensive	Hydraulic Project Approval (WDFW); possible shoreline permits from cities and counties; possible USACE & WA DNR reviews	Most likely a poor choice for water stargrass removal

Method	Likely Work Window	Effectiveness for Water Stargrass	Advantages	Disadvantages	Permit Required	Notes
Diver-operated dredging/Diver-assisted suction harvesting ***Scale:*** **Small, local** ***Duration:*** **Long-term**	Jun 1–Sep 15	Likely very effective	● May be useful in areas not accessible to other mechanical methods (e.g., areas with obstacles such as boulders) ● Does not require low-flow conditions ● Potentially faster than manual methods, but still allows for plant selectivity ● Plant fragmentation minimized	● Very labor-intensive and slow; most appropriate for localized areas ● Significant turbidity created, especially by diver-operated dredging ● Requires disposal of plant biomass ● Expensive	Hydraulic Project Approval (WDFW); possible shoreline permits from local agencies; other permits may be required for dredging	Diver-assisted suction harvesting may be a good choice; diver-operated dredging is most likely a poor choice
Sediment agitation (weed rollers) ***Scale & Duration:*** **Unknown**	No timing restrictions	Likely not effective	● Unknown	● Small weed rollers have proven to be ineffective for WSG in Yakima River ● Large weed rollers are limited to stationary installations ● Not practical in moving water or for large infestations	Hydraulic Project Approval (WDFW)	Appears to be a poor choice for WSG control but simple to pilot test in-situ
Mailbox blower ***Scale & Duration:*** **Unknown**	Unknown (likely Jun 1 – Sept 15)	Unknown	● May be useful to clear spawning gravels ● Relatively simple & inexpensive to install on any boat and pilot test method	● Impact on removal of aquatic vegetation is unknown ● Minimal information available for its treatment on aquatic macrophyte removal	Hydraulic Project Approval (WDFW)	
UV-C Light ***Scale & Duration:*** **Unknown**	Unknown	Unknown	● Not bed disturbing, no impact on in-stream turbidity ● Easy to install on small or large boats for control in different aquatic systems ● Relatively cost effective method, if boat is already available	● May result in high biomass decay impacting dissolved oxygen ● Effectiveness on WSG uncertain ● Requires multiple treatments given amount of biomass. ● May have impacts to other aquatic organisms (may require fish deterrent systems to be used in conjunction with UV-C light)	Hydraulic Project Approval (WDFW)	Newer treatment method, pilot study for effectiveness on WSG would need to be investigated Treatments early spring likely to be more impactful but outside of in-water work window

Method	Likely Work Window	Effectiveness for Water Stargrass	Advantages	Disadvantages	Permit Required	Notes
Environmental Manipulation Methods						
Bottom barriers ***Scale:*** **Small, local** ***Duration:*** **Long-term**	Jun 1–Sep 15	Possibly effective	● Can be implemented quickly, without a lengthy permitting process ● Does not require disposal of plant biomass ● Relatively low cost	● Will most likely require WSG to be cut before installation ● Largest environmental impact is to salmonid spawning habitat	2015 pamphlet (WDFW)	May be a possible choice for WSG control when combined with hand-cutting
Water level drawdown ***Scale:*** **Reach** ***Duration:*** **Unknown**	Irrigation Season	Possibly effective	● May allow for application of chemical treatment of emerged plants ● Could be coordinated with irrigation supply needs	● May pose risks to salmonids and could only be utilized when salmon are unlikely to be in river (>74F). ● As a stand-alone treatment it is not recommended and is unlikely to impact plants as WSG can survive as an emergent plant ● May make WSG problem worse	Hydraulic Project Approval (WDFW)	May be a possible option if coupled with chemical treatments effective only on emergent plants
Bubble Curtain ***Scale:*** **Small, local** ***Duration*:** **Short-term**	Jun 1 – Sept 15 (Depends on chemical treatment window)	Unknown	● May allow for application of chemical treatment of emerged plants ● May provide treatment for areas (side-channels) that are not accessible by large equipment	● Requires dye tracer study prior to implementation – may be challenging to fund ● Implementation depends on flow, mixing, and location hydrology for success	Aquatic plant and algae management (Ecology); Hydraulic Project Approval (WDFW)	Requires chemical treatment application (Potential constraints listed within "Chemical Methods", Table 1).
Shading ***Scale:*** **Small, local** ***Duration:*** **Long-term**	Year-round	Potentially effective	● WSG has a very high light requirement and does not grow in areas of the Yakima River that are very heavily shaded, such as bridge shadows	● Does not provide plant removal, but works as a supplement to keep growth low ● Takes years for trees to grow large enough for shading ● The mainstem is too wide to adequately shade ● Plants require intensive management for establishment in local arid climate	None	Shading may help control water stargrass in small, narrow side-channels

Method	Likely Work Window	Effectiveness for Water Stargrass	Advantages	Disadvantages	Permit Required	Notes
Biological Controls						
Grass carp ***Scale & Duration*:** **N/A**	No	Likely not effective	• N/A	• Introduction prohibited in rivers	Aquatic plant and algae management permit (Ecology)	Not considered further
Plant-specific biological control agents ***Scale & Duration*:** **N/A**	No	Unknown	• Passive control method	• Typically not an effective stand-alone method • No plant-specific biological control agent has yet been identified as effective for water stargrass	Aquatic plant and algae management permit (Ecology)	Not considered further
Chemical methods - warranting further consideration						
Endothall (Aquathol® K, Aquathol® Super K, Cascade®) ***Scale:*** **Reach** ***Duration:*** **Seasonal**	Jul 15–Sep 1	Possibly effective	• Very little environmental risk during timing window • Very few irrigation restrictions when applied at labeled rates • Rapid-acting herbicide; symptoms appear within a day • Does not require removal of plant biomass from water • Water stargrass listed as susceptible on label with recommendations for application rates in flowing water	• Contact herbicide; rhizomes/roots will remain and plants will likely re-grow • Some toxicity to fish; application restricted to July 15–September 1 • Restrictions for potable water intake • 24-hour swimming advisory required, boating advisory recommended • Decomposing biomass may deplete oxygen from water column; requires mitigation method(s) • Ineffective for water stargrass in flowing water in two studies	Aquatic plant and algae management permit (Ecology)	A possible choice for water stargrass control; a trial study may be required to determine level of control

Method	Likely Work Window	Effectiveness for Water Stargrass	Advantages	Disadvantages	Permit Required	Notes
Imazamox (Clearcast®) ***Scale:*** **Reach** ***Duration:*** **Long-term**	Late winter before Mar 15	Possibly effective	• Very little environmental risk • Systemic herbicide; completely kills target plants or severely inhibits growth • Rapid-acting herbicide; inhibits plant growth within one day; symptoms appear in about a week • Does not require removal of plant biomass from water • Water stargrass listed as susceptible on label	• Potential sublethal effects to juvenile salmonids • Serious irrigation restrictions mean application during irrigation intake period is infeasible • Application limited to brief period after plant growth begins and before irrigation begins • Decomposing biomass may deplete oxygen from water column; requires mitigation method(s) • Potential risk of herbicide resistance development	Aquatic plant and algae management permit (Ecology)	A possible choice for water stargrass control; a trial study may be required to determine level of control
Carfentrazone-ethyl (Stingray™ Aquatic Herbicide) ***Scale:*** **Reach** ***Duration:*** **Seasonal**	Jul 15–Sep 1	Unlikely	• When effective for aquatic plants, symptoms appear in 2–5 days • Considered a reduced risk pesticide by EPA; mostly nontoxic to animals and not persistent in the environment • Does not require removal of plant biomass from water	• Contact herbicide; rhizomes/roots will remain and plants will likely re-grow • Some toxicity to fish; application restricted to July 15–September 1 • Restrictions for potable water intake and irrigation water use • High pH levels in the Yakima River during timing window cause likely ineffective contact times • Decomposing biomass may deplete oxygen from water column	Aquatic plant and algae management permit (Ecology)	Most likely a poor choice for water stargrass control; Ineffective for water stargrass in one microcosm study

Method	Likely Work Window	Effectiveness for Water Stargrass	Advantages	Disadvantages	Permit Required	Notes
Fluridone (Sonar®) ***Scale:*** **Reach** ***Duration:*** **Long-term**	Late winter before Mar 15	Unlikely	● Very little environmental risk to non-target species ● Systemic herbicide; completely kills target plants ● Slow-release formulation available designed for use in flowing water ● Does not require removal of plant biomass from water	● Slow-acting herbicide; requires 30–90 days contact time ● May remain active in sediment up to one year after application ● Irrigation restricted for 7 days after application; application during irrigation period is infeasible ● Most likely not effective more than 2 weeks prior to irrigation start due to plant dormancy in cold water ● Decomposing biomass may deplete oxygen from water column	Aquatic plant and algae management permit (Ecology)	Most likely a poor choice for water stargrass control; Ineffective against water stargrass in three studies
Non-traditional Watershed Controls						
Flushing or Pulse flows ***Scale:*** **Reach** ***Duration:*** **Unknown**	Spring to early Summer	Unknown	● Natural hydrology likely suppressed WSG before modern, highly regulated flows. ● Sustained flows longer into the spring may help depress summer growth ● May be timed with harvesting operations, for flushing of biomass ● Frequent pulse flows early in growing season may disrupt plant growth ● Flushing and pulse flow events already designed to help migrant fish may also help control WSG	● Restrictions on water use and constraints on operational water supply ● Requires extensive coordination among multiple agencies and stakeholders	Uncertain	Currently researching feasibility

Method	Likely Work Window	Effectiveness for Water Stargrass	Advantages	Disadvantages	Permit Required	Notes
Turbidity increases and sedimentation ***Scale:*** **Reach** ***Duration:*** **Unknown**	Spring to early Summer	Unknown	● High turbidity likely held WSG in check under previous conditions ● Where WSG overwinters as rhizomes, it is vulnerable to sedimentation ● Springtime turbidity increases that benefit WSG mitigation also benefit migrating smolts	● Increased sedimentation is already a problem; covers spawning gravel ● Contradicts lower river TMDL for suspended sediments	Uncertain, likely multiple permits with several federal, state and local entities	Currently researching feasibility
Islands and restrictions ***Scale:*** **Sub-reach** ***Duration:*** **Long-term**	N/A	Unknown	● Pinch points could be artificially created to force bed-scouring flows ● May have additional benefits for fish passage, habitat and/or dissolved oxygen concentrations ● Incorporates natural river processes that may be self-sustaining (longevity)	● Implementation may be costly ● Will need to take into consideration the impact for flood control	Uncertain, likely multiple permits with several federal, state and local entities	Currently researching feasibility

3.2 Considerations applicable to all management methods

3.2.1 Beneficial uses of the Yakima River

Water Quality Standards for Surface Waters of the State of Washington, Chapter 173-201A WAC (Washington Administrative Code; Ecology 2011) established beneficial uses of waters and incorporated specific numeric and narrative criteria for parameters such as water temperature, DO, pH, and turbidity. The criteria define the level of protection necessary to support the beneficial uses. WAC 173-201A-600 and WAC 173-201A 602 list the use designations for specific areas. The state has not yet established regulatory criteria for river nutrients.

For the lower Yakima, the designated uses of the waters include the following:

- Primary Contact Recreation
- Water Supply Uses (Domestic Water, Industrial Water, Agricultural Water, Stock Water)
- Wildlife Habitat
- Commerce/Navigation
- Boating
- Aesthetics
- Aquatic Life

During research into possible plant management methods, impacts to beneficial uses were considered for each method and those deemed likely to cause significant harm to beneficial uses are noted as rejected from further consideration.

3.2.2 Considerations regarding other plant species

It is important to consider that while water stargrass is the focus of this project, other native and non-native invasive macrophytes (e.g., flowering rush [*Butomus umbellatus* L.] and Eurasian watermilfoil) are present in the lower Yakima River. Some of the management techniques investigated in this document may provide additional benefit to the ecosystem by removing invasive plants, while others may cause harm by removing beneficial native plants or by promoting the spread of invasive plants. When deciding among water stargrass management alternatives, it will be necessary to weigh the advantages and disadvantages of the potential effects on other vegetation.

3.2.3 Timing windows

Any conservation effort to control overabundant aquatic plant growth and improve habitat for other species imposes an ethical and legal obligation on the organizations involved to avoid adverse impacts to priority species (federal- and state-listed and other sensitive and vulnerable species; see Section 2.0). Therefore, physical water stargrass management work that could disturb spawning gravel should be confined to the times when spawning and incubating salmonids are least likely to be present. To this end, most physical projects will be required to occur during a WDFW-designated timing window of June 1–September 15, though this may be altered on an individual project basis (WDFW 2018). Additionally, many but not all chemical control methods are limited by Ecology to a narrower window of July 15–September 1, the time when salmonids of all life stages are least likely to be present in the lower Yakima (see Section 3.8.1.2; WDFW 2016).

3.2.4 Disposal of removed plant biomass

A key component of treatment and removal methods is the disposal or decomposition of the aquatic plant material. There are several considerations regarding disposal of material and will in part depend on the quantity of treated biomass. Like most aquatic plants, water stargrass is largely water by volume and weight. In the dry summer weather, stargrass desiccates quickly, thereby drastically reducing its volume. Aquatic plant material is generally more than 90 percent water and not suitable as a feed and cannot be sold or made into anything truly useful. Use as compost, mulch and ground cover have been investigated as feasible options for removed material. Due to the disposal problem with aquatic plants, some recent machine designs have included a shredder, chopper, or grinder to dispose of the plant material back into the lake (Madsen 2000**.** Plants killed by herbicides are not removed from the water, but as they decompose they may negatively affect dissolved oxygen conditions and release nutrients into the water column (see Section 3.8.1.3).

Benton CD experimented with compost disposal during pilot test removals in the early 2000s after hand-pulling large quantities of material. A local cherry orchardist allowed for the water stargrass to be composted and applied as mulch at the base of his trees. The orchardist had found that the applied harvested material had dried and reduced to such a small volume of material that it did not need to be moved, and instead was just left in place (Appel et al. 2011). Similarly, Chelan PUD as part of their annual harvesting operation, composts cut aquatic biomass on-site near harvesting operations. This allows for time and cost efficiencies. The large pile of wet plant material dries to a small pile by winter. By springtime cutting season, the disposal pile is depleted and Chelan PUD starts the process over again (personal communication with Chelan PUD, 2019).

