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Environmental Laboratory

Aquatic Plant Control Research Program

Flowering Rush Control in Hydrodynamic Systems

Part 2: Field Demonstrations for Chemical Control of Flowering Rush

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Abstract

A series of 10 water-exchange studies were conducted from 2019 to 2021 at two sites, Clover Island and Osprey Point, within the McNary Pool of the Columbia River on the Oregon-Washington border. Six of the studies incorporated a barrier curtain or bubble curtain, whereas the other four studies did not include any device to mitigate water exchange. Once annually, diquat aquatic herbicide was applied concurrently with rhodamine water tracing (RWT) dye at the Osprey Point site (2019–2021) to control flowering rush. An additional plot, Clover Island Reference, served as the nontreated control to the Osprey Point treatment plot. Pre- and posttreatment vegetation surveys were conducted in 2019, 2020, and 2021 to determine flowering rush control, treatment impacts to water quality, and nontarget species response. This study sought to (1) document the use of barrier curtains and bubble curtains as potential methods for reducing water exchange and increasing herbicide concentration exposure times within potential flowering rush treatment areas, (2) evaluate bulk water exchange and selective control of flowering rush under varying reservoir operations, and (3) use the results from these studies to provide guidance for managing submersed flowering rush infestations on the McNary Pool, Columbia River, and similar run-of-the-river impoundments.

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Preface

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The work was performed by the Aquatic Ecology and Invasive Species Branch (EEA), Ecosystem Evaluation and Engineering Division (EEED), ERDC-EL. The principal investigator of this work was Dr. Bradley T. Sartain (EEA). At the time of publication, Dr. Bradley Sartain was the acting branch chief; and Mr. Mark Farr was the division chief. The deputy director of ERDC-EL was Dr. Brandon J. Lafferty, and the director was Dr. Edmond J. Russo Jr.

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COL Christian Patterson was commander of ERDC, and Dr. David W. Pittman was the director.

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1 Introduction

1.1 Background

Flowering rush (*Butomus umbellatus* L.) is a particularly noxious aquatic plant that is dynamic in its ability to become well established in the littoral zones of both quiescent and flowing water systems. Once established, flowering rush can form dense monotypic stands that outcompete desirable native vegetation, limit recreational water use, reduce water flow, and negatively affect native fish species (Boutwell 1990; Parkinson et al. 2010). Since 2008, flowering rush has spread throughout the McNary Pool of the Columbia River on the Oregon-Washington border. The invasive plant was first reported in the upper portion of the reservoir at the mouth of the Yakima River in 2008. As of 2021, flowering rush has been documented in numerous locations within the reservoir, primarily small, isolated patches less than 1 ha* in size. Field observations indicate that most flowering rush populations in these isolated locations never break the water surface and remain submersed. In shallow areas (1–2 m), flowering rush grows in mixed stands with other aquatic species (e.g., milfoils [*Myriophyllum* spp.], elodea [*Elodea canadensis* Michx], and pondweeds [*Potamogeton* spp.]); however, in deeper waters (2–6 m) there is reduced competition from other aquatic plants. Potential impacts to salmonid fish species are a major concern because dense stands of flowering rush may physically block key migration routes and spawning habitat in tributary waters and may provide ambush cover for fish that prey on juvenile salmonids such as the northern pikeminnow (*Ptychocheilus oregonensis* Richardson) and northern pike (*Esox lucius* L). Northern pike have been confirmed as having serious predatory impacts on cutthroat (*Salmo clarki* Richardson) and bull trout (*Salvelinus confluentus* Suckley) in the Flathead River, Montana (Muhlfeld et al. 2008).

The dynamic reservoir system presents a complex matrix of management challenges with limited treatment options for controlling flowering rush—particularly using herbicides in short concentration and exposure time (CET) settings. Additionally, regulatory constraints concerning listed endangered salmonid species create narrow treatment timing windows and

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* For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52, https://www.govinfo.gov/content/pkg/GPO-STYLE-MANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

restrict control methods for submerged flowering rush. Although several environmental factors can affect herbicide performance (water temperature, target plant density, application rate, water quality, and turbidity), rapid dissipation of herbicide residues out of the treated areas is the primary cause of plant control failures in the field (Netherland et al. 1998). Therefore, to formulate an effective management strategy it is essential to understand the influences of water exchange and the dose-response relationship of select herbicides and individual plant species. The use of rhodamine water tracing (RWT) dye, an inert fluorescent tracer dye, has been instrumental in characterizing water exchange potentials in treatment sites. Prior RWT demonstrations have shown that once a chemical is applied to the water, residues often dissipate rapidly from the treatment area (Wersal et al. 2022; Sartain et al. 2023). Previous research has successfully used water exchange information from the field to develop herbicide CET relationships to predict plant control following herbicide exposure to target plants at various concentrations. This CET relationship has been established for several individual herbicides and target aquatic plant species (Getsinger and Netherland 1997). However, large reservoirs and flowing water systems that are subject to highly variable water-exchange conditions are hydrologically complex and present a challenge for the operational management of aquatic plant species using submersed herbicide applications. Management is more challenging when trying to control small, newly established populations that require spot treatments in larger water bodies (Getsinger et al. 1996) because water exchange may be too rapid to maintain effective herbicide concentrations in treatment areas.

Barrier curtains have successfully maintained adequate herbicide CETs for control of Eurasian water milfoil (*Myriophyllum spicatum* L.) in Fort Peck Lake, Montana (Pennington et al. 2015). Unfortunately, the installation of barrier curtains is labor intensive, time consuming, and susceptible to damage from wind and wave action. Bubble curtains, which produce a wall of bubbles by forcing air through perforated hoses, represent a possible alternative to barrier curtains (Zielinski et al. 2014). Bubble curtain technology has been evaluated as a potential tool to mitigate fish intrusion at power generation facilities (Taft 2000; Michaud and Taft 2000) and preventing/mitigating sedimentation (Sharp et al. 2012). Further, bubble curtains are relatively inexpensive, require minimal maintenance, and can be repositioned or removed if needed (Zielinski et al. 2014).

1.2 Objectives

This study sought to (1) document the use of barrier curtains and bubble curtains as potential methods for limiting water exchange to increase herbicide CETs within potential flowering rush treatment areas, (2) evaluate bulk water exchange and selective control of flowering rush under varying reservoir operations, and (3) use the results of these evaluations to provide guidance for managing submersed flowering rush infestations on the McNary Pool, Columbia River, and similar run-of-the-river impoundments.

1.3 Approach

A series of water-exchange studies were conducted from 2019 to 2021 at two sites, Clover Island and Osprey Point, within the McNary Pool of the Columbia River. In total, ten water-exchange evaluations were conducted; six incorporated a barrier curtain or bubble curtain, whereas the other four did not include any device to mitigate water exchange. Once annually, diquat (Reward, Syngenta Crop Protection LLC, Greensboro, North Carolina) aquatic herbicide was applied concurrently with RWT dye at the Osprey Point site to control flowering rush. An additional plot, Clover Island Reference, served as the nontreated control to the Osprey Point treatment plot. Pre- and posttreatment vegetation surveys were conducted in 2019, 2020, and 2021 to determine flowering rush control, treatment impacts to water quality, and nontarget species response to herbicide treatments.

2 Materials and Methods

2.1 Evaluation Site

The evaluation site was located on McNary Dam and Reservoir (Wallula Lake, 15,702 ha) located in the Columbia River Basin on the Oregon-Washington border in the Tri-Cities area of Washington State. From McNary Dam, the reservoir extends 105 km (65 miles) along the Columbia River, 16 km along the Snake River, and 9.7 km along the Yakima River. McNary is a run-of-the-river reservoir, and as such, acts as a hydrodynamic system with constantly flowing water.

2.2 Characterization of Study Plots

2.2.1 Clover Island

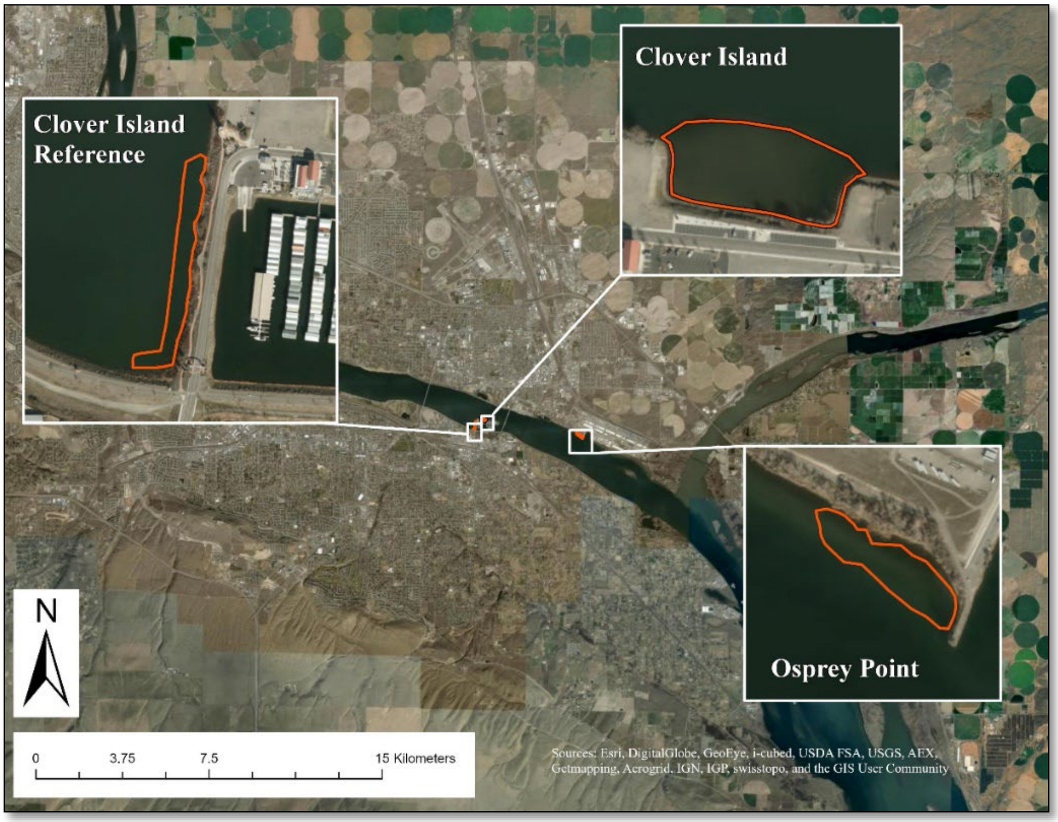
The Clover Island site (46°13′4.30″ N, 119°6′49.38″ W) was a small (0.73 ha), shallow engineered bay with an average depth of 1.3 m. It was located on the north side of Clover Island, which is a 6.5 ha, fully developed commercial property owned by the Port of Kennewick. The site was rectangular, bordered by land to the south, east, and west, and the Columbia River to the north (Figure 1). Depth within the site remained consistent (1–1.5 m) but gradually increased moving away from the site towards the main river channel. The site was heavily vegetated with elodea, coontail (*Ceratoyphyllum demersum* L.), water star grass (*Heteranthera dubia* [Jacq.] MacMill.), sago pondweed (*Stuckenia pectinata* [L.] Börner), clasping-leaf pondweed (*Potamogeton perfoliatus* L.), leafy pondweed (*Potamogeton foliosus* L.), and Eurasian watermilfoil. Sparsely established flowering rush was documented in several locations. Water-exchange data were only collected at Clover Island in 2019.