It is unclear if cut or removed plant material would be permitted to float downstream. This would not be permissible for invasive plants, but due to water stargrass' status as a native plant, it may be allowed. This method could represent a cost and time savings if it were feasible and permissible. Letting water stargrass float downstream could have significant consequences that need to be considered, even if allowed. These include clogging of irrigation intakes, further propagation of water stargrass from stem fragments, and potential dissolved oxygen impacts from decomposing cut biomass. In considering feasibility of this option it is important to also keep the following in mind:

- Currently, more water stargrass biomass floats downstream than would be expected to be released during a removal project. Allowing the added biomass to flush out of the system might not make much of a difference, as long as landowners with intake pipes were warned in advance. Also, since colonization is already so extensive, this may not represent much of an increased risk of spread.
- Letting plants float downstream could risk spreading intermixed invasive plants (Madsen 2000). This is especially critical for mechanical methods, where automation results in indiscriminate plant removal. If plants are allowed to float downstream, this will include small amounts of invasive plants.

3.3 No action alternative

The benefits and costs of any action taken to manage water stargrass in the lower Yakima River must be weighed against those of doing nothing. Simply leaving water stargrass alone may have significant positive and negative effects. The negative effects include exacerbation of all the problems detailed in Section 1.2—significant harms to the aquatic ecosystem and beneficial uses of the river. However, as previously mentioned, dense water stargrass growth likely suppresses the spread of invasive plants, including Eurasian watermilfoil. A water stargrass removal project may have the unintended side effect of facilitating the spread of this or other noxious weeds.

3.4 Manual methods

3.4.1 Considerations applicable to all manual control methods

3.4.1.1 Permitting requirements

Under Washington State law (WAC 220-660-290), to protect fish, wildlife, and critical habitats, any physical or mechanical removal and control of aquatic plants is required to be covered by a written Hydraulic Project Approval (HPA), issued by WDFW (Chartrand et al. 2017). For some types of plant control and removal, WDFW has issued a pamphlet (WDFW 2015) that serves as the required HPA. This pamphlet covers permit requirements for many methods for controlling and removing noxious weeds. However, because water stargrass is native to Washington, it is covered under the category of aquatic beneficial plants, which have much stricter permit requirements. Therefore, for management of water stargrass, the pamphlet will cover only removal by hand (which includes hand-pulling, using hand-held tools or equipment, or using equipment that is carried when used) and bottom barriers and screens. All other physical and mechanical control methods will require individual HPAs to be issued by WDFW.

3.4.1.2 Adverse impacts to other species

Any method of physically removing aquatic plants has the potential to disturb spawning gravel, as well as other benthic life. Therefore, WDFW has defined timing windows for each waterbody (or county-specific section of a waterbody) when salmonid eggs and fry are least likely to be incubating. For the portion of the Yakima River that flows through Benton County, this window is June 1–September 15, and projects to physically remove water stargrass will generally be required to occur during this window. Depending on site-specific conditions, circumstances, work proposed, and fish life stages present, this window may be further restricted on an individual project basis (WDFW 2018).

Manual methods of plant removal or control that are covered under the 2015 pamphlet are not required to follow the WDFW timing window for hydraulic projects. However, since this work may still pose a risk to fish life during vulnerable life stages, WDFW recommends that certain work times be followed. For the Yakima River in Benton County, this period is June 1–September 15—identical to the timing window. Outside of this window, manual removal projects require an individual HPA (WDFW 2015).

Though physical plant removal projects are either recommended or required to follow the timing window, spawning gravel in the lower Yakima River is already heavily impacted. Water stargrass plants and dense root mats cover the substrate in much of the river. Dense plant growth slows water flow and causes sedimentation, increasing the proportion of fine sediments and reducing the suitability of the substrate for spawning. As a result, most fall Chinook spawning now occurs upstream of the section of river dominated by water stargrass (Appel et al. 2011). During manual removal projects, the Benton CD has observed fine sediments carried away from the bed by water flow immediately after water stargrass removal. Within one day of removal, the substrate composition was qualitatively observed to switch from sand-dominated to gravel- and cobble-dominated (R. Little, Benton CD, personal communication). By the following autumn, fall Chinook were observed to have spawned in the removal site (Appel et al. 2011). Because of the potential improvement to fish habitat resulting from water stargrass removal and the fact that salmonids largely no longer spawn where water stargrass dominates, there may be cases where the benefits of control efforts outside the timing window outweigh the environmental risks (e.g., if a control method is more effective during the early or late growing season; see Section 3.2.3). In such cases, special permission to operate outside the timing window would need to be obtained from WDFW.

3.4.1.3 Additional impacts and restrictions

Since manual methods of aquatic plant control are generally confined to small, localized areas, environmental impacts are expected to be short-term and localized to the treatment area. These methods may result in sediment disturbances, increases in turbidity with consequences for water quality, and harms to animals, including threatened or endangered species. Additionally, manual and other physical methods of aquatic plant removal can cause fragmentation of aquatic plants, which may lead to further colonization downstream (Chartrand et al. 2017). Since water stargrass can spread by this method (Horn 1983), projects that use physical control methods should have a plan in place to prevent this. Additionally, invasive species such as flowering rush and Eurasian watermilfoil are present in the lower Yakima, so it is critical to avoid inadvertently facilitating further spread of these environmentally harmful plants.

To mitigate these potential impacts, WDFW imposes several restrictions for manual methods of aquatic plant control (WDFW 2015):

- For control of aquatic beneficial plants, work is restricted to small, localized areas.
- For noxious weeds, the entire plant should be removed if possible, with all plant fragments removed from the water and disposed of so they will not re-enter the water. Water stargrass is a native plant, so this requirement will not apply. However, since it functionally acts like an invasive species in the Yakima, this provision should be strongly considered.
- Existing fish habitat components such as logs, stumps, or large boulders cannot be removed or disturbed.
- Work must be done in a manner that minimizes the release of sediment and sediment-laden water from the treatment area.
- Contaminants from the project, such as petroleum products, hydraulic fluid, or any other toxic or harmful materials must be prevented from entering or leaching into the water.

- If a fish kill or fish life in distress results from project activities, work must immediately cease and WDFW and the Washington Military Department Emergency Management Division must be notified of the problem. Work cannot resume until WDFW gives approval, and they will require additional measures to mitigate project impacts.
- Contaminated equipment, which can spread plant parts, cannot be used until cleaned. All viable plants and plant parts must be removed from the equipment and disposed of before using the equipment in the water.

3.4.2 Hand-pulling

The simplest and most common forms of aquatic plant control are those performed by hand, both with and without tools (Madsen 2000). Hand-pulling, the removal of aquatic plants without tools, is the simplest of these. Because it is so simple, with no requirements for specialized skills, training, or equipment, the only cost is that of labor. Additionally, except for work in lakes where sockeye salmon spawn, hand-pulling does not require an individual HPA and is covered under the 2015 pamphlet. Therefore, this method can be implemented quickly, without a lengthy permitting process. However, since hand-pulling is so labor-intensive, it is generally most appropriate for plant control in localized areas (Chartrand et al. 2017).

Hand-pulling is expected to cause minimal environmental impacts, and those that do occur should be short-term and localized. These impacts include sediment disturbances, the creation of turbidity that can adversely affect water quality, and adverse effects for animals. Additionally, manual removal of plants can lead to plant fragmentation (Chartrand et al. 2017). Since water stargrass can spread via stem fragments (Horn 1983), hand-pulling could potentially lead to further colonization downstream. WDFW requirements to mitigate these impacts are described in Section 3.4.1.3.

One major drawback of hand-pulling is that shallow depths are required for it to be effective. Fortunately, the recommended timing window coincides with the period of lowest flow (USGS 2021). However, during this time flows can increase dramatically over a period of a few days and may remain high for a period of weeks. Therefore, even though hand-pulling is a flexible method that does not require advance planning for permitting purposes, planned work may have to be postponed if flows suddenly increase. Hand-pulling during high flows could be performed by divers, but this would dramatically slow the work compared to a removal project performed by many people working together.

The Benton CD has extensive experience using hand-pulling to remove water stargrass from the lower Yakima River. They found that when only aboveground biomass was removed, the plants quickly regrew. However, when the root mass was removed, the area remained clear. In the autumn after removal, the gravel and cobble remained clear, and fall Chinook salmon redds and adult fish were observed within the treatment area. However, because the stems break easily, care needs to be taken to pull the plant from near the sediment. Also, hand-pulling work was found to be most effective when done in conjunction with hand cultivators (also known as hand rakes; see Section 3.8.3), which more effectively pulled water stargrass roots from the sediment (Appel et al. 2011).

3.4.3 Digging

Digging by hand with trowels, shovels, hand cultivators, and other tools is covered under the 2015 WDFW pamphlet and faces the same restrictions applicable to all manual methods (see Section 3.4.1.3). The potential environmental impacts are nearly the same as those for hand-pulling, though digging has the potential to increase the level of sediment disturbance. Also, like hand-pulling, digging is low-cost but labor-intensive, and is generally most appropriate for plant control in localized areas (Pratt et al. 2017). Hand tools can make aquatic plants easier to remove by the root (Gibbons et al. 1994), and thus increase the likelihood of long-term control.

Like hand-pulling, the primary drawback of using digging to remove water stargrass in a localized area is that this method requires low-flow conditions. Because the use of hand tools to dig in the sediment requires workers to operate with their hands at the substrate level, deeper water would result in workers submerging themselves, which could be a safety hazard. A sudden increase in flows may necessitate postponing planned work, possibly for multiple weeks. Like with hand-pulling, digging during high flows may be accomplished by divers, but would be dramatically slower, as it removes the advantage of having the work conducted by many people at the same time.

The Benton CD has found a combination of digging and hand-pulling to be the most effective manual method for water stargrass removal from the Yakima River. Since water stargrass is rooted shallowly in the sediment, longer trowels or shovels are not needed. Instead, hand cultivators (shaped like a claw with several tines; also sold as hand rakes) were found to be the most effective tool for digging. The tines are helpful for breaking up dense mats of vegetation at the substrate, allowing the user to get purchase underneath a water stargrass plant and pull it by the roots. Once a section of a water stargrass mat is pulled from the sediment, it can then be rolled up like grass sod, removing the roots of multiple plants. Hand cultivators are then useful for gripping the large rolls of water stargrass and placing them on a raft to be towed to shore (Appel et al. 2011).

A combination of hand-pulling and digging may be a very effective method of localized water stargrass control, especially in combination with methods that are used at a larger scale, since it can be used in shallow areas and side-channels where other methods may not be feasible. Experience with this method in the Yakima River has shown that it was possible to remove entire beds by the roots, causing the dominant sediment to shift from sand to a mixture of gravel and cobbles within one day (R. Little, Benton CD, personal communication). Since an individual HPA is not required, work can be done quickly when needed and planning does not need to be done as far in advance as with other methods. However, it is very labor intensive and will be limited to treatment in small, localized areas. Also, though the recommended work window occurs primarily during low-flow periods, flows do sometimes become high enough during this time that work may not be possible due to safety concerns.

3.4.4 Hand-cutting

Hand-cutting is the use of handheld tools to remove only aboveground plant biomass from the waterbody. This method is covered under the 2015 WDFW pamphlet and faces the same restrictions applicable to all manual methods (see Section 3.4.1.3). Potential environmental impacts are similar to hand-pulling, though sediment disturbance should be lower with cutting. Hand-cutting may be faster than pulling the plants by the root, but since the roots and rhizomes remain, the primary drawback is that plants can regrow. Additionally, cut plant material must be removed from the water to avoid further spread (Gibbons et al. 1994).

Hand-cutting is a poor choice for control of water stargrass. During their management efforts, the Benton CD found hand-cutting to be ineffective at removing the plant. Because the stems are brittle, they often broke in workers' hands before they could be cut, so simply pulling on the stems was faster. Additionally, when belowground biomass was left in the sediment, water stargrass quickly regrew after removal work (Appel et al. 2011). Finally, removal of only aboveground plant biomass will most likely not be effective at improving dissolved oxygen conditions in the Yakima, since the leaves will no longer contribute to primary production but the belowground biomass will still contribute to ecosystem respiration (Sand-Jensen and Borum 1991). In line with this, some evidence from experimental plant removal suggests that cutting methods are less effective at improving low dissolved oxygen conditions than methods that remove the entire plant (Simonsen and Harremoës 1978, Kaenel et al. 2000). Therefore, hand-cutting will not be considered further for this project.

3.4.5 Raking

Raking is another manual method of removing entire plants from the waterbody. This method is covered under the 2015 WDFW pamphlet and faces the same restrictions applicable to all manual methods (see Section 3.4.1.3). Potential environmental impacts are also similar to hand-pulling, though sediment disturbance and plant fragmentation may be a greater risk.

Raking is likely not a viable method for removing water stargrass in the lower Yakima river due to difficulty working with wide rakes in the hard-packed cobble substrate and large, dense root beds. Instead, digging with small hand cultivators will likely be much more effective at digging between cobbles (see Section 3.4.3). Additionally, to avoid further spread, this method would require additional efforts to capture removed plants before they are carried downstream.

3.5 Mechanical methods

3.5.1 Considerations applicable to all mechanical methods

Mechanical methods of aquatic plant removal have similar permitting requirements, environmental impacts, and mitigation requirements as do manual methods, and so are detailed in Section 3.4.1. Differences from these requirements and impacts are detailed in individual sections. However, while manual methods are covered by the 2015 pamphlet, all mechanical methods of removing aquatic beneficial plants require individual HPAs. Additionally, though the potential environmental impacts of manual and mechanical methods are similar, mechanical methods are non-selective due to being automated and operate at much greater scale. Therefore, compared to manual methods they are more likely to cause inadvertent impacts like the spread of invasive species, removal of desirable plants, and killing or otherwise disturbing aquatic animals, and these impacts have the potential to occur across a broader scale (Chartrand et al. 2017).

It may be tempting to assume that manual and mechanical methods of aquatic plant management are automatically superior to herbicide use, since they do not involve putting potentially environmentally hazardous chemicals into a waterbody. However, serious adverse environmental impacts can result from non-chemical control methods, especially mechanical methods, and these need to be thought about seriously to mitigate potential harms (Madsen 2000)**.**

Finally, accessibility is an important consideration for mechanical methods. Machines like harvesters and rotovators are large, heavy, and need to be transported on trucks or trailers to a location near the treatment site. Boat launches will typically be required for these machines to enter the water, so areas of the Yakima River that are inaccessible from boat launches (e.g., with large boulders in the way that make navigation by mid-sized boat impossible) will not be feasible to treat with these methods.

3.5.2 Harvesting

Mechanical harvesting typically combines cutting plants above the sediment with a method of plant removal from the water, often in one machine. These single-stage harvesters are typically boats with a cutting blade that extends a maximum of 5–8 feet below the water's surface, and a conveyor belt that loads the cut plant fragments onto the boat (Gibbons et al. 1994, Madsen 2000). Another, more recently-developed type of harvester replaces the cutting blade with a rotating drum that is designed to pull plants from the sediment, ideally removing the roots as well (Lake Weeders Digest LLC N.D.). Any harvesting project designed to remove aquatic beneficial plants will require an individual HPA from WDFW, as well as possible Shoreline Master Program permits from local agencies (Chartrand et al. 2017). Any organization planning harvesting activities will need to investigate and obtain any additional permits required, such as, but not limited to, a solid waste disposal permit.

Harvesters are useful for clearing aquatic plants from large areas, but they may create a number of environmental impacts to the water body. Their most significant environmental consequence is by-catch. As cutting-type harvesters slice through stands of aquatic plants, they can also chop up fish and other organisms that live among the plants (Madsen 2000). It is uncertain if pulling-type harvesters would have the same by-catch issues, but it seems possible that aquatic animals could be killed or removed from the water by the rotating drum. Fish by-catch may be reduced by assessing species' habitat use and behavior in the proposed treatment area, then restricting harvesting to the times fish are least likely to be present (Chartrand et al. 2017). Additionally, since harvesters remove plants indiscriminately, the potential exists for desirable plants to be included as part of the by-catch. Therefore, operators should be careful to avoid areas where these plants may grow. However, as long as the conveyor belt is effective at removing plant biomass from the water, harvesters have an advantage over other cutting or pulling methods that require additional efforts to prevent plant fragments from floating downstream.

To mitigate potential environmental impacts, WDFW will require organizations using harvesters to abide by several restrictions (WDFW 2015):

- Harvesting projects will be required to adhere to the WDFW timing window of June 1–September 15.

- For noxious weeds, all plant fragments must be removed from the water and disposed of so they will not re-enter the water. Water stargrass is a native plant, so this requirement will not apply. However, some noxious weeds (e.g., Eurasian watermilfoil) grow intermixed in water stargrass patches, and extra care should be taken to avoid letting these fragments enter the water.
- Contaminants from the project, such as petroleum products, hydraulic fluid, or any other toxic or harmful materials must be prevented from entering or leaching into the water. Equipment must be well-maintained and food-grade oil must be used in the hydraulic system.
- If a fish kill or fish life in distress results from project activities, work must immediately cease and WDFW and the Washington Military Department Emergency Management Division must be notified of the problem. Work cannot resume until WDFW gives approval, and they will require additional measures to mitigate project impacts.
- Existing fish habitat components such as logs, stumps, or large boulders may be relocated to allow operation of the machine. However, they cannot be removed from the waterbody.
- Harvesters must be operated only in water deep enough to prevent the blades from contacting the sediments.
- Harvesters must be operated in a way that causes the least adverse impact to fish life.
- Any fish that become entrained in the removed vegetation must be immediately and safely returned to the water.
- Contaminated equipment, which can spread plant parts, cannot be used until cleaned. All viable plants and plant parts must be removed from the equipment and disposed of before using the equipment in the water.
- Alteration or disturbance of the bank and bank vegetation must be limited to that required to conduct the project. All disturbed areas must be protected from erosion using vegetation or other means. Disturbed banks must be replanted within one year with native or other approved woody species.

The two types of harvesters dramatically differ in their purported effectiveness at removing dense aquatic plant growth. Cutting-type harvesters are likely to be ineffective for long term water stargrass control, as they allow for plants to regrow from undisturbed root systems, though repeated harvests of plants in the same area may improve the level of control (Madsen 2000). However, since pulling-type harvesters are designed to remove the entire plant, including the root system, they are more likely to provide long-term control. The Benton CD has recently purchased a pulling-type harvester and will conduct a pilot study in July and August, 2021 to determine its effectiveness at removing water stargrass in the Yakima River. With this pilot study, they hope to answer several questions:

- Will the pulling-type harvester be effective at removing entire water stargrass plants from the hard-packed cobbles? Water stargrass stems tend to break easily during hand-pulling, at least when only a few stems at a time are pulled. If the harvester's rotary drum is able to pull many stems at the same time close to the roots, breakage may be prevented.
- Will the harvester be able to operate in the water depths experienced in the Yakima? Cutting-type harvesters typically require water depths of five feet or more (Madsen 2021), but the manufacturer of the harvester the Benton CD has purchased claims the

machine can operate in depths as little as one foot (Lake Weeders Digest LLC N.D.). Also, even if flows are deep enough in the thalweg (i.e., the area of deepest and fastest flow) for effective harvesting, it is uncertain how closely the machine will be able to operate to shore before the water becomes too shallow. To operate, cutting-type harvesters typically require open areas with few surface obstructions (Gibbons et al. 1994)**.** It seems unlikely that a pulling-type harvester will be able to operate in an area with many boulders, but it may be more effective at handling obstructions.

- How difficult and expensive will plant disposal become? If the harvester is effective at removing large swaths of water stargrass, the removed biomass will need to be moved from the boat to the shore, then transported to a disposal site (see Section 3.2.4 for a discussion of general disposal considerations). The efficiency of this process may limit how quickly plants can be removed from the river, and thus the size of the area that can be treated.

Evidence from other removal projects suggests that harvesting may be an effective method for controlling large areas of nuisance aquatic plants. The Chelan Public Utility District (Chelan PUD) has utilized large-scale harvesting of milfoil on the Columbia River behind their reservoirs that are part of the Rocky Reach Hydroelectric Project. They have implemented harvesting as a treatment control method since 2010, and harvest during the peak growing season of May – September. They use an Aquarius harvest system with a cutter head. Additional evidence of the utility of harvesting was demonstrated in 2015, when the Columbia Irrigation District (CID) hired a harvester to clear biomass at the operational head-gates behind the Wanawish Dam on the lower Yakima River. Drought conditions led to an overabundance of water stargrass in a low flow water year. The water stargrass dammed the river and prevented flow into the head-gate of the CID canal system. The mechanical harvesting improved river flows immediately upon clearing of the vegetation with subsequent filling of the irrigation canal.

In conclusion, harvesting may be an effective method of water stargrass control across large sections of the lower Yakima River. The experience of organizations working in other aquatic systems has indicated some success with pulling-type harvesters. When appropriate mitigation measures are followed, environmental impacts are expected to be minimal, though some by-catch of fish and other aquatic animals will likely occur. Harvesters are expensive, though they may be less expensive than other mechanical methods of plant control, especially rotovation (Gibbons et al. 1994). Work will likely be limited to the WDFW timing window of June 1–September 15, which is also the time during which low flows occur in the Yakima, so periods of lowest flow may limit the area that can be treated. The upcoming pilot study planned by the Benton CD should provide an indication of how useful and effective a pulling-type harvester will be for this project.

3.5.3 Rotovation

Rotovators are large rototillers that work by tilling the sediments of a waterbody, cutting and dislodging plant roots. Because rotovation causes plant fragments to float in the water column, its use requires a concurrent method to collect removed plants from the water and prevent them from colonizing downstream (Madsen 2021). Any rotovation project will require an individual HPA from WDFW, as well as possible shoreline permits from cities and counties.

Rotovators work relatively quickly to control submersed plants by destroying and/or dislodging their root systems, but for the same reasons they can have significant environmental impacts, including large increases in turbidity (though usually only temporarily), movement of nutrients from the sediments to the water column, fragmentation and spread of invasive plants, and disruption of the benthic community (Gibbons et al. 1994, Madsen 2000).

There are no universal requirements that apply to all rotovation projects (WDFW 2015). However, to mitigate potential impacts, WDFW may impose significant restrictions for any approved rotovation project. Restrictions and recommendations include (Chartrand et al. 2017):

- Rotovation projects will be required to adhere to the WDFW timing window of June 1–September 15.
- An evaluation of the proposed treatment site should be performed to determine whether the site provides important habitat for fish and other animals. The plan should be revised to avoid or limit areas of critical use, or schedule rotovation to avoid times of critical use. Based on the evaluation, WDFW may require a narrower timing window than the maximum allowable (see Section 3.4.1.2).
- The individual HPA will detail how existing fish habitat components such as logs, stumps, or large boulders may be handled. In many cases, removal of woody debris will not be allowed.
- Efforts should be made to minimize erosion, turbidity, and other water quality impacts.
- Contaminants from the project, such as petroleum products, hydraulic fluid, or any other toxic or harmful materials must be prevented from entering or leaching into the water. Because equipment failure or poor maintenance may lead to contaminant leakage, permitting agencies may require a detailed inspection plan. Also, oil-spill materials may be required to be carried on the rotovator and a spill contingency plan may be required.
- Plant fragments may be required to be removed from the water and disposed of so they will not re-enter the water.
- To prevent damage, areas around water intake pipes should be avoided, or pipe owners should be given adequate notice of the treatment and asked to pull their pipes from the water during treatment.
- Areas containing desirable species (e.g., native plants other than water stargrass) should be avoided if possible.
- Contaminated equipment, which can spread plant parts, cannot be used until cleaned. All viable plants and plant parts must be removed from the equipment and disposed of before using the equipment in the water.

Rotovators have proven to be very effective at providing long-term control of submersed plants (Gibbons et al. 1994), but they are likely a poor choice for water stargrass control, due to the characteristics of the Yakima River. Since they work by dislodging plant roots, these machines tend to work well in soft substrate and even in loose cobble sediments (Madsen 2021). However, the lower Yakima River substrate is primarily composed of hard-packed cobbles, so it is unlikely that a rotovator would be effective, and the rotovator arms may even be damaged. Also, rotovators are only effective in areas with few bottom obstructions, so large sections of the lower Yakima that are dominated by large boulders will be inaccessible for treatment. In the event that rotovation is effective at tilling up the substrate, Yakima River sediments likely have a high nutrient load (see Section 1.5), so nutrients may be released into the water column and contribute to eutrophication. Finally, rotovators are extremely expensive (Chartrand et al. 2017), so a pilot study to determine their effectiveness in the Yakima River would be prohibitively costly, especially given the possibility of damaging the machine.

3.5.4 Diver-operated dredging and diver-assisted suction harvesting

Diver-operated dredging, also referred to as suction dredging, is a technique of aquatic plant removal using portable dredges with suction heads. These are operated by SCUBA divers, who use tools to dislodge plants, then suction up the entire plant and sediment slurry, which travels through hoses to a small barge or boat. Onboard, the plant parts can be sieved out for later disposal, while the sediment slurry may be discharged back to the water or piped for disposal on land (Gibbons et al. 1994).

An updated method, diver-assisted suction harvesting, is similar to but meant to replace diver-operated dredging. This method is designed to reduce the water column turbidity created by suction dredging, as divers manually insert harvested plants into a suction tube or hose (Chartrand et al. 2017). With suction harvesting, unlike dredging, sediments are not removed through the suction tubes. Sediments will be resuspended in the water column by this method, but a sediment curtain can be used to mitigate this (Madsen 2000).

Any project using diver-operated dredging or diver-assisted suction harvesting (hereafter collectively referred to as “suction methods”) will require an individual HPA from WDFW, as well as possible shoreline permits from local agencies (Chartrand et al. 2017). Additionally, diver-operated dredging may require additional permission from Ecology for water quality standards and the U.S. Army Corps of Engineers for dredging (Gibbons et al. 1994).

Suction methods have a significant advantage over other mechanical plant removal methods, as they allow divers to be selective about which plants are harvested. However, if significant turbidity is created in areas where unique, rare or listed plants are present, work should be stopped to avoid harvesting desirable plants. Also, due to the potential impacts of resuspending sediments, diver-operated dredging should not be conducted in areas known or suspected to contain contaminated sediments. Release of stored nutrients from sediments is also a risk (Chartrand et al. 2017).

To mitigate potential environmental impacts, WDFW will require organizations using suction methods to abide by several restrictions (WDFW 2015):

- Projects will most likely be required to adhere to the WDFW timing window of June 1–September 15.
- Contaminants from the project, such as petroleum products, hydraulic fluid, or any other toxic or harmful materials must be prevented from entering or leaching into the water. Equipment must be well-maintained and food-grade oil must be used in the hydraulic system.
- If a fish kill or fish life in distress results from project activities, work must immediately cease and WDFW and the Washington Military Department Emergency Management

Division must be notified of the problem. Work cannot resume until WDFW gives approval, and they will require additional measures to mitigate project impacts.

- Existing fish habitat components such as logs, stumps, or large boulders may be relocated to allow operation of the equipment. However, they cannot be removed from the waterbody.
- Projects must always use equipment types and methods that cause the least adverse impact to fish life.
- Contaminated equipment, which can spread plant parts, cannot be used until cleaned. All viable plants and plant parts must be removed from the equipment and disposed of before using the equipment in the water.
- To avoid stranding fish, the bed must not contain pits, potholes, or large depressions when work is finished.
- Alteration or disturbance of the bank and bank vegetation must be limited to that required to conduct the project. All disturbed areas must be protected from erosion using vegetation or other means. Disturbed banks must be replanted within one year with native or other approved woody species.
- For noxious weeds, all plant fragments must be removed from the water and disposed of so they will not re-enter the water. Plants and plant parts must also be removed from the dredge slurry before returning it to the waterbody. Water stargrass is a native plant, so this requirement will not apply. However, since it functionally acts like an invasive species in the Yakima, this provision should be strongly considered. Also, some noxious weeds (e.g., Eurasian watermilfoil) grow intermixed in water stargrass patches, and extra care should be taken to avoid letting these fragments enter the water.
- Hydraulic dredges must be operated with the intake at or below the surface of the material that is being removed. The intake may be raised up to three feet above the bed only for brief periods of purging or flushing the intake system.