2.2.2 Osprey Point

The Osprey Point site (46°12′48.66″ N, 119°4′33.91″ W) was located just upstream from a loading dock at the Port of Pasco Industrial Park, Washington. The site was positioned along the shoreline of a narrow flat (average depth 1.7 m) that ran southeast to northwest paralleling the main channel of the Columbia River (Figure 1). The site was bordered by a riprap shoreline on the northern perimeter and a small peninsula on the downstream side that extended out into the river channel. The total area of the site was 1.7 ha (4.2 acres) and water depth increased quickly from

1.2 m along the shoreline to upwards of 3 m along the plot edge toward the main channel. The peninsula on the downstream end provided a current break that allowed multiple plant species to establish along the shoreline. Prior to treatment in 2019, flowering rush occupied 100% of the sampling site and was one of the largest stands of emergent and submersed growth flowering rush within McNary Reservoir. Additional plant species present included coontail, elodea, sago pondweed, curly leaf pondweed, Eurasian watermilfoil, and water star grass.

Figure 1. Location of study plots within the McNary Pool Columbia River, Tri-Cities, Washington.



2.2.3 Clover Island Reference

The Clover Island Reference site was a narrow (0.73 ha) plot positioned along a riprap shoreline on the western side of Clover Island. The average depth of the plot was 2.2 m (7.3 ft). Water depth adjacent to the shoreline was relatively shallow (approximately 1 m) and increased approximately 3–3.5 m near the western plot edge. Several aquatic plant species were documented growing at the site over the duration of the project. These species included flowering rush, coontail, water stargrass, elodea, Eurasian watermilfoil, white waterlily (*Nymphea odorata* Aiton), and several pondweed species. Plant density was highest in the shallower waters adjacent to the riprap shoreline, with more isolated plant stands observed at greater depths.

2.3 Water-Exchange Evaluations

RWT dye was used to assess water-exchange patterns within two of the three sites described in Section 2.2. The RWT dye resists absorption by plants and sediments (Smart and Laidlaw 1977; Turner et al. 1991, 1994), and has been used for dilution and time-of-travel studies in streams (Kilpatrick and Wilson 1989). Additionally, research has demonstrated significant correlations between dissipation patterns of aquatic herbicides and RWT fluorescent dye (Fox et al. 1991, 1992, 1993; Turner et al. 1994; Wersal and Madsen 2011). In the Pacific Northwest and other regions of the United States, RWT dye has also been commonly used in conjunction with herbicide treatments to gauge herbicide movement and dissipation within treated water columns (Fox et al. 1992; Turner et al. 1994; Getsinger and Netherland 1997; Getsinger et al. 2000; Poovey et al. 2004; Getsinger et al. 2013). RWT dye data collected during each of the evaluations described in the subsequent sections were subjected to a nonlinear exponential decay regression analysis using SigmaPlot 11.0 statistical software (Systat Software, San Jose, California) to calculate a whole-plot dye half-life.

2.4 Herbicide Treatments

Diquat (Reward) was applied at the Osprey Point site (1.7 ha) in 2019, 2020, and 2021. To provide a real-time estimate of water-exchange processes within the site, RWT dye was tank mixed and applied simultaneously. These data were used to estimate diquat exposure to flowering rush stands, draw comparisons to previous water-exchange evaluations, and associate water-exchange and herbicide-efficacy data for managing flowering rush. Diquat was applied as a subsurface injection at the maximum labeled rate of 18.7 L per ha (2 gal. per surface acre). Total product applied to the site during each treatment was 31.8 L (8.4 gal.). Like the water-exchange evaluations previously described in Section 2.3, RWT dye was applied to achieve a nominal aqueous concentration of 10 µg L^{-1}. RWT dye data collected during each of the herbicide treatments, described in the sections that follow, were subjected to a nonlinear exponential decay regression analysis using SigmaPlot 11.0 statistical software (Systat Software, San Jose, California) to calculate a whole-plot dye half-life.

2.5 Vegetation Assessments

Prior to the initial herbicide application in 2019, a point intercept survey was conducted on 29 July 2019 to assess the plant community at the Osprey Point treatment site and Clover Island Reference site (Figure 1). Point intercept survey methods were similar to those used during other projects in the Pacific Northwest (Madsen and Wersal 2009; Wersal et al. 2009, 2010; Madsen et al. 2015; Sartain et al. 2022; Wersal et al. 2022) and are considered standard for this type of project (Madsen and Wersal 2017). A total of 19 points were surveyed at each site. The initial 2019 assessment was identified as the pretreatment, 0 weeks after treatment (WAT) sampling period. Posttreatment surveys were conducted on 28 August 2019 (4 WAT), 3 October 2019 (8 WAT), and 17 October 2019 (10 WAT) to assess short-term treatment efficacy on flowering rush, in addition to selectivity on the native plant community. Additionally, pre- and posttreatment assessments were performed in 2020 and 2021 and are given in Tables 1 and 2.

Vegetation surveys were conducted by boat, and navigation to each point was done using the ArcGIS Field Maps app (Esri, Redlands, California) on an iPhone XR (Apple Inc., Cupertino, California) or a Lowrance HDS12 (Navico Group, Mettawa, Illinois) chart-plotter with an internal GPS receiver. Survey accuracy was 1–5 m depending on satellite reception. At each survey point, a weighted thatch rake was deployed (directly off the side of the boat) to determine the presence of plant species. Spatial data (plant presence/absence) were recorded electronically in the ArcGIS Field Maps Application or manually recorded onto data sheets. Electronically collected data were recorded in feature class attribute templates in ArcGIS Field Maps that were constructed exclusively for this project using ArcGIS Pro and ArcGIS online software (Esri, Redlands, California). Data records were automatically synced (at 15 min intervals) to the virtual data cloud.

Table 1. Percent frequency of occurrence of plant species reported during pre- and posttreatment aquatic vegetation assessments at the Osprey Point Treatment Plot.

Common Name	Species	Status[a]	Pretreatment 29 July 2019	4 WAT 28 Aug. 2019	8 WAT 3 Oct. 2019	10 WAT 17 Oct. 2019	1 YAT[b] 23 July 2020	4 WAT 26 Aug. 2020	10 WAT 13 Oct. 2020	2 YAT[b] 27 July 2021	6 WAT 20 Sept. 2021
			Frequency of Occurrence (%)								
Flowering rush	*Butomus umbellatus*	E	100	100	56	53	90	90	63	84	58
Coontail	*Ceratophyllum demersum*	N	32	26	42	68	16	74	47	26	26
Water stargrass	*Heteranthera dubia*	N	37	10	37	23	63	42	47	21	74
Elodea	*Elodea canadensis*	N	63	42	47	58	84	63	74	37	37
Eurasian watermilfoil	*Myriophyllum spicatum*	E	58	16	11	11	11	26	58	32	47
White water lily	*Nymphoides odorata*	N	0	0	0	0	0	0	0	0	0
Curly leaf pondweed	*Potamogeton crispus*	E	53	21	11	16	21	5	5	16	5
Clasping leaf pondweed	*Potamogeton perfoliatus*	N	5	5	16	16	5	26	11	16	5
Leafy pondweed	*Potamogeton foliosus*	N	53	16	0	0	16	42	0	84	0
White stem pondweed	*Potamogeton praelongus*	N	0	0	5	0	0	0	0	26	26
American Pondweed	*Potamogeton nodosus*	N	0	0	0	0	0	5	0	0	0
Flatstem pondweed	*Potamogeton zostraformis*	N	0	0	0	0	0	5	5	5	0
Sago pondweed	*Stuckenia pectinata*	N	0	0	0	0	0	0	0	0	0

[a] E = Exotic/nonnative species; and N = native species.

[b] YAT = Year after treatment.

Table 2. Percent frequency of occurrence of plant species reported during aquatic vegetation assessments at the Clover Island Reference Plot.

Common Name	Species	Status[a]	Pretreatment 29 July 2019	4 WAT 28 Aug. 2019	8 WAT 3 Oct. 2019	10 WAT 17 Oct. 2019	1 YAT 23 July 2020	4 WAT 26 Aug. 2020	10 WAT 13 Oct. 2020	2 YAT 27 July 2021
			Frequency of Occurrence (%)							
Flowering rush	*Butomus umbellata*	E	53	58	16	0	26	68	11	46
Coontail	*Ceratophyllum demersum*	N	53	53	68	53	16	79	90	14
Water stargrass	*Heteranthera dubia*	N	32	42	58	42	21	59	53	14
Elodea	*Elodea canadensis*	N	48	42	74	63	58	63	90	0
Eurasian watermilfoil	*Myriophyllum spicatum*	E	16	5	5	0	68	32	37	0
White water lily	*Nymphoides odorata*	N	5	5	0	0	5	0	0	5
Curly leaf pondweed	*Potamogeton crispus*	E	26	21	5	5	16	47	26	0
Clasping leaf pondweed	*Potamogeton perfoliatus*	N	0	0	5	5	0	5	0	0
Leafy pondweed	*Potamogeton foliosus*	N	21	11	0	0	0	0	0	5
White stem pondweed	*Potamogeton praelongus*	N	0	0	0	0	0	0	0	0
American Pondweed	*Potamogeton nodosus*	N	0	0	0	0	0	0	0	0
Flatstem pondweed	*Potamogeton zostraformis*	N	21	21	11	0	37	0	0	0
Sago pondweed	*Stuckenia pectinata*	N	5	5	0	0	5	32	5	0

[a] E = Exotic/nonnative species; and N = native species.

3 Field Demonstrations 2019

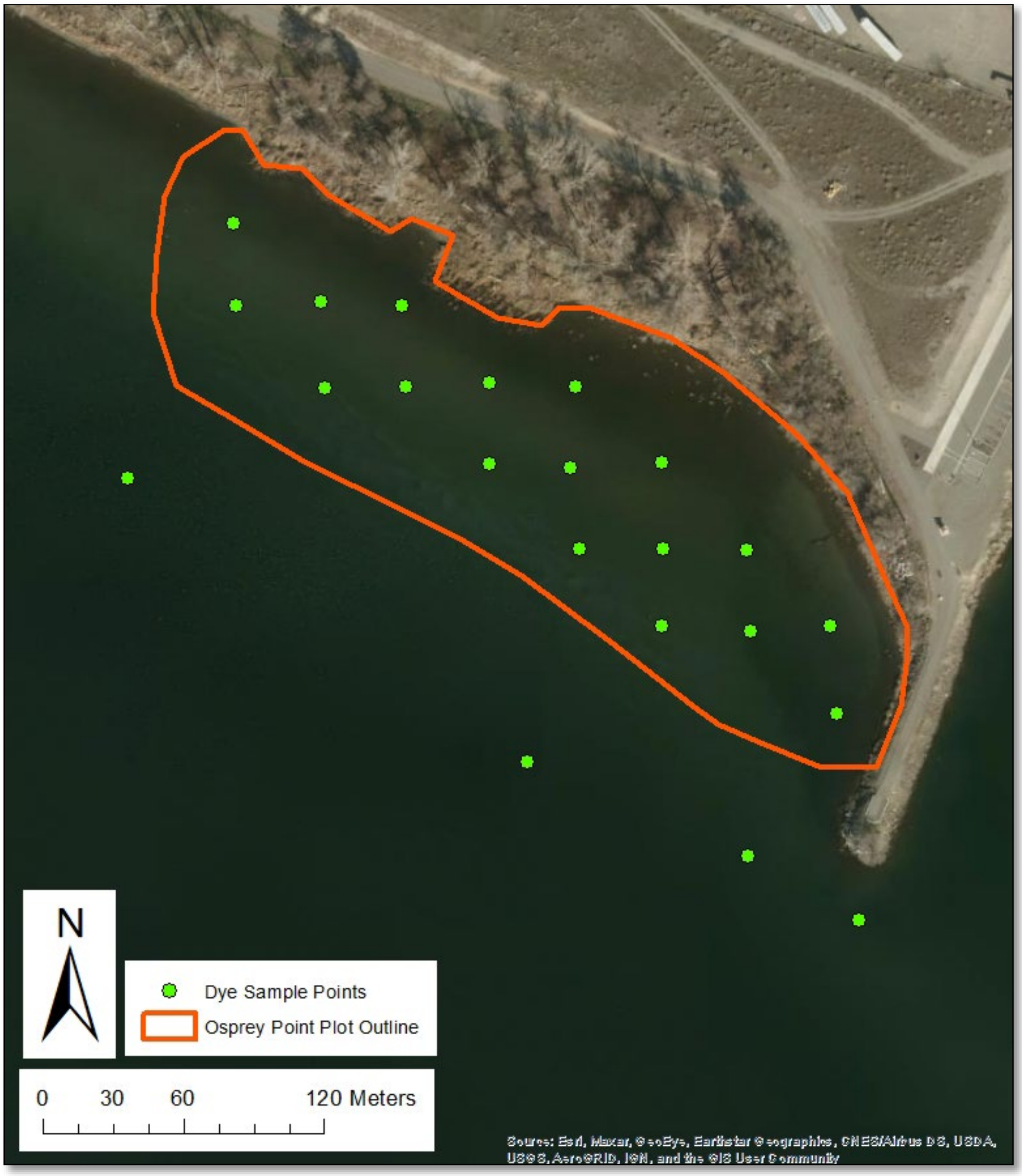
3.1 Water Exchange

Five water-exchange evaluations were conducted at the Osprey Point site in 2019. The first evaluation was conducted without the use of a bubble curtain, while the other evaluations were conducted with BubbleTubing (Canadianpond.ca Products, Montreal, Canada). BubbleTubing is a flexible, durable, linear-aeration 2.54 cm inside diameter (ID) tubing equipped with two rows of perforated holes, spaced 1.27 cm apart that span the entire length of the tubing. BubbleTubing (hereafter referred to as bubble curtain) is weighted with a solid-core ballast along its entire length, allowing it to sink and remain in place along the river bottom. Each bubble curtain evaluation used one or two Doosan HP375 (Doosan Group, Seoul, South Korea) diesel air compressors (375 ft^3/min, 150 psi [10.62 m^3/min, 1,034.21 kPa]) pressure rating to deliver a continuous stream of air. The mainline from each compressor was fitted to a six-valve manifold equipped with a pressure gauge and bleeder valve. Because of the size of the demonstration plot and limitations on the length of bubble curtain [122 m (400 ft)] that could be powered from a single manifold valve, multiple segments of bubble curtain had to be strategically arranged to ensure even and adequate air flow throughout each line. A more detailed explanation for each bubble curtain configuration and RWT dye application is provided in the subsections below.

3.1.1 No Bubble Curtain

RWT dye was applied on the morning of 23 July 2019 (start: 0835 hours, end: 0847 hours) under favorable weather conditions (water and air temperatures 20°C and 80°C, respectively) with south-southwest winds at 8–16 kmh (5–10 mph). Immediately following application, dye concentrations were measured at 1/3 and 2/3 depth of the water column using a Turner Designs Databank handheld data logger equipped with a Cyclops-7F sensor with Rhodamine WT optics (Turner Designs, Sunnyvale, California) at 18 predetermined sampling points evenly distributed throughout the plot. Dye sampling points were also established outside the plot to track dye dissipation from the treatment area (Figure 2). Measurements were taken at 0.5, 3, 6, and 8 hours after treatment (HAT). Total water discharge and forebay elevation (EL) at McNary Dam was 144.10 thousand cubic feet second (KCFS) and 339.40 EL at 0800 hours.

Figure 2. Outline of Osprey Point study plot with rhodamine water tracing (RWT) dye sampling points. Direction of river flow is Northwest to Southeast.



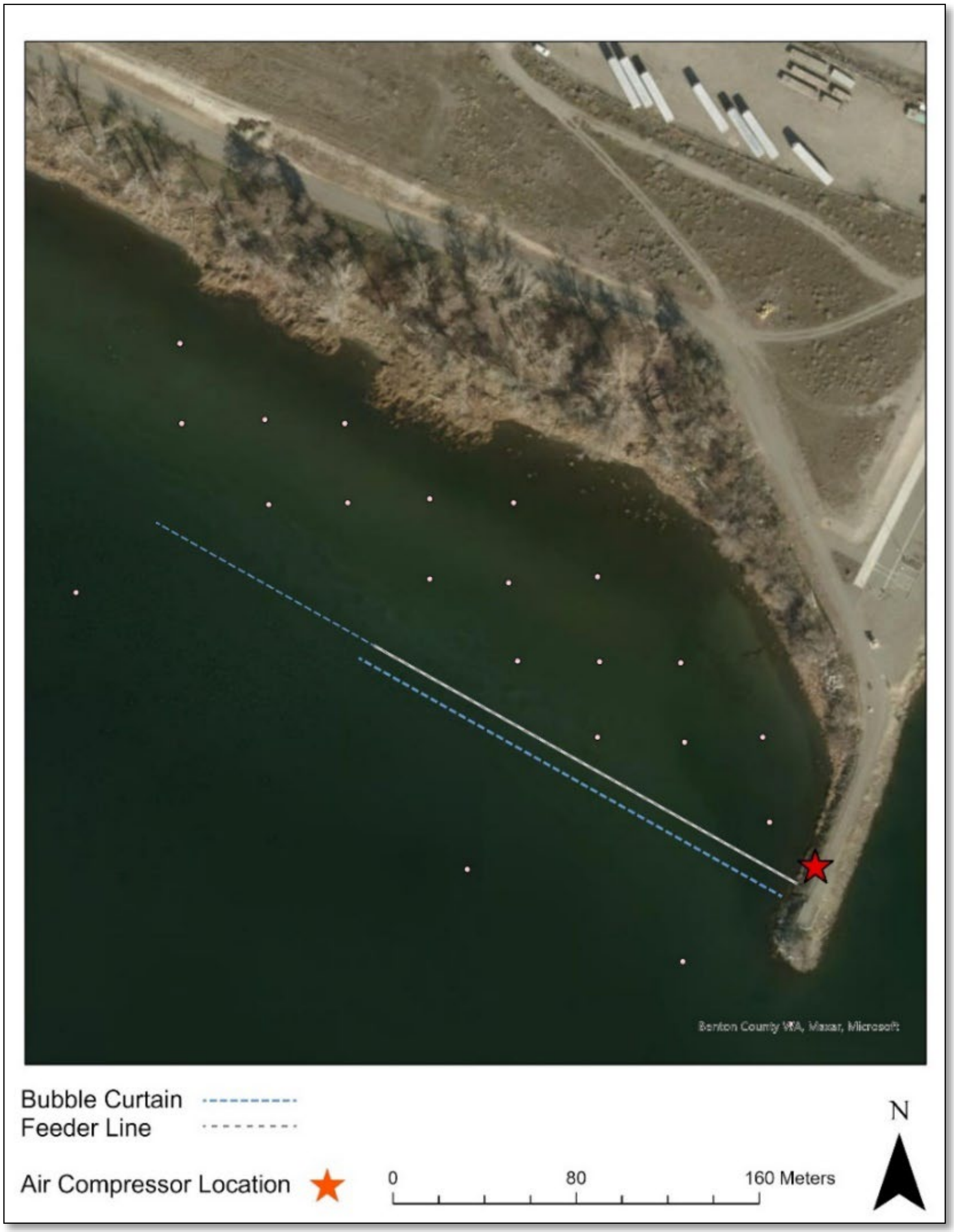
Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