Suction methods, especially diver-assisted suction harvesting, may be effective methods of localized water stargrass control. They are slower than other mechanical methods such as harvesting, but they allow the operator to be selective and to work in places with obstacles that would preclude the use of large machinery. Therefore, they may be a good choice when used in combination with methods that operate at a larger scale. These methods can cover areas larger than is practical by hand removal, though they are still labor-intensive, slow, and ideal for areas where plant density is low. Since roots and rhizomes are removed, long-term control is likely. They are especially useful for removal projects where plant fragmentation should be minimized and have been used for successful control of Eurasian watermilfoil. Suction methods are also expensive, due to the cost of equipment and the need for certified divers (Chartrand et al. 2017). Due to the environmental risks of dumping sediment slurry back into the river, diver-operated dredging would likely be a poor choice for water stargrass control. However, diver-assisted suction harvesting may deserve consideration, especially in places or at times where manual methods are desired but water depth prohibits their use.

3.5.5 Sediment agitation (weed rollers)

Weed rollers are used in waterbodies to control all types of aquatic plants. In Washington, the use of weed rollers will require an individual HPA from WDFW.

To mitigate potential environmental impacts, WDFW will require organizations using weed rollers to abide by several restrictions (WDFW 2015):

- For noxious weeds, all plants and plant fragments must be removed from the water and disposed of so they will not re-enter the water. Water stargrass is a native plant, so this requirement will not apply. However, since it functionally acts like an invasive species in the Yakima, this provision should be strongly considered. Also, some noxious weeds (e.g., Eurasian watermilfoil) grow intermixed in water stargrass patches, and extra care should be taken to avoid letting these fragments float downstream.
- Work must be performed in a manner that minimizes the release of sediment and sediment-laden water from the job site.
- Contaminants from the project, such as petroleum products, hydraulic fluid, or any other toxic or harmful materials must be prevented from entering or leaching into the water.
- If a fish kill or fish life in distress results from project activities, work must immediately cease and WDFW and the Washington Military Department Emergency Management Division must be notified of the problem. Work cannot resume until WDFW gives approval, and they will require additional measures to mitigate project impacts.
- Existing fish habitat components such as logs, stumps, or large boulders may be relocated to allow operation of the equipment. However, they cannot be removed from the waterbody.
- Contaminated equipment, which can spread plant parts, cannot be used until cleaned. All viable plants and plant parts must be removed from the equipment and disposed of before using the equipment in the water.

Small weed rollers have proven ineffective at removing water stargrass in the Yakima River based on trials by Benton CD. Initial findings regarding large weed rollers suggest these are limited to permanent installations in lakes. They do not appear to be practical in moving water or for large infestations, both of which apply to water stargrass in the lower Yakima River.

3.5.6 Mailbox blowers

Mailbox or “muck” blowers are attached to motorboats and provide a strong jet of water directly to the sediment bed. This method is similar to providing a localized scouring flow to help dislodge the plant. Primarily, mailbox blowers are utilized for clearing of sediment and muck. While there is not much literature available regarding the use of mailbox blowers to control water stargrass, there has been frequent suggestion that they could be used in a pilot treatment of biomass control in the lower Yakima River. Mailbox blowers can be easily built and installed on a motorboat for treatment trials. Treatment timing will need to coincide with the instream work window. However, it likely that this treatment would be successful earlier in the growing season before the establishment of large rooted plants. It may also have a secondary benefit of clearing gravels for redds.

3.5.7 UV-C light treatment

UV-C light treatment is a technique that has been successful at controlling aquatic plant growth within irrigation canals. More recently, its use has been successfully expanded to control plants in Lake Tahoe, where chemical treatment methods are not allowed. Ultraviolet C (UV-C) light is short wave electromagnetic radiation that damages the DNA and cellular structure of aquatic plants and their fragments. A motorboat-mounted light that emitted high concentrations of UV-C was shown in Lake Tahoe to kill and control invasive species, with plants deteriorating within 7–10 days following treatment (Tahoe Resource Conservation District 2018). As with other mechanical treatment methods, the treatments will likely need to be repeated multiple times during the growing season to be effective. It is unclear how well this treatment method would work on water stargrass in flowing waters, as there is limited research, but given the relative ease of the method and relatively low cost, the treatment method could be easily implemented in a pilot trial study on the Yakima River. Controlled test studies in the laboratory using UV-C light and water stargrass are recommended before trials are conducted in the field. As UV-C is considered a germicide and can cause cellular damage, care must be taken to protect other species in the river and its use should be restricted to times with native smolts are not present. Additionally, appropriate shielding of the UV-C light must be used for the safety of the operators.

3.6 Environmental manipulation methods

3.6.1 Bottom barriers

Bottom barriers are synthetic or natural fiber sheets of material used to cover and kill plants growing on the bottom of a water body (Gibbons et al. 1994). Opaque barriers that block light tend to work best, but even clear plastic barriers have been used effectively (Madsen 2000). They may be placed by hand, and in deep water installation can be performed by divers (Gibbons et al. 1994).

Barriers may be most useful when used in a way that takes advantage of the life cycle of water stargrass (see discussion of phenology in Section 1.4). However, since water stargrass in the lower Yakima mostly overwinters as whole plants, barrier placement would most likely not be able to wait for a period when aboveground biomass is low enough to simply cover. Instead, plants could be cut in the spring while biomass is at its lowest, then barriers could be installed to prevent plant regrowth.

This method would be feasible for only relatively small area control. They may be beneficial in areas of small private irrigation intakes, where only a limited amount of biomass needs to be cleared for functional operation of the fish screen and intake. Bottom barriers are relatively low cost when used for control in small areas. However, they tend to be too expensive to use over a large area, where their impact to the benthic community would be greater (Madsen 2000).

For the lower Yakima River there are a few key items of note:

- Barriers do not require an individual HPA. They are covered under the 2015 pamphlet. However, they are subject to the timing window of June 1–September 15. Special permission to operate outside the timing window would need to be obtained from WDFW and would require an individual HPA (WDFW 2015).
- Barriers are most effective in the spring, before plants begin to grow, in the fall after senescence, or after plants have been cut (Chartrand et al. 2017). These tend to kill plants

under them within a couple of months, after which time they may be relocated to another area (Gibbons et al. 1994, Madsen 2000).

- Barriers may be left in place for control over several years. However, as they are covered by sediment, new plants will be able to colonize on top of them (Madsen 2000).
- Their largest potential environmental impact is to spawning gravel used by fish (Chartrand et al. 2017). However, spawning gravel in the lower Yakima River is already heavily impacted, and most fall Chinook spawning now occurs upstream of the section of river dominated by water stargrass. Most of the spawning gravel in the lower Yakima appears to be currently unusable by salmonids, as the substrate is covered by dense plant growth, which also slows water flow and causes increased sedimentation (Appel et al. 2011). Because of the potential improvement to fish habitat, bottom barriers may represent a case where the benefits of control efforts outside the timing window outweigh the environmental risks. Special permission to operate outside the timing window would need to be obtained from WDFW.

3.6.2 Water level drawdown

Water level drawdowns manipulate the target plant's environment by lowering the water level to a given depth for enough time—generally at least one month—to allow drying (Madsen 2000). Drawdowns require an individual HPA from WDFW, but due to the environmental and agricultural impacts that would result, they may be difficult to obtain for the Yakima River. As water stargrass colonizes the entire width of the river channel in many places, a drawdown is unlikely to completely expose the majority of the plant population that resides in the deeper portions of the river. Even for those plants that become exposed, this method is likely to be ineffective, as experimental evidence suggests water stargrass leaves die when de-watered, but the plant can shift to an emergent growth form and produce new leaves (Horn 1983). Moreover, drawdowns may potentially exasperate the problem, as lower water levels in the Yakima River seem to result in higher water stargrass biomass during low flow years (M. Appel, Benton CD, personal communication).

It may be possible to use drawdown methods in conjunction with other treatment options, such as summertime herbicide applications to effectively target emergent and floating plants. One of the primary challenges with drawdown includes timing so as to not impact sensitive species. Drawdown timing would need to coincide with summer river temperatures that are inhospitable to native fish species (> 23°C), which occurs during baseflow conditions. Considerations would also have to be made and investigated on the impact to irrigation so as to not impact water allotments or harm agricultural production. More studies and research would need to be conducted specific to the Yakima River to determine if coupling of water drawdown at baseflow conditions with targeted herbicide treatments would be an effective strategy for water stargrass control while not greatly impacting irrigation or harming sensitive ecological species.

3.6.3 Water column dye

Non-toxic dyes are included in the Ecology APAM permit as shading products. These are applied to waterbodies to reduce the amount of light penetrating the water column, thereby reducing plant and algae growth. However, these dyes cannot be applied to rivers or other flowing water in Washington (Ecology 2021b). Therefore, water column dies will not be considered further for this project.

3.6.4 Bubble Curtain

The U.S. Army Engineer Research and Development Center (ERDC) is investigating an innovative method for the control of flowering rush in Lake Wallula on the Columbia River. This technique involves the use of a bubble curtain to create a physical barrier between a treatment area and the flowing river (D. Walters, ACOE, personal communication). The technology works by releasing a "curtain" of air bubbles from submerged pressurized tubing. The bubble curtain creates an underwater zone of relative isolation that can then undergo chemical treatment application. The bubble curtain is designed to decrease water exchange between the treatment and non-treatment area allowing for longer chemical contact times than typically provided in a flowing river system. The air bubble barrier may also keep the chemical application within the treatment area, thereby potentially limiting impacts to downstream water users. Bubble curtain technology has been used successfully to mitigate noise and harmful impacts on aquatic life during pile-driving operations, reduce spread of floating surface debris, and for control of fish movements. Coupling this newer technique with chemical application is an innovative use of readily available technology for aquatic vegetation treatment. Deployment of a bubble curtain and herbicide application is showing promising results on the nearby Columbia River system (D. Walters, ACOE, personal communication). The combination of bubble curtain with chemical treatment may provide a treatment option for smaller areas of the Yakima River, such as side-channels, where larger equipment access may be challenging. Studies using inert dyes to test the bubble curtain local isolation area are recommended prior to any chemical treatment application. These precursor studies are important for understanding the bulk water exchange processes and hydrology of the treatment area and potentially critical to permitting or regulatory challenges. The primary costs involved with this method are personnel and chemical costs, along with upfront investments in the bubble curtain technology and air compressor rental or purchase.

3.6.5 Shading

Water stargrass, like most macrophytes, has a high light requirement, and shading significantly reduces its growth while increased irradiance increases biomass and abundance (Blackburn et al. 1961, Zhu et al. 2008). On the lower Yakima River, places with significant shading (e.g., bridges or narrow and densely vegetated side-channels) do inhibit water stargrass growth. Adding riparian vegetation to the lower river may have an added benefit by taking up nutrients entering the channel from runoff (O'Brien et al. 2014), stabilizing the riparian banks, as well as mitigating local in-stream river temperatures by decreasing solar inputs (Gendaszek and Appel 2021). While trees or hedges planted on riparian margins can increase shading of a waterbody and decrease the growth of aquatic plants, there are several factors that make shading an impractical method for plant control within many areas of the lower Yakima River. Some of these considerations include:

- It can take a long time for riparian shade trees to grow large enough to provide adequate shading.
- The river is too wide to adequately shade the entire width of the river corridor.

- The lower Yakima River flows through a semi-arid region, so plants require lots of water and management to establish and grow.

While there are challenges, shading may be a worthwhile strategy to investigate for water stargrass control in small, narrow side-channels, or for control within in smaller tributaries as shading may be useful in some narrow streams (Madsen 2000).

3.7 Biological methods

3.7.1 Grass carp

Sterile, triploid grass carp (*Ctenopharyngodon idella*)—generalist herbivores—are used in some Washington waterbodies as biological agents to control aquatic plant growth. However, in the summer the lower Yakima River is used by carp that browse on water stargrass without an apparent population-level impact (M. Appel, Benton CD, personal communication), so additional carp are unlikely to be effective. The use of grass carp is regulated by WDFW, and they are prohibited in open river systems (N. Lubliner, Ecology, personal communication). Therefore, grass carp will not be considered further for this project.

3.7.2 Plant-specific biological control agents

Several biological agents that target specific plant species have been investigated for plant-control use in Washington waters. These include herbivorous insects, plant pathogens (e.g., fungi), and plant growth regulators. The use of these agents is regulated by the federal government, but many of them are still in experimental stages and are not yet realistic considerations for aquatic plant control (Chartrand et al. 2017). Additionally, these agents often have limited effectiveness when used by themselves, and tend to work better when used in conjunction with other control methods (Madsen 2021).

Harms et al. (2011) evaluated 23 herbivorous insect taxa for their feeding habits and ability to damage water stargrass. Three groups of insects showed the most potential to exert control pressure on water stargrass. However, two of these groups, and the majority of the insect taxa evaluated, were generalists, and so might pose a risk to other plant species should they be introduced as control agents.

To date, no plant-specific biological control agent has been identified for water stargrass, and we do not know of any present research. Therefore, they will not be considered for this project, though they remain a possibility in the future if water stargrass remains a problem. If biological control agents effective for water stargrass control are later identified, investigations into permitting requirements can begin by enquiring with the Washington State Department of Agriculture and the U.S. Department of Agriculture.

3.8 Chemical methods

3.8.1 Considerations applicable to all chemical control methods

3.8.1.1 Permitting requirements

Under state and federal law, any herbicide or nutrient-inactivation product applied in the lower Yakima River will require coverage under a National Pollution Discharge Elimination System (NPDES) permit. In Washington, this is Ecology's APAM permit, which regulates when, where, how, and the amount and type of products that can be applied for aquatic plant control. It also provides details on monitoring, reporting, and public notification requirements for these products. Additionally, because water stargrass is native to Washington, it is covered in the permit under the category of native nuisance plants, which are treated differently than noxious weeds where eradication is the goal. Thus, herbicide application will be limited to a maximum percentage of the littoral zone (i.e., the area shallow enough for vegetation to grow) depending on the waterbody size (Ecology 2021a). In rivers, this percentage will most likely be determined based upon the size of the reach (N. Lubliner, Ecology, personal communication).