3.1.2 Bubble Curtain Evaluation #1 (Single Curtain)

Two sections of bubble curtain, 115 and 91 m total length, were used for bubble curtain evaluation #1 on 24 July 2019. The curtain was powered by a single Doosan HP375 diesel powered air compressor stationed on a small peninsula that extended toward the main river channel, which made up the downstream shoreline of the plot. A heat resistant 1.9 cm ID hose affixed to the compressor was fitted to a six-valve manifold equipped with a pressure gauge and bleeder valve (Figure 3). Two feeder lines (2.54 cm ID) were connected to the six-valve manifold and used to join each bubble curtain segment. Prior to joining each feeder line and bubble curtain segment, a one-way flow valve was installed to prevent back flow of water from the curtain segment into the feeder line. One feeder line joined the 115 m curtain segment at the water's edge, whereas the second feeder line extended into the water, parallel to the 115 m curtain segment, and connected to the 91 m curtain segment at the termination point of the 115 m segment. This provided a "single" bubble curtain arrangement that extended from the downstream shoreline of the demonstration plot 206 m upstream (Figure 4). RWT dye was applied 24 July 2019 (start: 0820 hours, end: 0850 hours) under clear skies with a strong west-northwest wind blowing into the treatment area at 32–40 kmh (20–25 mph). Dye measurements were collected at 0, 1, and 3 HAT using the same methodology previously described. Total water discharge and forebay elevation at McNary Dam was 149.8 KCFS/339.36 EL and 146.5 KCFS/339.37 EL at 0900 and 1200 hours, respectively.

Figure 3. Six-valve manifold equipped with a pressure gauge and bleeder valve that provided constant air flow throughout each bubble curtain during the water exchange studies at Osprey Point in 2019.

Figure 4. Arrangement of the single bubble curtain #1 at the Osprey Point Study Plot on 24 July 2019. Direction of river flow is northwest to southeast.

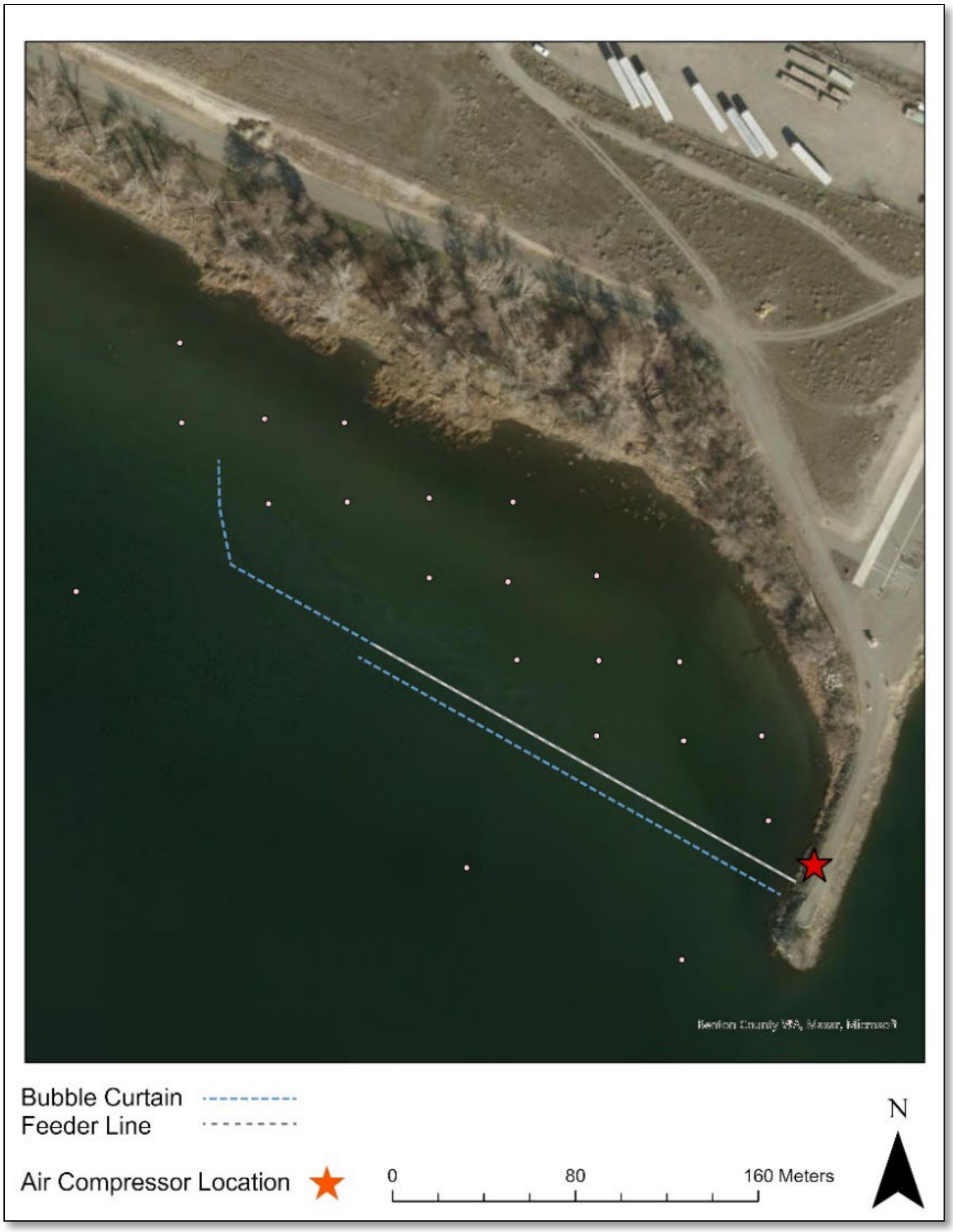


Benton County WA, Maxar, Microsoft

3.1.3 Bubble Curtain Evaluation #2 (Single Curtain)

Bubble curtain evaluation #2 was conducted 25 July 2019 using the same materials and methods as evaluation #1; however, the curtain was arranged so that the 91 m section was angled towards the shoreline in a “dog leg” orientation (Figure 5). It was hypothesized that this arrangement may divert the river current away from the treatment plot and back toward the main river channel. RWT dye was applied 25 July 2019 (start: 1005 hours, end: 1040 hours) under clear skies and calm winds (0–4.8 kmh). Dye measurements were collected at 0, 1, and 3 HAT using the same methodology described in the previous section. Total water discharge and forebay elevation at McNary Dam was 157.9 KCFS/339.57 EL and 161.2 KCFS/ 339.32 EL at 1000 and 1400 hours, respectively.

Figure 5. Arrangement of the single bubble curtain #2 at the Osprey Point Study Plot on 25 July 2019. Direction of river flow is northwest to southeast.