3.8.1.2 Adverse impacts to other species

To avoid adverse impacts to priority species (discussed in section 3.2), the application of many aquatic herbicides in Washington waters is allowable only during the period when these species are least likely to be present in the waterbody. For each waterbody (or county-specific section of a waterbody) where priority species are known to occur, WDFW has defined timing windows for aquatic pesticide application and Ecology requires that these be adhered to for any pesticide that poses a risk to these species (Ecology 2021a). In the Yakima River within Benton County, this window is between July 15–September 1 for salmonids (WDFW 2016). Recently, a few aquatic herbicides were tested in studies funded by Ecology and were found not to have lethal or sub-lethal effects on priority species. Therefore, Ecology changed the requirement for timing windows to be adhered to for these herbicides (Ecology 2021a). Additionally, some herbicides and other chemicals not subject to the salmonid timing window may pose a risk to other listed priority species in Washington. However, none of these species are present in Benton County, so no additional timing window will apply in the lower Yakima River. Chemicals not subject to timing windows for salmonids include aminopyralid, bispyribac-sodium, florpyrauxifen-benzyl, fluridone, glyphosate, imazapyr, imazamox, penoxsulam, topramezone, triclopyr TEA, and phosphorus sequestration products (Ecology 2021b).

In addition to adverse impacts to priority species, the APAM permit considers whether there may be an adverse impact from chemical treatments to sensitive, threatened, or endangered plant species (i.e., rare plants). Before issuing coverage under the permit, Ecology's permit manager consults the Washington Department of Natural Resources Natural Heritage Program database to determine the potential presence of any aquatic rare plants. If this is determined, or if the applicant/permittee/sponsor is aware of any rare plants present in the treatment area, the permittee must hire a botanist to conduct a detailed plant survey. If any rare aquatic plants are found in the proposed treatment area, mitigation measures to protect the rare plant population will be required to be implemented (Ecology 2021a). The Natural Heritage Program does not currently indicate the likely presence of any rare aquatic plants in the lower Yakima River (DNR 2021).

3.8.1.3 Additional impacts and restrictions

Many chemical control methods face additional restrictions, however. Since aquatic herbicides may also kill or damage land plants, when applied to water used to irrigate crops and other plants, many herbicide labels impose restrictions on when irrigation can occur or on where treatments can be applied. Since irrigation is a listed beneficial use of the Yakima River (see Section 3.2.1), water stargrass management methods need to be chosen carefully so as not to impair this. Many herbicides require irrigation to be turned off during application and for a certain number of days thereafter. A restriction like this will not be feasible beyond a very brief time for the Yakima River, because crops will die. An irrigation restriction of only one day might be possible, but even then, this would be difficult to implement and would require a much more in-depth discussion with stakeholders.

Irrigation intake in the lower Yakima begins March 15 each year, so it may be possible to apply an herbicide treatment well enough in advance of this date to allow any residue to be taken up by plants, decomposed, or flushed from the system. Water stargrass remains dormant until water temperatures reach 8 °C, when spring growth is triggered (Horn 1983). Yakima River temperatures do not reach this high until early–mid March (USGS 2021), so any treatments that require plants to be actively growing (and thus have the potential of taking up and translocating herbicides) will have a very brief window where application might be possible. Specific details of irrigation restrictions are discussed further within individual herbicide sections.

One consideration especially pertinent to the treatment of aquatic vegetation with herbicides is that the potential exists to cause further impairment to a waterbody. Unlike many other plant control methods, when plants are killed by herbicides the dead biomass remains in the waterbody (see Section 3.2.4 for further discussion of methods for handling dead plant biomass). After plants die and begin to decompose, dissolved oxygen can be depleted from the water column by the microbial decomposers. Also, phosphorus may be released from decomposing plants. Since phosphorus is often a limiting nutrient in freshwater ecosystems, this may lead to increased phytoplankton (i.e., algal) blooms in the water body, especially in warm and sunny summer months. When algae later die and decay, their decomposition may further deplete oxygen from the waterbody (Hamel 2012, Ecology 2021a).

If a waterbody is listed for impairment of dissolved oxygen or phosphorus under Section 303(d) of the federal Clean Water Act, the Ecology APAM permit prohibits further impairment (Ecology 2021a). The lower Yakima River is listed for dissolved oxygen, so certain requirements will apply to any application of herbicide to control water stargrass. Ecology requires any permittee treating waters impaired for oxygen to monitor dissolved oxygen and report the results to Ecology within 30 days of the post-treatment monitoring date. Also, permittees will be required to implement one or more mitigation measures. These measures include (Ecology 2021a):

- Limiting the area treated: Contact herbicides quickly kill aquatic vegetation, causing large amounts of plant matter to decompose rapidly. These herbicides have the greatest potential to lower dissolved oxygen concentrations within a waterbody, so their labels restrict the amount of area treated at any one time and specify retreatment intervals. By treating different areas at different times, herbicide applicators can reduce the amount of affected biomass and thus limit the amount of nutrients released and the oxygen required by microbial decomposers.

- Chemical choice: The risk of oxygen depletion and algae blooms can be further lessened by choosing systemic herbicides, which are slower acting. Because plants gradually die back over weeks rather than days, prolonging the decomposition process, dissolved oxygen levels typically remain acceptably high and nutrients are released at lower concentrations after treatment with systemic herbicides.
- Treatment timing: Treating early or late in the season can reduce additional dissolved oxygen and nutrient impairment from decomposition. Oxygen is more soluble in colder water, so waterbodies in the spring and fall may have higher concentrations, lowering the chances of dissolved oxygen depletion. In the spring, plants have less biomass than in the summer, so the amount of decomposition is limited. Fall treatments may limit additional nutrient release, since many plants are already releasing nutrients into the water column through senescence. Also, fall treatments may be even more effective because plants can translocate the chemicals to their root systems. If chemical control of water stargrass is used, the ability to use this mitigation measure will be dependent on the herbicide chosen, since many are restricted to summer use during the WDFW timing window.
- Maintaining aquatic plants: Retaining healthy aquatic plant populations can help ameliorate algae blooms by removing nutrients from the water column that may otherwise be used by algae. Refer to the discussion in Section 2.0 of the need to retain some part of the water stargrass population in the lower Yakima River.
- Removal of biomass: Mechanical or manual methods can be used to remove decaying biomass from the water after treatment. By preventing further decomposition in the water, this may reduce the total nutrient release and prevent low oxygen conditions from developing.

3.8.1.4 Water stargrass and herbicide research

Research on the effectiveness of herbicide control methods specifically for water stargrass is limited, likely because it is native to the United States and a focus of conservation concern in many waterbodies around the country. Of the published research that does document water stargrass response to herbicides, much of the time it is present as a non-target species, but these studies are limited. Therefore, it is possible that use of herbicide control in the lower Yakima River may end up being experimental or pilot. As such, use of a specific herbicide may likely come down to other factors such as allowable use in salmon bearing streams, agricultural impacts, EIS and permitting restrictions, etc. Trial studies may then be used as the best option to determine effectiveness of control, application rates, and contact times

One early study examined water stargrass susceptibility to a comprehensive list of herbicides and concluded that the plant is “difficult to control.” It was not susceptible to many systemic herbicides, likely due to both its limited ability to translocate herbicides and resistance of its meristems to herbicides, which allowed for regrowth of tissue that was killed. Also, since most systemic herbicides are slow acting, water stargrass was less susceptible to them in flowing water, which causes reduced contact times. The researchers concluded that contact herbicides, which tend to be fast acting, will generally provide better control in flowing water (Hollingsworth and Wilkinson 1965). However, only a few of those tested are currently allowed under the APAM permit, and many modern herbicides were not available at the time these trials were performed, so newer technology may have overcome these difficulties (e.g., imazamox is a fast-acting systemic herbicide introduced in 1997).

The choice between systemic and contact herbicides is an important one. Systemic herbicides work when they are taken up by plants and translocated to the roots, where they can kill the entire plant. Contact herbicides tend to be much faster acting, but only kill the plant tissue they come in contact with, and so only provide temporary control, since belowground roots and rhizomes can survive to regrow. Efforts are ongoing to find new selective, systemic herbicides with short exposure time requirements to better control major aquatic weeds (Chartrand et al. 2017).

Another factor to consider when choosing herbicides is the issue of herbicide resistance. Aquatic plant populations can contain or develop plants that are naturally resistant to certain herbicides. When these herbicides are used repeatedly for a given population, the resulting selection pressure can lead to the domination of the waterbody by plants that are resistant to that herbicide. The largest risk factor for the development of herbicide resistance is reliance upon a single systemic herbicide, especially ALS inhibitors like imazamox, imazapyr, and penoxsulam. To prevent it, any project that relies on herbicides for aquatic plant control should use them as part of an IPM program, use herbicides with different modes of action, and monitor treated plant populations for loss of herbicide efficacy (Richardson 2008, Chartrand et al. 2017).

3.8.1.5 Summary of herbicide conclusions

We investigated all herbicides and other methods of chemical plant management that are potentially applicable to the control of nuisance aquatic plants in Washington, including all those listed in the current Ecology APAM permit. Herbicides that might be effective for control of water stargrass but are not allowed under the permit (e.g., acrolein [Magnacide™ H Herbicide]) were not investigated. In the process of researching these chemical control methods, we quickly eliminated many of them from consideration. Those eliminated include herbicides allowable under the APAM permit but labeled only for control of non-submersed plants (i.e., emergent and nearshore vegetation), those whose long contact time requirements preclude their use in rivers, and those whose use is prohibited in salmon-bearing waters or waterbodies used for irrigation. These chemicals are discussed in only brief detail here and are summarized in Appendix A with the reason for rejection and the note, “not considered further.”

Chemical control methods are listed in the following sections according to potential application in the Yakima River. Section 3.8.2 addresses those that might have potential use and Section 3.8.3 briefly summarizes those that are not considered any further. Most of the herbicides and other chemical control methods were eliminated during the research process; only endothall, imazamox, carfentrazone-ethyl, and fluridone remain under consideration. Carfentrazone-ethyl and fluridone are possible but unlikely candidates for use in the Yakima, as carfentrazone-ethyl would likely degrade rapidly at the pH levels observed in the river, and fluridone was ineffective against water stargrass in three studies. Endothall and imazamox remain the best choices for chemical control, though each has significant drawbacks. Endothall is a fast-acting contact herbicide and is labeled specifically for control of water stargrass. However, in two separate studies it did not reduce water stargrass abundance in flowing water. Imazamox is a fast-acting systemic herbicide and is labeled specifically for control of water stargrass, so it should kill the entire plant. However, due to irrigation restrictions, its application would be restricted to a very brief period in the late winter. Trial studies would be needed before either endothall or imazamox could be used for this project to determine their effectiveness against water stargrass, as well as the application rates and contact times required to be effective at the flow rates observed in the lower Yakima.

3.8.2 Chemical methods warranting possible consideration

3.8.2.1 Endothall

Endothall (7-oxabicyclo[2.2.1]heptane-2,3dicarboxylic acid) is a rapid-acting, broad-spectrum contact herbicide available in two forms, a mono(N,N-dimethylalkyalmine) salt and a dipotassium salt (Chartrand et al. 2017). The mono salt is also an algaecide, and Ecology restricts its use under the APAM permit to the control of filamentous algae, cyanobacteria, or harmful algae only (Ecology 2021b). The dipotassium salt is available commercially as Aquathol® K, Aquathol® Super K Granular, and Cascade® Aquatic Herbicide and is labeled for use in quiescent, slow-moving, and flowing water aquatic sites (EPA/United Phosphorus, Inc. 2019).

Endothall disrupts solute transport processes in plant cells and is used to control plants at a variety of concentrations and contact times, typically at low concentrations and short contact times (Skogerboe and Getsinger 2001, Chartrand et al. 2017). Since it is a contact herbicide, the likely effect on water stargrass will be that, even if aboveground stems and leaves are killed, belowground rhizomes and roots will persist undamaged and plants will re-grow if they are not otherwise prevented from doing so (Chartrand et al. 2017).

Endothall may have some negative effects on fish. When applied at the maximum labeled rate of 5.0 mg/L, no acute or chronic harm to salmonids or other aquatic animals are anticipated. Also, Low Observed Effect Concentrations (LOECs) in a series of challenge experiments on juvenile fish were 9 mg/L for steelhead and 12 mg/L for coho and Chinook salmon. However, there is some evidence of reduced mortality for steelhead, and it is recommended that the exposure of wild fisheries to endothall should be avoided (Chartrand et al. 2017). Accordingly, endothall is subject to the WDFW timing windows for salmonids (Ecology 2021b).

In addition to being subject to fish timing windows, endothall usage faces a few other restrictions defined by the label and Washington State regulations. Because of the potential for mild eye irritation in humans, a swimming advisory is required during treatment and for 24 hours afterward (Chartrand et al. 2017, Ecology 2021b). Additionally, a boating advisory is recommended during the same time period due to the potential for eye irritation due to spray from boat engines or propellers (Chartrand et al. 2017). There is no prohibition on the use of treated water for irrigation, but no more than a total of 5 ppm may be applied within a 7-day period and no more than 30 ppm may be applied within a growing season. If any potable water intakes are present in the treatment area, they must be closed while endothall concentrations are above 0.1 ppm, or treatment must be made downstream from the intake. Finally, the label specifies that in areas with very high plant density, waterbodies should be treated in sections to prevent decomposition of dead plants from depleting oxygen and causing fish kills (EPA/United Phosphorus, Inc. 2019).

There is conflicting evidence of endothall's effectiveness at controlling water stargrass. The Aquathol® K label lists water stargrass as one of the species controlled in flowing water at application rates and contact times ranging from 0.5 mg/L and 72 hours to 5.0 mg/L and 6 hours (EPA/United Phosphorus, Inc. 2019). However, in an early study of herbicide effectiveness against water stargrass, endothall was effective in non-flowing water, but not in flowing water, even when applied at very high concentration. The researchers hypothesized that since they used a granular formulation, the combination of the current and the slow release from the granules prevented a sufficient concentration from accumulating in the water column (Hollingsworth and Wilkinson 1965). Also, a mesocosm study that evaluated endothall effectiveness against a variety of aquatic plants found no effectiveness at reducing water stargrass biomass. Application rates of 1, 2, and 5 mg/L were tested in a flowing water system that resulted in an endothall half-life of 24 hours. While leaves and stems in all treatments began to turn black within a day after treatment, this effect only lasted a week and new growth was observed by the end of this time. With an application rate of 5 mg/L, water stargrass biomass was not significantly reduced 3 or 6 weeks after treatment. In both the 1 and 2 mg/L treatments, water stargrass biomass increased 3 weeks after treatment and then doubled by 6 weeks after treatment, presumably due to reduced competition from species that were controlled (Skogerboe and Getsinger 2001).