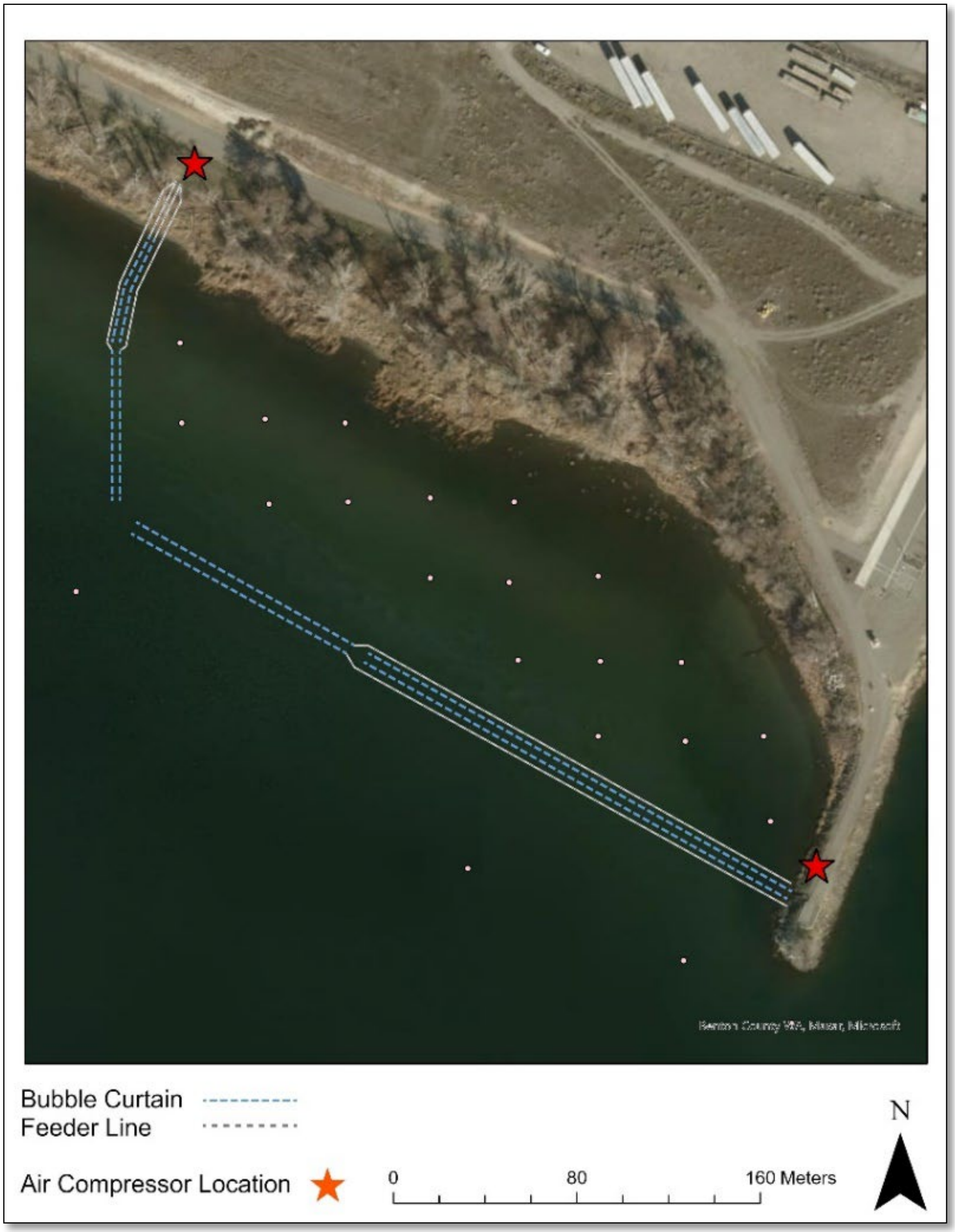


3.1.4 Bubble Curtain Evaluation #3 (Double Curtain)

Bubble curtain evaluation #3 was conducted on 26 July 2019 and consisted of a double curtain arrangement that enclosed the entire treatment plot. This required two Doosan HP375 diesel powered air compressors positioned on the upper and lower end of the treatment plot (Figure 6). One double curtain extended from the small peninsula on the lower end of the plot and ran parallel to the main river channel. Like the previous evaluations, heat resistant 1.9 cm ID hose affixed to the compressor was fitted to a six-valve manifold equipped with a pressure gauge and bleeder valve (see Figure 3). Four feeder lines (2.54 cm ID) were connected to the six-valve manifold and used to join each bubble curtain segment. Prior to joining each feeder line and bubble curtain segment, a one-way flow valve was installed to prevent back flow of water into the feeder line. Two of the four feeder lines were connected to each 115 m curtain segment at the water edge. Two additional feeder lines extended into the water and ran parallel to each 115 m curtain segment and were connected to a pair of 91 m curtain segments at the termination of the 115 m segments. This provided the double curtain arrangement that extended from the downstream shoreline of the demonstration plot 206 m upstream. The second compressor, positioned at the upper end shoreline of the plot, was rigged in the same manner as the first compressor. A section of the heat resistant, 1.9 cm ID hose was affixed to the compressor and fitted to a six-valve manifold equipped with a pressure gauge and bleeder valve. Four feeder lines (2.54 cm ID) were connected to the six-valve manifold and used to join each bubble curtain segment. Prior to joining each feeder line and bubble curtain segment, a one-way flow valve was installed to prevent back flow of water into the feeder line. Two of the four feeder lines were connected to 61 m curtain segments at the water edge. Two additional feeder lines extended into the water and ran parallel to each 61 m bubble curtain segment and connected a pair of 76 m curtain segments at the termination of the 61 m segments.

RWT dye was applied 26 July 2019 (start: 0945 hours, end: 1015 hours) under clear sunny skies and light winds from the east at 1.6–4.8 kmh (1–3 mph). Dye measurements were collected at 0.5, 1.5, and 3 HAT using the same methodology described in the previous sections. Because of boat complications at the 3 HAT sampling interval, only seven points on the lower end of the plot were sampled. Total water discharge and forebay elevation at McNary Dam was 151.2 KCFS/ 339.77 EL and 146.8 KCFS/ 339.61 EL at 1000 and 1300 hours, respectively.

Figure 6. Arrangement of the double bubble curtain at the Osprey Point Study Plot on 26 July 2019. Direction of river flow is northwest to southeast.



3.1.5 Barrier Curtain Assessment at Clover Island 2019

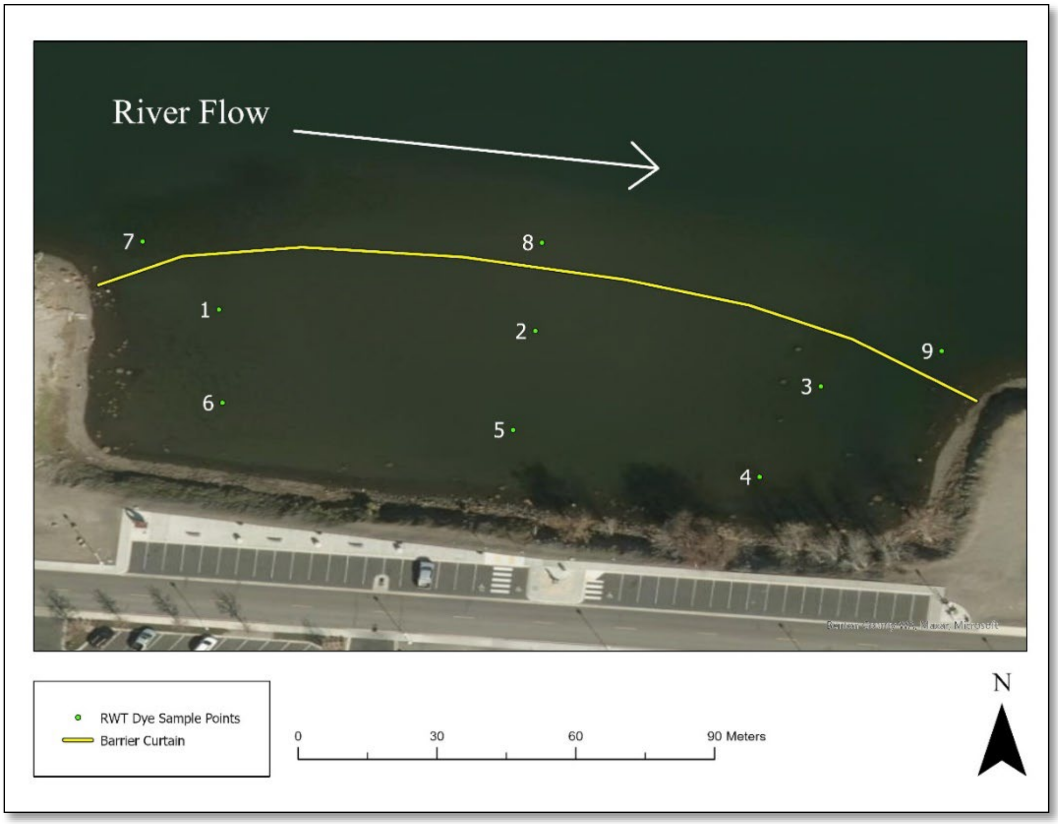
A barrier curtain was installed to evaluate the efficiency at decreasing bulk water exchange and draw comparisons to water-exchange data previously collected, with and without a bubble curtain, at the Clover Island site in

2018 (Sartain et al. 2022). The curtain (DOT Medium Duty/Moving Water Turbidity Curtain, Enviro-USA, Cape Canaveral, Florida) consisted of nine 15.2 × 4.5 m deep sections. When connected, the total curtain length was 136.8 m. The top of the curtain was buoyed with microfoam floatation devices while the bottom was weighted with a galvanized chain ballast. The curtain was anchored on the upstream side of the plot, towed downstream by boat, and anchored at the opposite downstream end of the plot (Figure 7). To stabilize the curtain, Danforth-style anchors were deployed at 30 m intervals along the curtain.

Figure 7. Barrier curtain deployed at the Clover Island study plot 29 July 2019.

RWT dye was uniformly applied throughout the water column using a boat-mounted spray boom affixed with eight equally spaced weighted hoses on the morning of 30 July 2019 (start: 0515 hours, end: 0534 hours) to achieve an aqueous target concentration of 10 µg L^{-1}. Weather conditions at the time of treatment were favorable with clear skies and southwest winds 9.6–11.2 kmh. Immediately following application, dye concentrations were measured using a handheld Turner Designs field fluorometer (Turner Designs, Sunnyvale, California) at 1/3 and 2/3 water column depths at nine predetermined sampling locations (six locations within the barrier curtain and three locations outside the barrier curtain) (Figure 8). Measurements were taken immediately after treatment (0) and at 1, 3, 6, 9, 12, 24, 27, 33, and 48 HAT. Total water discharge at McNary Dam was 131.8 KCFS at treatment and fluctuated between a minimum and maximum discharge of 130.4 and 215.4 KCFS, respectively, throughout the duration of the study. Total outflow from Priest Rapids Dam on the upstream end of the McNary Pool was 76.5 KCFS at treatment and fluctuated between a minimum and maximum discharge of 60.5 and 168.9 KCFS, respectively, throughout the duration of the study.

Figure 8. RWT dye sampling points within and outside the barrier curtain deployed at Clover Island site in 2019.

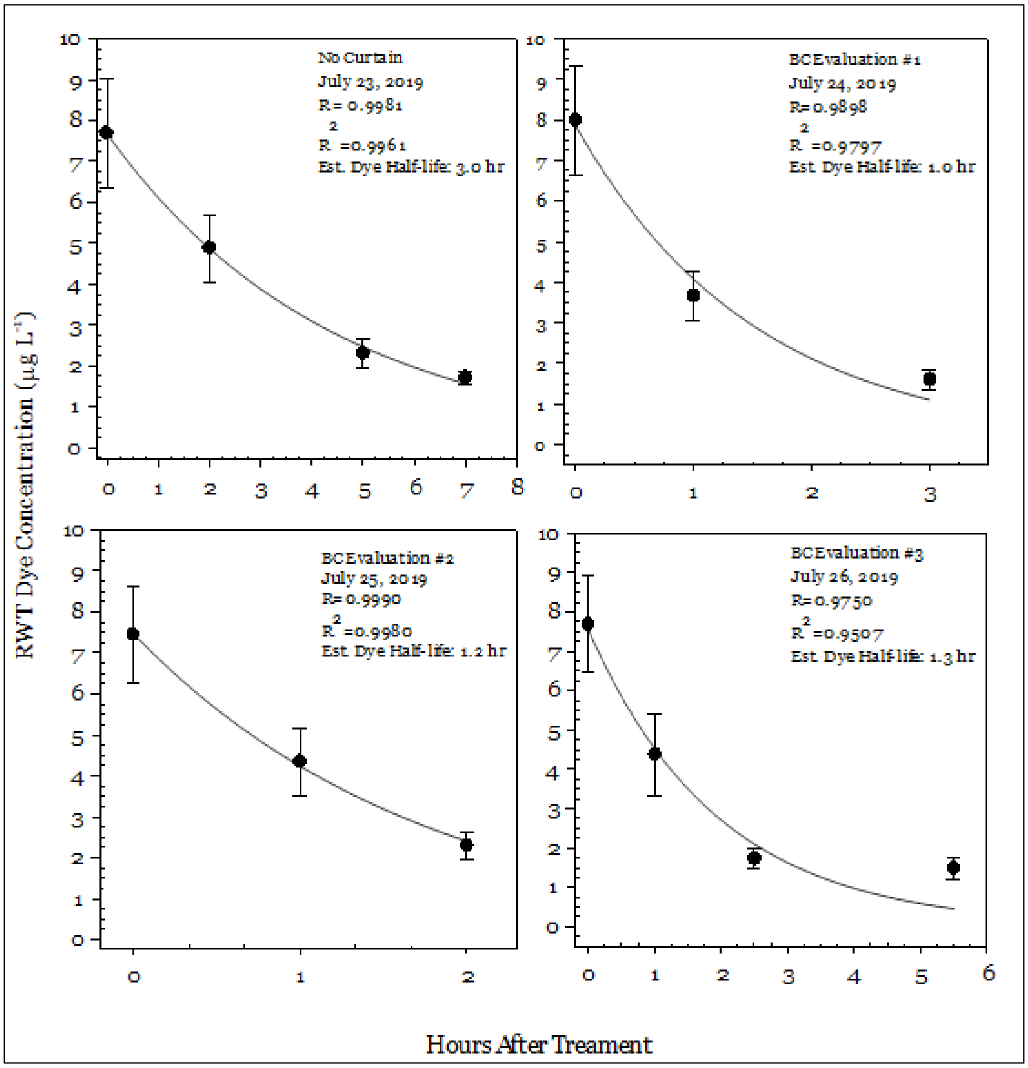


3.2 Water Exchange 2019: Results and Discussion

3.2.1 Bubble Curtain Evaluations

The utilization of bubble curtains at Osprey Point did not lead to a substantial reduction in bulk water-exchange processes within the treatment site when compared to the no curtain assessment. Bubble curtain evaluations 1, 2, and 3 resulted in RWT dye half-lives of 1, 1.2, and 1.3 hours, respectively, whereas no curtain resulted in an estimated RWT dye half-life of 3 hours (Figure 9). Mean (±SE [standard error]) RWT dye concentrations 0 HAT were similar for each water-exchange demonstration and ranged between 7.4 ± 1.2 and 7.9 ± 1.3 µg L^{-1}. The rate of water exchange reported from each bubble curtain evaluation closely aligned with previously collected water-exchange data at the site in 2018 where a 1.3-hour dye half-life was reported (Sartain et al. 2022).

Figure 9. RWT dye dissipation during each water-exchange evaluation at the Osprey Point site in 2019. Dye dissipation and dye half-life was estimated using nonlinear regression (exponential decay, $f = a \exp[-b\,x]$).



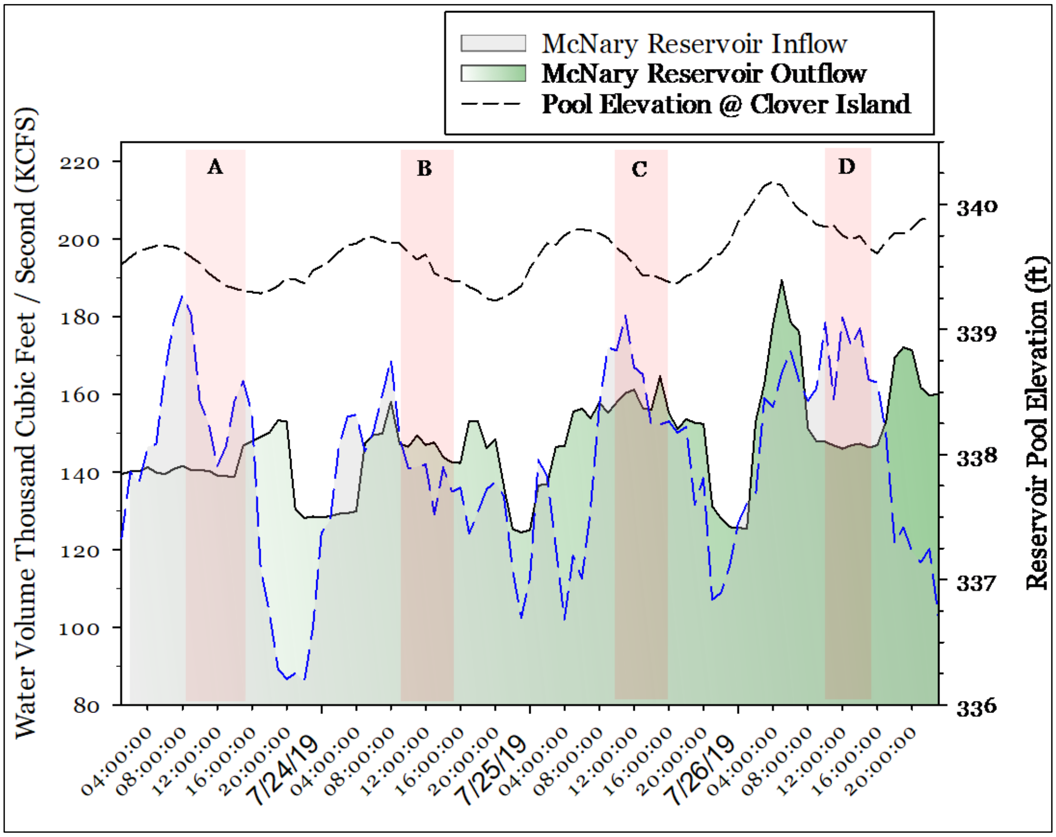
Dye concentrations measured 1 HAT for each bubble curtain evaluation decreased immediately following dye application (0 HAT) by 53%, 41%, and 43% for evaluations 1, 2, and 3, respectively. In contrast, dye concentrations with no bubble curtain were estimated to decrease only 21% from 0 to 1 HAT and 37% from 0 to 2 HAT. Overall, dye dissipation followed a similar pattern for all water-exchange evaluations at Osprey Point. As expected, downstream portions of the plot maintained the highest dye concentrations for extended periods compared to upstream areas where dye dissipated most rapidly. As such, these water-exchange processes indicate that adequate control of flowering rush will likely be more difficult at the upstream end of the plot.

A thorough explanation as to why water exchange was less with no bubble curtain compared to each bubble curtain evaluation is challenging. Although each evaluation was performed at the same identical location, variations in water-exchange processes are driven by dam operations, which dictate the inflow and outflow of water from McNary Reservoir. The volume of water McNary Reservoir receives (i.e., inflow) is influenced primarily by water releases at Priest Rapids Dam and Ice Harbor Dam as well as inflows from small tributaries such as the Yakima and Walla Walla Rivers. Water flow rates also vary at different locations within the McNary Pool. In the more riverine section (north of I-81 to Priest Rapids Dam), water flow velocity averages approximately 8 kmh (5 mph), whereas the lower sections of McNary Pool have slower average flows of approximately 3.2 kmh (2 mph) (John Heitstuman, personal communication). Given the location of the Osprey Point study site, it is estimated that changes in dam operations at Priest Rapids Dam and Ice Harbor Dam require approximately 17–20 and 8 hours post dam release, respectively, before water flow and pool elevation changes are reflected (John Heitstuman, personal communication). Further, change in water discharge rates at McNary Dam may not be reflected at the study site for approximately 1.5–2 hours (John Heitstuman, personal communication).