In conclusion, endothall is a possible candidate for control of water stargrass in the Yakima River. It is subject to the WDFW timing window for salmonids (July 15–September 1 in the lower Yakima), but does not have significant irrigation restrictions, so it should be able to be used during this time. There is strong evidence that it poses very low environmental risk during this timing window as long as it is not applied at concentrations greater than labeled rates, though some restrictions will be required to prevent human consumption and eye contact. Finally, endothall is labeled specifically for control of water stargrass, with specific application and contact time recommendations for control in flowing water. Since it is a rapid-acting herbicide, it is more likely than slower-acting herbicides to be effective in a flowing system like the Yakima. However, two studies call into question this assumption, and trial studies would be needed to determine if endothall might be effective at flow velocities that occur in the lower Yakima River, as well as what contact time and application rate would be required. Even if control is achieved, endothall use would most likely need to be coupled with at least one other management method, since contact herbicides typically kill only aboveground biomass and regrowth can occur from undamaged roots and rhizomes.

3.8.2.2 Imazamox

Imazamox (2-[4,5-dihydro-4-methyl-(1-methylethyl)-5-oxo-1H-imidazol-2yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid) is a selective, fast-acting systemic herbicide approved for control of submersed and emergent vegetation in Washington waters (Chartrand et al. 2017). An aquatic formulation is available as Clearcast®, which is labeled for use in a variety of waterbodies, including "rivers, creeks and other slow-moving" waterbodies (EPA/BASF Corporation 2016). This herbicide works by inhibiting the acetolactate synthase (ALS) enzyme, which is used in the biochemical pathways for the synthesis of three amino acids. Imazamox demonstrates low toxicity to animals, likely due in part to the absence of these biochemical pathways in animals (Chartrand et al. 2017).

Imazamox inhibits plant growth within one day of application, and visual symptoms appear in about a week. Sensitive plants develop a yellow or discolored appearance that is first visible on new growth, then eventually die or suffer severe growth inhibition. Since imazamox is fast-acting, submersed plants can be controlled without having to maintain a given concentration in the water column for an extended time. Since it is a systemic herbicide, translocated through vascular tissue, it concentrates in the actively growing portions of roots and shoots, killing or damaging the entire plant (Chartrand et al. 2017).

Imazamox is EPA classified as a reduced-risk pesticide and has an EPA exemption for tolerance designation. The exemption waives all food residue tolerance requirements for potential food or feed uses of imazamox, including fish, shellfish, crustaceans, and irrigated crops (Hamel 2012). Toxicity testing has shown that it is practically non-toxic to fish, birds, mammals, and invertebrates, and Ecology considers the most serious environmental impact to be the risk posed to sensitive, threatened, and endangered plants (see the discussion in Section 3.8.1.2 regarding the likelihood of these plants being present in the Yakima River and the requirements if they are found). Also, imazamox does not readily bioaccumulate within tissues or bioconcentrate within sediments. As long as label specifications are followed for aquatic applications of imazamox, Ecology does not expect any impact to swimming or other aquatic recreation activities (Chartrand et al. 2017).

Despite the low level of environmental risk, there are some application restrictions for imazamox defined by label usage and Ecology regulations (EPA/BASF Corporation 2016, Chartrand et al. 2017).

- Though imazamox has a very low level of toxicity, there are potentially sublethal effects to juvenile salmonids. While imazamox application is not required to follow the WDFW timing window, Ecology may impose a timing restriction in the permit.
- Any application of imazamox upstream of a hatchery water intake will require the permittee to coordinate with Ecology, WDFW, and affected tribes to ensure treatments will not adversely affect hatchery fish or hatchery operations.
- For ALS-inhibiting herbicides like imazamox, Ecology may require post-treatment monitoring as part of permit requirements to evaluate non-target effects.
- For applications to water, the maximum allowable concentration of imazamox is 500 ppb.
- Treated water cannot be used for irrigation unless the imazamox concentration is less than or equal to 50 ppb.
- Treated water cannot be used for irrigation in greenhouses, nurseries, hydroponics, vineyards, golf courses, and sod farms unless the imazamox concentration is less than or equal to 1 ppb.
- Where soils have been previously irrigated with imazamox-treated water, sugar beets, onions, potatoes, and non-Clearfield® canola cannot be planted unless a soil bioassay successfully demonstrates acceptable levels of crop tolerance.
- For any applications within ¼ mile of an active potable water intake, imazamox concentration cannot exceed 50 ppb.

These irrigation restrictions would pose a challenge, as the label-recommended concentration for water stargrass control is too high for treated water to be used for irrigation. However, since the contact time required to kill or damage plants is brief, it may be possible to apply it early in the growing season and allow it to be removed from the system before irrigation intake begins on March 15. Systemic herbicides like imazamox work by being translocated through the plant (Ecology 2021a), and so are unlikely to be effective while plants are in dormancy. Water stargrass remains dormant until water temperatures reach 8 °C, when spring growth is triggered (Horn 1983). Yakima River temperatures reach this high by early–mid March (USGS 2021), so there may be a small application window. Additionally, for some plants the label recommends applying early in the growing season to maximize effectiveness (EPA/BASF Corporation 2016), so this timing may provide an additional benefit.

Some evidence suggests that imazamox may be effective against water stargrass. Early research demonstrated that water stargrass is notably resistant to systemic herbicides, at least those available at the time (Hollingsworth and Wilkinson 1965). However, the Clearcast® label specifically lists water stargrass among the most susceptible vascular aquatic plants and recommends imazamox concentrations of 50–200 ppb (EPA/BASF Corporation 2016). This claim does not appear to have been backed up by literature, as a search did not reveal any studies that investigated the effectiveness of imazamox for water stargrass, whether as a target or non-target species. Therefore, a trial study may be required to determine the likely level of control. Additionally, the use of ALS inhibitor herbicides like imazamox poses the risk of target plants developing herbicide resistance. This risk is heightened by repeated application in the same area or if used as the primary method of control over successive years (see discussion on herbicide resistance in Section 3.8.1.4; Hamel 2012).

In conclusion, imazamox is a possible candidate for control of water stargrass in the Yakima River. The irrigation restriction will restrict its use to the late winter, prior to March 15. However, since imazamox is a rapid-acting herbicide, it may be possible to apply it after growth begins and allow it to be removed from the system before this point. There is strong evidence that it poses very low environmental risk in the Yakima, though it remains possible that Ecology could impose timing restrictions. Finally, it is labeled specifically for control of water stargrass, though this does not yet appear to be documented in the literature.

3.8.2.3 Carfentrazone-ethyl

Carfentrazone-ethyl (ethyl α,2-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1H -1,2,4-triazol-1-yl]-4-fluorobenzenepropanoate) is a rapid-acting, light-dependent, narrow-spectrum contact herbicide approved for use in Washington waters. The liquid formulation is available as Stingray™ Aquatic Herbicide, which is emulsifiable in water and may be used in ponds, lakes, reservoirs, marshes, wetlands, drainage ditches, canals (non-irrigation), streams, and rivers (Chartrand et al. 2017). This herbicide works by inhibiting the enzyme protoporphyrinogen oxidase (abbreviated as protox). This inhibition interferes with chlorophyll synthesis, leading to the formation of peroxides that damage cell membranes, causing them to leak their contents (Hamel 2012, Glomski and Netherland 2013).

In the land plants it was originally licensed for, carfentrazone-ethyl results in drying and disintegration within 24 to 48 hours. In aquatic plants, symptoms including leaf discoloration and necrosis tend to appear within two to five days. Because of the destruction of plant tissue, herbicide translocation is limited, so damage is restricted to the point of contact (Chartrand et al. 2017). For water stargrass, the likely result of this will be that, even if aboveground stems and leaves are killed, belowground rhizomes and roots will persist undamaged and plants will re-grow if they are not otherwise prevented from doing so.

EPA has classified Stingray™ as a reduced-risk pesticide, but it does have potential harmful effects for non-target species. EPA considers it practically nontoxic to birds, mammals, and beneficial insects, but it is moderately toxic to some fish and invertebrate species. Since the maximum application rate is low and it breaks down quickly in the environment, EPA considers the risk to non-endangered animals as low. However, a single application in shallow waters exceeds EPA's acute and chronic level of concern for endangered freshwater fish, so Ecology requires application to be restricted to the WDFW timing windows for priority species (Hamel 2012, Chartrand et al. 2017).

In response to these risks, there are a number of application restrictions for carfentrazone-ethyl defined by label usage and Ecology regulations (Chartrand et al. 2017):

- The maximum application rate is 200 µg/L for submersed plants, or otherwise 0.2 lb of active ingredient per acre.
- Treatment of submersed aquatic plants requires subsurface injection. In flowing water, this needs to be applied while traveling upstream to prevent the water column concentration from exceeding the maximum allowed.
- A maximum of one-half of the waterbody may be treated at a time, with at least 14 days required before treating the other half, or before retreatment.
- Application is not allowed within 0.25 miles of an active potable water intake unless the water intake is turned off prior to and for a minimum of 24 hours after application. If the herbicide treatment could potentially affect large numbers of the public through municipal and community water intakes, the potentially affected water right holder must agree to the treatment before Ecology will issue permit coverage.
- If 20% or more of the surface area of the waterbody is treated, there is a one-day livestock watering restriction.
- Since irrigation with treated water may result in injury to vegetation, treated water cannot be used in commercial nurseries or greenhouses. If less than 20% of the surface area of the waterbody is treated, there is a one-day irrigation restriction for crops. If 20% or more of the surface area is treated, the irrigation restriction is 14 days. However, irrigation may resume if laboratory testing determines that the concentration of carfentrazone-ethyl and its major degradates is less than 5 µg/L.
- Ecology's water quality permit mitigates for the possible loss of irrigation water rights by allowing project proponents to provide an alternative water supply to affected parties holding legal water rights while irrigation restrictions are imposed. This would most likely be impractical for large-scale irrigators that rely on the Yakima River, even for a single day.

A number of factors suggest that carfentrazone-ethyl may be ineffective against water stargrass in the Yakima River. First, the same property of rapid degradation (i.e., hydrolysis) that reduces its environmental risk will likely make it less effective in the Yakima River. Carfentrazone-ethyl is stable at pH 5, but has a half-life of 8.6 days at pH 7, and a half-life of only 3.6 hours at pH 9 (Hamel 2012). However, in the lower Yakima River during the allowable herbicide treatment window, daytime pH levels are usually above 9 (USGS 2021), which will likely result in contact times that are too short to be effective. Indeed, some evidence suggests that high pH levels reduce the effectiveness of carfentrazone-ethyl by causing degradation before a lethal contact time is achieved (Wersal et al. 2010). While it is light-activated, it does appear to be effective when applied in the dark (Wersal et al. 2010), though nighttime pH levels in the Yakima only drop as low as 8 during the treatment window (USGS 2021). Secondly, carfentrazone-ethyl performs best when target plants are actively growing (Chartrand et al. 2017). For water stargrass in the Yakima River, this period is well before the allowable treatment window of July 15–September 1. Finally, the Stingray™ label claims treatment efficacy for just a few species found in Washington State (Chartrand et al. 2017). Studies examining its effectiveness for water stargrass are limited, but one small-scale microcosm experiment found no evidence of water stargrass sensitivity to carfentrazone-ethyl at pH 6.5 (Glomski and Netherland 2013).

Carfentrazone-ethyl will most likely be a poor choice for treatment of water stargrass in the lower Yakima River. Treatment will be restricted to less than 20% of the waterbody, and even then will require a one-day irrigation restriction. Treatment of more than 20% of the waterbody will not be feasible, as this would require a 14-day irrigation restriction. Also, under the pH levels observed in the Yakima, carfentrazone-ethyl will probably break down too quickly to have sufficient contact time. Finally, there is some evidence that it is not effective against water stargrass.

3.8.2.4 Fluridone

Fluridone (1-methyl-3-phenyl-5-[3-(trifluoromethyl)phenyl]-4(1H)-pyridinone) is a slow-acting systemic terrestrial and aquatic herbicide. A commonly available aquatic formulation is Sonar®, which is applied just before or just after plants begin to grow. This herbicide works by interfering with RNA and protein synthesis. It also interferes with the formation of carotenoid pigments, causing chlorophyll to be degraded by sunlight and photosynthesis to be inhibited (Chartrand et al. 2017, EPA/SePRO Corporation 2019). Fluridone application is not subject to the WDFW timing window, so early season application for water stargrass may be possible.

The environmental risk of fluridone to humans and other animals is low. It is not teratogenic (i.e., causing developmental malformations), not mutagenic, and is not listed or considered to be carcinogenic. Also, there are no label restrictions against drinking, swimming, or fishing in water treated with fluridone. Toxicity studies of fluridone do not suggest danger to aquatic animals, including salmonids, when used at concentrations permitted by the label (Chartrand et al. 2017). The primary risk of fluridone is damage to non-target plants. It may persist in sediments for up to one year after treatment, so it may affect colonization of non-target plant species in areas where target plants were removed (Ecology 2000).

However, a few factors may prevent usage of fluridone in the Yakima River. First, fluridone is a slow-acting herbicide. Symptoms (white or pink growing points) appear within 7–10 days, but 30 to 90 days under optimum conditions are required to completely kill plants (EPA/SePRO Corporation 2019). To overcome the difficulty of allowing long contact times in flowing waters, researchers have investigated various methods to prolong its presence (Ecology 2000). Largediameter fibers that become entangled among submersed aquatic plants have been effective at allowing controlled delivery of fluridone and extending its release over a period of 40 to 50 days (Van and Steward 1986). Additionally, Sonar® is available in several pellet formulations that are labeled for use in rivers, including one designed for slow release in faster-moving waters (SePRO Corporation 2021). However, since water treated with fluridone may harm vegetation if it is used for irrigation, it cannot be used for irrigation for 7 days following treatment in rivers. Also, treated water cannot be used for hydroponic farming or greenhouse and nursery use unless a high-performance liquid chromatography (HPLC) test indicates fluridone concentration is less than 1 ppb (EPA/SePRO Corporation 2019).