Taking these water flow variables into account, Figure 10 shows McNary Reservoir inflow, outflow, and pool elevation at Clover Island (2.3 km upstream from study site) during each water-exchange evaluation. McNary Reservoir inflow was estimated using discharge data at Priest Rapids Dam, Ice Harbor Dam, and the Yakima River. Priest Rapids Dam discharge data are presented on an 18-hour time of travel (e.g., Priest Rapids Dam discharge on 24 July 2019 at 0100 hours is presented in Figure 10 at 24 July 2019, 1900 hours) while Ice Harbor Dam discharge is presented on an

8-hour time of travel. Water discharge at McNary Dam is presented on a 2-hour time of travel.

Figure 10. Inflow and outflow of water into McNary Reservoir and pool elevation at Clover Island gauge station. *Red transparent boxes* indicate the occurrence of a water-exchange evaluation for (*A*) no bubble curtain, (*B*) bubble curtain evaluation #1, (*C*) bubble curtain evaluation #2, and (*D*) bubble curtain evaluation #3. McNary Reservoir inflow is estimated based off discharge data at Priest Rapids Dam, Ice Harbor Dam, and the Yakima River. Priest Rapids, Ice Harbor, and McNary Dam discharge data are presented on an 18-, 8-, and 2-hour time of travel, respectively.



These data suggest the rates of water inflow and outflow were not synchronal across all water-exchange evaluations; however, pool elevation data indicates that each evaluation was somewhat synchronous as water levels declined based on the nearest pool elevation gauge 2.4 km (1.5 miles) upstream. Given the small size of the study site and the number of confounding variables that can ultimately affect water exchange, it is increasingly difficult to pinpoint a single factor that led to the no curtain evaluation to have less water exchange compared to each bubble curtain evaluation. However, these data provide valuable information and support findings from Wersal et al. (2022) that demonstrate exposure time of a submersed herbicide treatment can be maximized if treatments are precisely timed to coincide with favorable dam operation schedules.

3.2.2 Barrier Curtain Evaluation

The deployment of a barrier curtain at the Clover Island site resulted in an estimated RWT dye half-life of 32.7 hours (Figure 11); a substantial reduction in water exchange compared to previously collected data at the site in 2018 (Sartain et al. 2022). Immediately following treatment (0 HAT) and at 1 HAT, dye concentrations were higher in the upper portion of the water column. This was somewhat expected because the dye was applied just below the water surface and had not had time to uniformly mix throughout the water column. Dye readings 3 HAT showed minute differences in concentration between the upper and lower water depths, indicating that the dye was evenly distributed (Figure 12). Whole-plot dye concentrations gradually decreased from 15.4 µg L^{-1} at 0 HAT, to 9.7 µg L^{-1} at 12 HAT, with higher dissipation rates occurring at the downstream end of the plot (Figure 13). Dye measurements recorded along the outside perimeter of the barrier curtain indicated that dye was dissipating out of the treatment plot primarily at the midpoint of the barrier curtain as opposed to the downstream end (Figure 13).

Figure 11. Mean RWT dye concentration (±SE [standard error]) for each sampling period during the barrier curtain assessment at the Clover Island 30–31 July 2019. Dye dissipation and dye half-life was estimated using nonlinear regression (exponential decay, $f = a \exp[-b x]$).

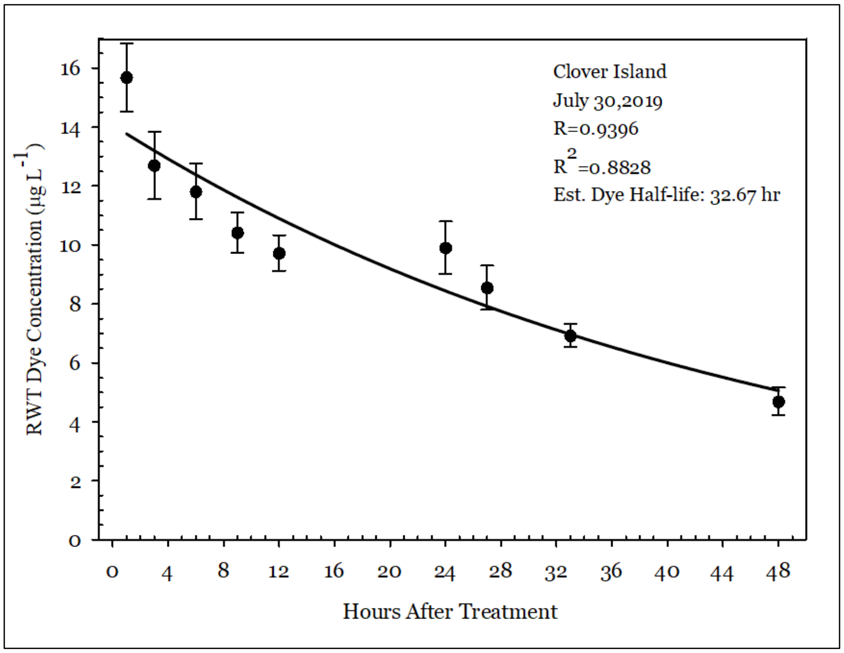
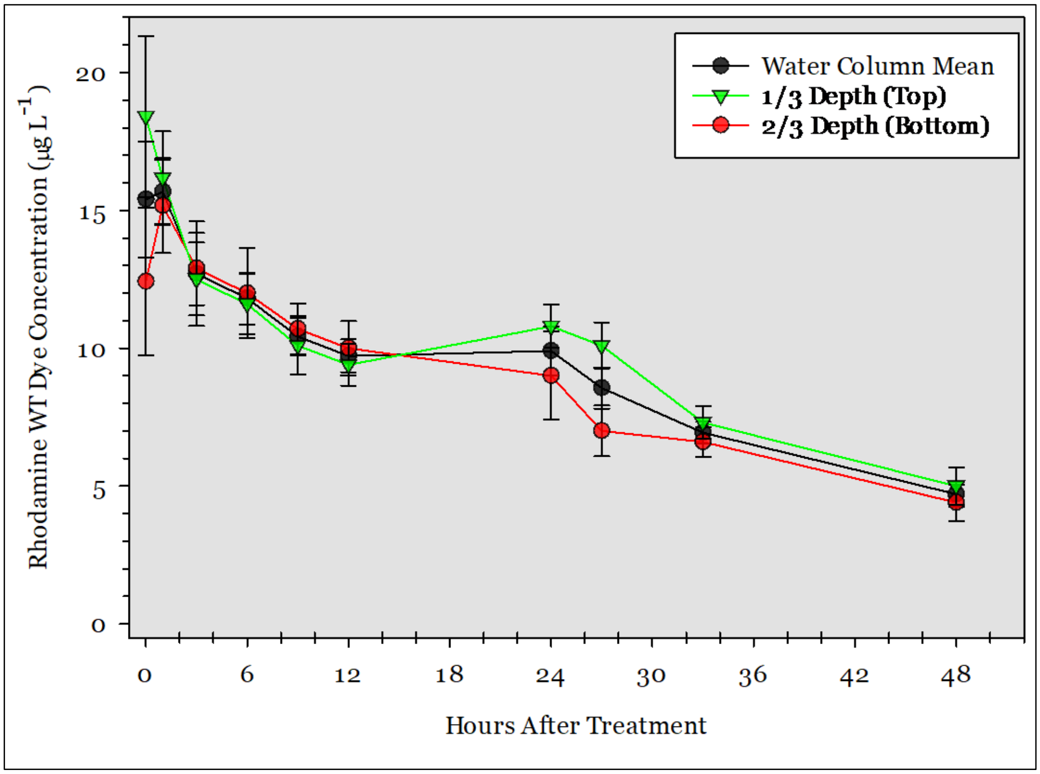


Figure 12. Mean RWT dye measurements collected at 1/3 and 2/3 depths of the water column and mean across depths during each dye sampling event during the barrier curtain assessment at Clover Island 30–31 July 2019.



From 12 to 24 HAT, aqueous dye concentrations within the plot remained relatively stable with higher concentrations being detected in the top portion of the water column. This was somewhat unexpected as previous readings indicated a consistent dissipation rate of RWT from 0 to 12 HAT. Building off the discussion in the previous section, McNary Reservoir inflow, outflow, and pool elevation at Clover Island (location of barrier curtain study site) are shown in Figure 14. McNary Reservoir inflow was estimated based off discharge data at Priest Rapids Dam, Ice Harbor Dam, and the Yakima River. Priest Rapids Dam discharge data are presented on an 18-hour time of travel, while Ice Harbor Dam discharge is presented on an 8-hour time of travel. Water discharge at McNary Dam is presented on a 2-hour time of travel. Pool elevation data are presented in real time and the duration of the barrier curtain evaluation is indicated by the highlighted portion of the graph (Figure 14). These data show that from 12 to 24 HAT, pool elevation increased by approximately 1 ft at the study site. The rise in water level likely led to a backflow of water reducing the dissipation of RWT dye and enabling concentrations to remain relatively stable in the treatment area for an extended period.

Figure 13. Predicted RWT dye concentrations during the barrier curtain assessment at Clover Island at 6, 12, 24, and 48 hours after treatment (HAT). These data were estimated using inverse distance weight modeling of mean in situ RWT dye measurements recorded throughout the water column. River flow is from upper left to right in all figures.