The 7-day irrigation restriction alone would eliminate the application of fluridone from consideration during the spring and summer. However, it may be possible to overcome this restriction by applying it regularly from early February through early March, allowing a 30-day contact time followed by a no-treatment period of at least 7 days before irrigation begins on March 15. Unfortunately, this strategy is unlikely to work. Systemic herbicides like fluridone work by being translocated through the plant (Ecology 2021a), and so are unlikely to be effective while plants are in dormancy. Water stargrass remains dormant until water temperatures reach 8 °C, when spring growth is triggered (Horn 1983). Yakima River temperatures do not reach this high until early–mid March (USGS 2021), so it is unlikely that water stargrass will actively take up fluridone for a long enough period before the irrigation restriction goes into effect.

Some evidence suggests that fluridone may not be effective against water stargrass. First, it is not included on the label under the list of plants controlled or partially controlled by fluridone (though it is also not included in the list of plants not controlled; EPA/SePRO Corporation 2019). Also, water stargrass was present as a non-target species in three studies that evaluated the effectiveness of fluridone in mesocosms and in two lakes. Water stargrass abundance was not reduced by fluridone in any of these and its frequency increased after treatment in two of them (Netherland et al. 1997, Smith and Pullman 1997, Crowell et al. 2006). In another study of the effects of whole-lake fluridone treatments on the entire aquatic plant community, water stargrass abundance either increased or did not change following treatment (Edgell 2007).

In conclusion, fluridone will most likely be a poor choice for treatment of water stargrass in the lower Yakima River. The 7-day irrigation restriction restricts its use to the late winter, prior to March 15. During most of this time, water stargrass is not actively growing, so an adequate dosage will most likely not be taken up by the plants. Finally, there is moderate evidence that it is not effective against water stargrass.

3.8.3 Rejected chemical methods

Rejected chemical methods are summarized in Table 1, Appendix A. Below are listed summaries of the rejected chemical methods, and reason why they were not included for further consideration.

3.8.3.1 2,4-D

Post-emergent herbicides containing the active ingredient 2,4-D (2-4-dichlorophenoxy acetic acid) are available in two forms: 2,4-D ester (butoxyethyl ester; BEE) and 2,4-D amine (dimethylamine salt; DMA). Two commonly used aquatic forms of this herbicide are Aqua-Kleen® and Navigate®. These herbicides are used to control submersed aquatic vegetation in Washington, including water stargrass and Eurasian watermilfoil (Chartrand et al. 2017). However, 2,4-D ester cannot be used in salmon-bearing waters under Ecology's APAM Permit (Ecology 2021b). Additionally, under labeled usage, neither form of 2,4-D may be applied to waters used for irrigation, agricultural sprays, watering dairy animals, or domestic water supplies (Chartrand et al. 2017). All of these uses apply to the lower Yakima River, so herbicides containing 2,4-D will not be considered further for this project.

3.8.3.2 Aminopyralid

Herbicides containing aminopyralid (4-amino, 3,6-dichloropyridine-2-carobxylic acid) are currently approved for non-aquatic use in a variety of natural areas, including shorelines and riparian areas (Ecology 2019). In the U.S., aminopyralid herbicides are available primarily under the trade name Milestone®. Field trials were conducted to support the addition of aquatic uses to aminopyralid product labels, but no in-water uses were proposed (Chartrand et al. 2017). It is now listed under Ecology's APAM permit (Ecology 2021b), but the current label does not allow use in water (EPA/Dow AgroSciences 2020). Therefore, herbicides containing aminopyralid will not be considered further for this project.

3.8.3.3 Bispyribac-sodium

Herbicides containing bispyribac-sodium (sodium, 2,6-bis [(4,6-dimethoxy-pyrimidin-2-yl)oxy] benzoate) are used in Washington to control submersed, surface-dwelling, and emergent aquatic vegetation (Chartrand et al. 2017). It is available commercially as Tradewind™ Aquatic Herbicide. However, bispyribac-sodium is a slow-acting systemic herbicide, requiring contact times of 60–90 days, and its label prohibits application to flowing water (Hamel 2012). Therefore, herbicides containing bispyribac-sodium will not be considered further for this project.

3.8.3.4 Diquat

Diquat (Dibromide salt of 6,7-dihydrodipyrido (1,2-a:2',1"-c) pyrazinediium) is a broad-spectrum contact herbicide used to control submersed and floating aquatic plants in a variety of waterbodies in Washington. The only commercially available form registered for use in public waterways is Reward® Landscape and Aquatic Herbicide. Diquat is toxic to a number of aquatic animals, including some benthic invertebrates that are important as prey species for fish, and is subject to the WDFW timing windows for salmonids (Chartrand et al. 2017). Also, the labeled use of diquat requires a 5-day irrigation restriction (EPA/Syngenta Crop Protection, Inc. 2009), which is too long a period to be acceptable in the Yakima River. Therefore, herbicides containing diquat will not be considered further for this project.

3.8.3.5 Florpyrauxifen-benzyl

Florpyrauxifen-benzyl (2-pyridinecarboxylic acid, 4-amino-3-chloro-6-(4-chloro-2-fluoro-3-methoxyphenyl)- 5-fluoro-, phenyl methyl ester) is a selective systemic herbicide that was first approved for use in freshwater by the EPA in 2018 and added to the Ecology APAM permit in 2019. It is available commercially as ProcellaCOR™ Aquatic Herbicide. However, the ProcellaCOR™ label only permits application to rivers for the management of invasive aquatic plants, and even then, only to slow-moving or quiescent areas of rivers (e.g., coves and oxbows). For management of non-invasive plants, application is restricted to slow-moving or quiescent waterbodies with little or no continuous outflow (EPA/SePRO Corporation 2018). Therefore, herbicides containing florpyrauxifen-benzyl will not be considered further for this project.

3.8.3.6 Flumioxazin

Flumioxazin (2-[7-fluro-3,4-dihydro-3-oxo-4-(2-propynyl)-2H-1,4-benzoxazin-6-yl]-4,5,6,7-tetrahydro-1H-isoindole-1,3(2H)-dione) is a broad-spectrum contact herbicide and algaecide registered for terrestrial and aquatic uses. The aquatic formulation is available in granular form as Clipper™. Its labeled usage allows control of aquatic plants in drainage ditches, freshwater ponds, lakes, marshes, and reservoirs as long as these waterbodies have limited or no outflow at the time of treatment (Chartrand et al. 2017). As the label does not allow for usage in rivers, flumioxazin herbicides will not be considered further for this project.

3.8.3.7 Glyphosate

Glyphosate (N-(phosphonomethyl)glycine, isopropylamine salt) is a terrestrial and aquatic systemic herbicide, available in aquatic formulations as Rodeo® and Pondmaster®. However, glyphosate rapidly loses its effectiveness in water, and under Ecology's APAM permit, its aquatic uses are limited to shoreline, emergent and floating leaf plant treatments (Chartrand et al. 2017). Therefore, herbicides containing glyphosate will not be considered further for this project.

3.8.3.8 Imazapyr

Imazapyr (2-(4,5-dihydro-4-methyl-4-(1-methyleth7yl)-5-oxo-1H-imidazol-2-y1)-3-Pyridinecarboxylic acid) is a broad-spectrum, systemic herbicide used in Washington to control weeds along freshwater riparian corridors. It is available commercially under the brand names Arsenal™ and Habitat. However, imazapyr does not demonstrate any in-water herbicidal activity and so will not be effective for treatment of submersed plants (Chartrand et al. 2017). Therefore, imazapyr will not be considered further for this project.

3.8.3.9 Penoxsulam

Penoxsulam (2-(2,2-difluoroethoxy)--6-(trifluoromethyl-N-(5,8-dimethoxy[1,2,4] triazolo[1,5-c]pyrimidin-2-yl)) benzenesulfonamide) is a terrestrial and aquatic broad-spectrum systemic herbicide approved for use in Washington. The aquatic formulation is available as Galleon SC™ and is used to control floating, submersed, and emergent aquatic plants in ponds, lakes, reservoirs, wetlands, drainage ditches, non-irrigation canals, and other slow-moving and quiescent bodies of water. It is a slow-acting herbicide, requiring 60 to 120 days for complete control of target plants, and its label does not include treatment in rivers (Chartrand et al. 2017). Therefore, herbicides containing penoxsulam will not be considered further for this project.

3.8.3.10 Topramezone

Topramezone ([3-(4,5-dihydro-isoxazol-3-yl)-4-methylsulfonyl-2-methylphenyl] (5- hydroxy-1-methyl-1H-pyrazol-4-yl)methanone) is a selective, systemic herbicide with both terrestrial and aquatic uses. The aquatic formulation is commercially available as Oasis®Aquatic Herbicide, which is used for control of floating and submersed aquatic plants (Chartrand et al. 2017). While not labeled for use in rivers (labeled uses in flowing water include, “drainage ditches, canals, and slow-moving or quiescent bodies of water”), the 2013 version of the label mentions rivers and streams while discussing irrigation restrictions.

Restrictions on the use of topramezone are significant. In flowing water, Oasis® needs to be applied to maintain a continuous concentration between 5–50 ppb, depending on the plant to be treated (the label does not give guidance on determining the necessary concentration). This should begin immediately after plants begin active growth and the concentration needs to be maintained for a minimum of 60 days, or until satisfactory plant control is achieved, and cannot exceed a cumulative total of 150 ppb per year. Water treated with Oasis® cannot be used for irrigation of crops other than corn until the concentration reaches 1 ppb or less (EPA/BASF Corporation 2013). Since the time between the start of plant growth and the beginning of irrigation water intake is only a few weeks at best (see the discussion of irrigation restriction in Section 3.8.1.3), it will not be feasible to reach the necessary contact time in the Yakima River. Therefore, topramezone will not be considered further for this project.

3.8.3.11 Triclopyr TEA

Triclopyr TEA (Triethylamine salt of 3,5,6-trichloro-2-pyridyloxyacetic acid) is a selective, systemic herbicide used to control a variety of terrestrial and aquatic plants. Two aquatic formulations are available commercially as Garlon® 3A and Renovate®. Only one formulation of triclopyr TEA, Renovate® MAX G, is approved for use in unimpounded rivers. However, this granular formulation also includes 2,4-D amine as an active ingredient, which increases the application restrictions for waters used for irrigation (Chartrand et al. 2017). Also, water stargrass is listed on the label as one of the species least susceptible to this herbicide (EPA/SePRO Corporation 2014). Therefore, triclopyr TEA will not be considered further for this project.

3.8.3.12 Copper compounds

Copper compounds, including copper sulfate and copper chelates, are available as registered herbicides and algaecides. However, they are toxic to fish and aquatic invertebrates and remain persistent in the environment (Chartrand et al. 2017). Copper chelates have often been considered to be more effective (Gibbons et al. 1994) and less toxic to non-target organisms than other forms of copper herbicides. However, in field trials, chelated copper compounds have been shown to increase fish mortality, especially in warm waters (Wagner et al. 2017). Ecology does not permit the use of copper compounds in Washington waters, with two exceptions: usage under the Irrigation System Aquatic Weed Control General Permit and the Invasive Species

Management General Permit (N. Lubliner and J. Parsons, Ecology, personal communication). Neither of these are applicable to water stargrass control in the Yakima River and therefore will not be considered further for this project.

3.8.3.13 Phosphorus sequestration products

Four types of phosphorus sequestration products are included in the Ecology APAM permit: alum (aluminum sulfate and sodium illuminate), calcium products (calcium hydroxide/oxide and calcium carbonate), lanthanum-modified bentonite clay, and iron (powdered or granulated). These chemicals work by binding to phosphorus in the water column, causing it to settle out and rendering it unavailable to plants and algae (Chartrand et al. 2017). Since phosphorus is commonly a limiting nutrient in freshwater systems (Dodds and Whiles 2010), this can be effective at reducing macrophyte growth and algae blooms, primarily in lakes and especially when macrophytes obtain their nutrients from the water column (Chartrand et al. 2017).

However, several factors indicate that phosphorus sequestration products would not be effective at controlling water stargrass growth. While water stargrass uptake of nutrients in the Yakima River has to our knowledge not been directly measured, it does not appear to obtain a measurable amount from the water column. This, combined with a historical sediment nutrient load that is likely quite high, indicate that reducing phosphorus in the water column would likely have no effect on water stargrass growth (Wise et al. 2009). Additionally, measured water concentrations of phosphorus in the Yakima River tend to already be fairly low (USGS 2021), well below the eutrophic levels that often promote excessive plant and algae growth (Dodds 2007). Finally, because the phosphorus load in the Yakima River comes primarily from sources upstream, even if the removal of phosphorus from the water column was sufficient to reduce water stargrass growth in the lower river, the phosphorus load would be immediately replaced by incoming flow as soon as treatment ceased. Therefore, phosphorus sequestration products will not be considered further for this project.

3.9 Non-traditional watershed controls

3.9.1 Introduction

With dam construction and agriculture management in the Yakima watershed, historical factors that may have kept water stargrass growth in check were altered. Benton Conservation District in collaboration with the TAG (see Section 3.1) investigated the potential to modify characteristics of the river that may help mitigate water stargrass growth and help restore lower Yakima River function. Implementation of these methods would take collaboration with multiple agencies and partners and would need to be further researched or pilot tested. However, these techniques may have the potential to mitigate growth on a larger scale and provide a greater time for the impact of treatment.

3.9.2 Flow management (flushing flows)

While water stargrass biomass is problematic in summer months across most water years, there is a noticeable difference in biomass density and coverage between high- and low-flow water years. In unshaded streams, growth and plant distribution are more likely to be influenced by local hydraulic conditions such as water depth, velocity, and sedimentation (Chambers et al. 1991, Riis and Biggs 2003). In drought years (such as 2005 and 2015) or years with earlier sustained low flows, water stargrass density becomes especially problematic and exasperates an already stressed water system. Conversely, total biomass abundance is diminished in years with higher spring flows that extend later in the season or in years with scouring freshets (e.g., 2011). The impact of the scouring freshets on total biomass growth is noticeable in the subsequent growing season. There is also some research evidence in other lotic systems that more frequent high velocity flood events (frequent flushing flows) impact plant abundance, presumably through uprooting of the plants through sediment bed erosion (Riis and Biggs 2003).

The Yakima River basin is highly modified with a system of reservoirs, diversion dams, and canals, and agriculture in the basin relies on this complex system for irrigation. These modifications have altered the timing and quantity of flows in the river system. The highly regulatory nature of the river system is likely to have impacted macrophyte dynamics with much of the spring freshet impounded behind dams and the frequency of flushing flow events greatly attenuated. While we cannot return the river to historical flow conditions, there is a concerted effort within the Yakima Basin to manage flows for both fish and irrigators. Carefully timed managed flow releases from the reservoirs are currently utilized in the late spring and early summer to help salmonid migration. Given the highly regulated nature of the Yakima River, there may be an opportunity to time flow releases in the spring to aid late spring salmon migration while stalling early water stargrass biomass growth to prevent its early foothold in the lower river. Sustained flows that extend longer into the spring season are likely to delay late-spring plant growth and offset summer biomass abundance. Managed flushing flow or pulse flow events in the late winter and spring may also diminish the establishment of plant growth, thus helping attenuate peak total river biomass later in the summer. This mitigation effort would need to be pilot tested with monitoring to determine success rates for delaying early biomass growth utilizing flow management techniques.

3.9.3 Turbidity increases and sedimentation

Even after high nutrient runoff from agriculture created conditions favorable for water stargrass growth in the lower Yakima River prior to the 2000s, its abundance was most likely held in check by high turbidity resulting from the same runoff. Periods of increased turbidity and sedimentation during the spring are not unheard of in the lower Yakima River. Increases in turbidity consistently occur during times of natural flow increases (e.g., storms) and timed dam releases as measured by the lower river USGS monitoring stations at Benton City and West Richland.

Therefore, it may be possible to utilize flushes of sedimentation within the reservoirs during key life cycle stages of water stargrass to help mitigate plant growth. Increased turbidity can also be a benefit for out-migrating juvenile salmonids, as increased turbidity is known to provide greater cover for juveniles. As with flushing flows, there may be a symbiosis gained by briefly altering turbidity conditions during a critical period to benefit both juvenile migrants and water stargrass mitigation efforts in the late spring and early summer.

In a river system where water stargrass largely overwinters as rhizomes, it is likely to be vulnerable to sedimentation events (N. Rybicki, USGS, personal communication). Dredge sediments, sand, silt, and clay have all been used as a form of bottom barrier (Madsen 2000). Furthermore, there is evidence that turbid water from dredging operations seems to have been effective at markedly reducing heavy water stargrass growth in Missouri (Hollingsworth 1966). However, we already see sedimentation driven by overabundant plant growth and it is unclear if added sedimentation would control the plant population in the lower Yakima River, especially since water stargrass in the Yakima seems to overwinter largely as entire plants. Additionally, there is added concern with increasing sedimentation, as it covers spawning gravel and decreases habitat suitability for salmonid spawning. Any controls involving turbidity and sedimentation would need to take into consideration environmental compliance and adhere to the Yakima Basin TMDL's listing by the Department of Ecology for turbidity. A temporary exemption permit for short term increases in turbidity may need to be obtained.

3.9.4 Flow velocity enhancement (islands and in-stream restrictions)

Water stargrass establishment in the lower Yakima River is impacted by river velocity. In locations of "pinch points" where river flows naturally increase as a result of constrictions (e.g., islands or narrowing of the channel) water stargrass is noticeably absent. Furthermore, in areas of moderately flow velocities where the plant establishes the stem length is shorter (smaller plants). Locations with swift, fast moving water or rapids are also noticeably absent of macrophytes (e.g., Prosser bedrock falls). Once established, water stargrass plants propagate their own micro-environment for growth. The first initial colonizing plants take root, slowing nearby flows, increasing sedimentation, and allowing for new plants to expand outward from the initial plant colony edge margins (M. Appel, Benton CD, personal communication). Overtime the plant communities create localized conditions that are more favorable to propagate their own species' expansion. There is evidence that establishes a relationship between current velocity and plant growth in flowing waters for other macrophytes. For instance, a study of macrophytes in two slow flowing rivers in western Canada showed that biomass decreased with increasing current velocity between 0.01 – 1 m/s and at velocities over 1 m/s aquatic macrophytes were rare (Chambers and others, 1991). Their results indicated that current velocity is an important factor in regulating macrophyte biomass and that even modest increases in velocity reduces abundance of submerged macrophytes. Investigating the thresholds at which in-stream velocities limit water stargrass growth would be helpful in identifying management options to leverage velocities for plant control.

By superficially creating higher velocity flows in targeted priority areas (e.g., migration corridors, spawning habitats, etc.) we may be able to disrupt or moderate plant growth in the lower Yakima River. This could be done with instream structures at critical areas designed to increase river velocity. Areas with higher flow velocities could have additional benefits for fish and dissolved oxygen concentrations. Research would need to be done to determine what velocities are necessary to restrict biomass growth and abundance in the Yakima River. Lastly, it should be noted that islands within the river are already naturally accruing as a result of heavy sedimentation from water stargrass biomass. Water stargrass may already be shifting the current edge margins of the river farther out into the mainstem channel. It remains to be seen what impact these newly formed islands and expanding riparian areas will have on the lower river system. Monitoring the already occurring changes to the instream channel geomorphology and the resulting impacts to flow velocities as a result of abundant macrophyte growth is highly recommended.

4.0 Summary

Multiple mitigation techniques, as presented within this report, will be necessary to combat and effectively reduce water stargrass abundance in the lower Yakima River. The combination of treatments for mitigation will need to consider the specific goals for removal, available budget, along with the likely duration of the applied treatment. Decisions regarding treatment timing will also need to be made so as to minimize the impact to irrigation/agriculture, recreation, and fish migration/spawning windows. Some treatments may be better suited for small-scale applications while others may optimize removal on a reach scale. For instance, hand-pulling and installation of weed barriers are relatively cheap, easy to permit and are likely to be effective for small area clearings. Hand-pulling (with or without application of weed barriers) may be utilized in clearing small side-channels, or in locations where small private irrigators need to keep the bed clear for appropriate function of their fish screens. Hand-pulling is not feasible on a larger scale as it is time intensive, often requiring a crew of several people over the course of multiple days to weeks depending on the treatment area size. In areas requiring larger scale treatment, options such as harvesters, mailbox blowers and/or UV light treatments may be more costly upfront, but provide greater treatment coverage in less time. Mailbox blowers and harvesters fitted to pull the plant from the roots may have an added advantage of improving the sediment bed, clearing away fines that may impede spawning in the lower river. Furthermore, these larger scale techniques may also improve dissolved oxygen levels, if the removal area of biomass is significant. Trial removal treatments with a harvester that has both a cutter head and rolling drum head will be pilot tested in the lower Yakima in 2022 by the Benton CD. Monitoring the impacts of the harvesting application (e.g., plant regrowth time, dissolved oxygen levels, velocity, etc.) may help refine future mechanical options for large-scale removal efforts. While useful for larger areas, these techniques will be challenging to implement in shallower areas or areas without adequate boat access. Mechanical harvesters come in many sizes with various options and features, and a second smaller machine may be needed to clear areas that are otherwise inaccessible to large machines. Lastly, the required frequency of treatments and timing will need to be ascertained by monitoring plant regrowth. It is likely multiple treatments will need to occur within a season if using mechanical removal methods.

Of the herbicide and chemical control methods researched, only endothall, imazamox, carfentrazone-ethyl, and fluridone remained as potential treatment candidates. Of these, endothall and imazamox provided the greatest promise for chemical control, though each has potential drawbacks for application in the lower Yakima River. Endothall is a fast-acting contact herbicide and is labeled specifically for control of water stargrass. However, in two separate studies it did not significantly reduce water stargrass abundance in flowing water. Imazamox is a fast-acting systemic herbicide and is labeled specifically for control of water stargrass, so it should kill the entire plant. However, due to irrigation restrictions its application would be restricted to a very brief period in the late winter. There may be potential to couple water level drawdown with herbicide treatment timings during periods when fish are least likely to be in the lower river (>74°F). This would allow for the application of chemical treatments that are not as effective in flowing waters to be applied to water stargrass beds that become floating or emergent with the drawdown. Another promising coupling of techniques is the utilization of bubble curtains in conjunction with chemical treatment application. Recent studies on the Columbia River using a combination of bubble curtains and herbicide application have shown promise in the treatment of flowering rush. In this context, bubble curtains work by extending the contact time of the chemical application within the treatment area by decreasing mixing with the larger river. This method has the potential to either exclude an area for treatment or protect an area (e.g., irrigation intakes) depending on how the bubble curtain is deployed. Trial studies should be conducted before any chemical treatments are used to determine their effectiveness on water stargrass, as well as the application rates and contact times required to be effective at the flow rates observed in the lower Yakima. While chemical control treatments may have utility, especially when coupled with other methods, there are additional considerations to ensure safety to local end users as well as to native fish populations. As the Yakima River is the primary source of local irrigation water, utilization of chemical control methods must be must done in such a way as to not impact local crops and agriculture. Furthermore, the lower Yakima is heavily used for recreational sports and enjoyment, so considerations must be made for protection of public health.

Watershed control methods, such as flow management, velocity enhancers, and sedimentation, are less tried-and-true methods for plant control, may be costly, and will require extensive coordination in the basin. However, they should not be discounted simply because of these aspects. There may be great opportunity to pilot test these novel techniques in the lower Yakima River, especially since the benefits gained in plant biomass control may be significant on a larger reach scale. Furthermore, watershed control methods may have added side benefits for native fish and habitat that are inherently coupled with the treatment method. For instance, timed turbidity releases in the late spring and/or increased sustained flows may aid in fishery goals for juvenile out-migrants. Also, late spring water releases that slowly decrease in volume have added benefit in support of cottonwood recruitment throughout the lower basin. Development of possible watershed control techniques to enhance velocity such as artificial islands may create added habitat. All watershed control techniques will require more research regarding their potential applications and feasibility, as well as coordinated discussions with basin-wide partners.

The impact of water stargrass on native migratory fish species in the lower Yakima River is multi-faceted and complex. As such, combating the challenge of abundant macrophyte growth in the lower Yakima River will require the integration of multiple management techniques, likely at different times throughout the plant's life cycle, in order to effectively combat the problem. Over the last 20 years, we have seen a near total loss of fall Chinook spawning grounds from Prosser to the confluence with the Columbia River as a result of water stargrass spread within the lower river. Moreover, recent work by USGS (2018 – 2020) indicates water stargrass in the lower river is a driver of daily swings in dissolved oxygen levels, with night time levels falling below the Washington State surface water quality standard of >8.0 mg/L. Water stargrass is also implicated as having a potential net beneficial effect for non-native predator fish species over natives. McMichael (2017) surmises that the combination of decreased dissolved oxygen, increased pH, elevated water temperatures, and dense stands of macrophytes may provide more suitable habitat for non-native predator species such as smallmouth bass and walleye. Dense stands of water stargrass may also serve as refuge for small predator species, which may be increasingly recruited during years when water stargrass abundance is elevated. If we are to preserve our river and fully realize our salmon recovery efforts and goals, it will be critical to develop an integrated management plan utilizing several of the methods outlined within this review to help combat and mitigate water stargrass growth in the lower Yakima River.

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Appendix A. Rejected Chemical Controls

Table 2. Summary of rejected chemical control alternatives for water stargrass in the lower Yakima River

Method	Likely Work Window	Effectiveness for Water Stargrass	Advantages	Disadvantages	Permit Required	Notes
Chemical Treatments – Rejected from further consideration						
2,4-D (Aqua-Kleen®, Navigate®)	N/A	N/A	● N/A	● 2,4-D ester cannot be used in salmon-bearing waters ● Cannot be applied to waters used for irrigation, agricultural sprays, watering dairy animals, or domestic water supplies	N/A	Not considered further
Aminopyralid (Milestone®)	N/A	N/A	● N/A	● Not labeled for in-water use	N/A	Not considered further
Bispyribac-sodium (Tradewind™ Aquatic Herbicide)	N/A	N/A	● N/A	● Requires very long contact times, so not labeled for use in flowing water	N/A	Not considered further
Diquat (Reward® Landscape and Aquatic Herbicide)	Jul 15–Sep 1	N/A	● N/A	● 5-day irrigation restriction; application during irrigation intake period is not feasible ● Toxic to some aquatic animals; application restricted to timing window	N/A	Not considered further
Florpyrauxifen-benzyl (Procellacor™)	N/A	N/A	● N/A	● Cannot be applied to rivers for management of non-invasive plants	N/A	Not considered further
Flumioxazin (Clipper™)	N/A	N/A	● N/A	● Label does not allow for usage in rivers	N/A	Not considered further

Method	Likely Work Window	Effectiveness for Water Stargrass	Advantages	Disadvantages	Permit Required	Notes
Glyphosate (Rodeo®, Pondmaster®)	N/A	N/A	- N/A	- Not effective for submersed plants	N/A	Not considered further
Imazapyr (Arsenal™, Habitat)	N/A	N/A	- N/A	- Not effective for submersed plants	N/A	Not considered further
Penoxsulam (Galleon SC™)	N/A	N/A	- N/A	- Requires very long contact times, only labeled for use in very slow-moving water	N/A	Not considered further
Topramezone (Oasis®Aquatic Herbicide)	N/A	N/A	- N/A	- Requires very long contact times which would extend into irrigation season - Irrigation use not allowed during treatment time	N/A	Not considered further
Triclopyr TEA (Garlon® 3A, Renovate®)	N/A	N/A	- N/A	- The only formulation approved for use in unimpounded rivers contains 2,4-D amine, which cannot be applied to waters used for irrigation - WSG is included on the label as a less susceptible species	N/A	Not considered further
Copper compounds	N/A	N/A	- N/A	- Toxic to fish & persistent in environment - Use not permitted in Washington	N/A	Not considered further

Method	Likely Work Window	Effectiveness for Water Stargrass	Advantages	Disadvantages	Permit Required	Notes
<u>Phosphorus sequestration products (alum, calcium, lanthanum clay, and iron)</u>	N/A	N/A	● Effective at removing phosphorus from the water column	● WSG most likely obtains phosphorus from river sediments ● Phosphorus concentrations in the Yakima River are already low ● Removed phosphorus would be immediately replaced from sources upstream	N/A	Not considered further