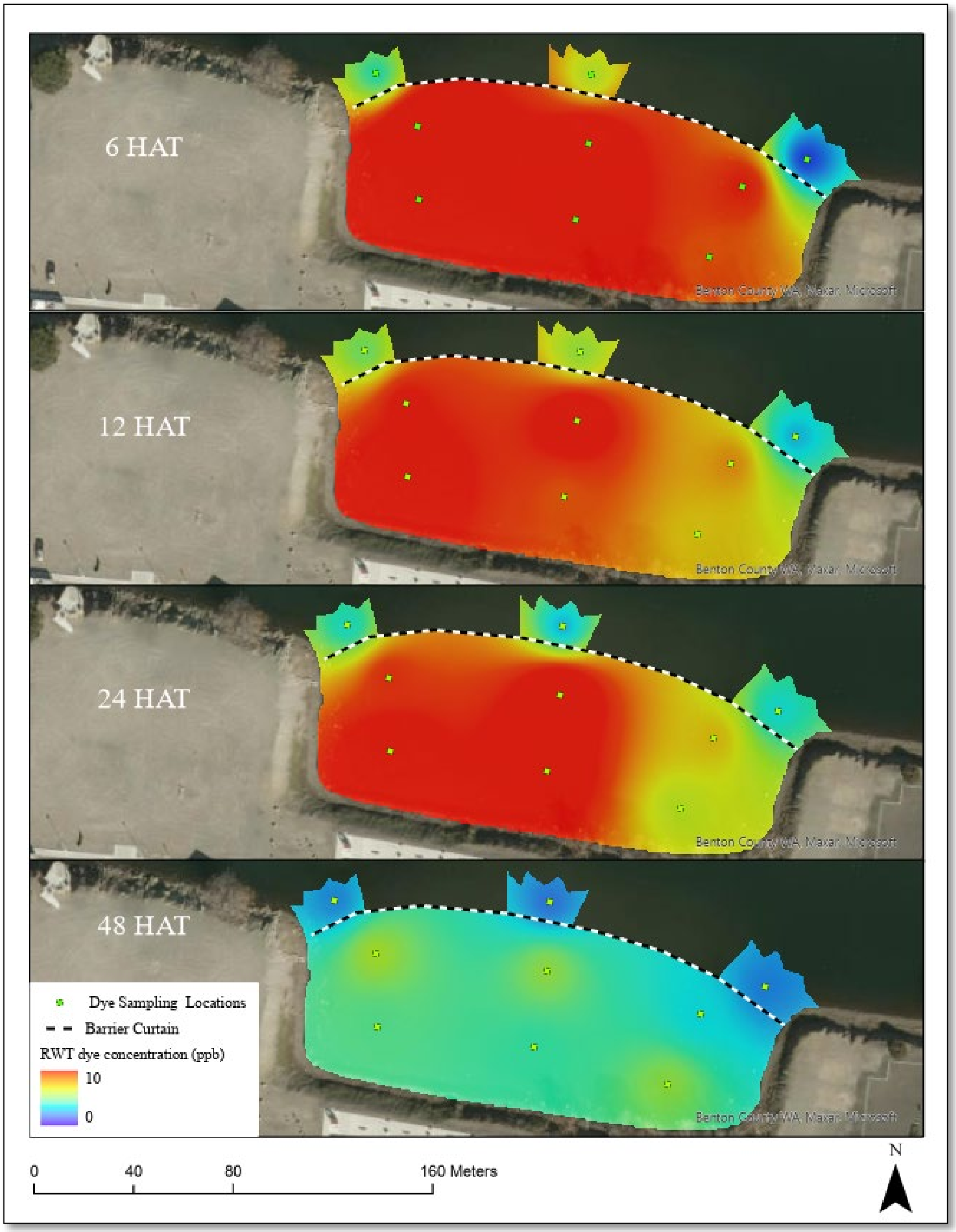
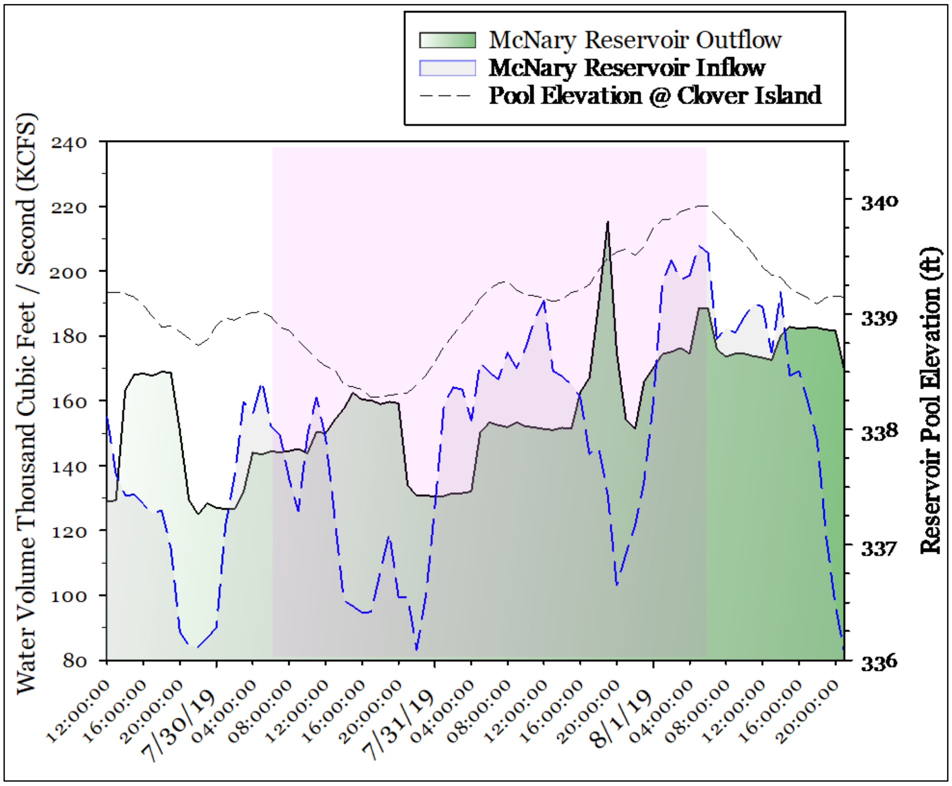


Figure 14. Inflow and outflow of water at McNary Reservoir and pool elevation at the Clover Island gauge station 29 July to 1 August 2019. The *red transparent box* represents the duration of the barrier curtain assessment. McNary Reservoir inflow is estimated based off discharge data at Priest Rapids Dam, Ice Harbor Dam, and the Yakima River. Priest Rapids, Ice Harbor, and McNary Dam discharge data are presented on an 18-, 8-, and 2-hour time of travel, respectively.



3.3 Herbicide and RWT Dye Application 2019: Discussion and Results

Based off the results of the previous water-exchange evaluations, it was hypothesized that herbicide exposure could be increased if the application coincided with periods of low dam discharge and a rising pool elevation. To assess this as an opportune treatment window, diquat herbicide plus RWT dye was applied during the early morning hours (treatment start: 0400, end: 0416) on 30 July 2019 within the confines of a double bubble curtain that enclosed the treatment site. The bubble curtain was arranged in the same manner as described in Section 3.1.4. Herbicide and RWT were applied uniformly below the water surface using a boat-mounted spray boom affixed with eight equally spaced weighted hoses. Weather conditions at the time of treatment were fair with south winds 14.5 kmh (9 mph). Immediately following application, dye concentrations were measured at 1/3 and 2/3 depth of the water column with a Turner Designs

Databank handheld data logger equipped with a Cyclops-7F sensor with Rhodamine WT optics (Turner Designs, Sunnyvale, California) at 18 predetermined sampling points evenly distributed throughout the plot. Dye sampling points were also established outside the plot to track dye dissipation from the treatment area (see Figure 2). Measurements were taken immediately after treatment (0 HAT) and at 1, 3, 5, and 7 HAT. Total water discharge at McNary Dam was 126.5 KCFS at treatment and steadily increased to 150.40 KCFS throughout the duration of the study. Forebay elevation at McNary Dam was 338.75 ft at treatment and decreased to 338.50 ft at 7 HAT.

The estimated whole-plot RWT dye half-life following herbicide application was 1.79 hours (Figure 15) and the precision timing of the application provided a slightly longer exposure period than the RWT dye concentration evaluations conducted the week prior (apart from the no bubble curtain dye study). Whole-plot dye concentrations immediately following application were 9.6 ± 1.3 $\mu g\ L^{-1}$ and were within acceptable tolerance of the target RWT treatment rate of 10 $\mu g\ L^{-1}$. Dye was concentrated primarily in the mid to lower portions of the treatment plot, with minute amounts of dye being detected at the upstream end (Figure 16). Trace amounts of dye were also being detected just outside the treatment plot along the outer edge of the bubble curtain. In addition to river currents, it is likely that wave fetch generated from the sampling vessel contributed to some of the dye movement outside the plot because it had not thoroughly mixed vertically throughout the water column. Apart from four sampling points located in the mid-downstream portion of the plot, dye concentrations measured at all sampling points were below 10 $\mu g\ L^{-1}$. Elevated dye concentrations appeared to occur in areas where dense flowering rush was present because plants likely diverted water currents around these areas, enabling dye to persist longer than in less vegetated areas in the proximity. This dye concentration trend persisted through the 3 HAT sampling interval, where dye concentrations were substantially lower in the upstream portion of the plot relative to those downstream. Like the previous water-exchange evaluations, dye dissipation from the plot primarily occurred at the downstream end as dye concentrations greater than or equal to 1 $\mu g\ L^{-1}$ were frequently detected at the termination of the riprap peninsula that acted as the downstream plot boundary. At the 7 HAT sampling interval, dye concentrations at 14 of the 18 sampled locations were below 1 $\mu g\ L^{-1}$, with only two locations with documented aqueous concentrations of dye exceeding 3 $\mu g\ L^{-1}$.

Figure 15. Mean RWT dye concentration (±SE) for each sampling period during the RWT dye plus diquat treatment at Osprey Point 30 July 2019. Dye dissipation and dye half-life was estimated using nonlinear regression (exponential decay, *f* = *a* exp[−*b x*]).

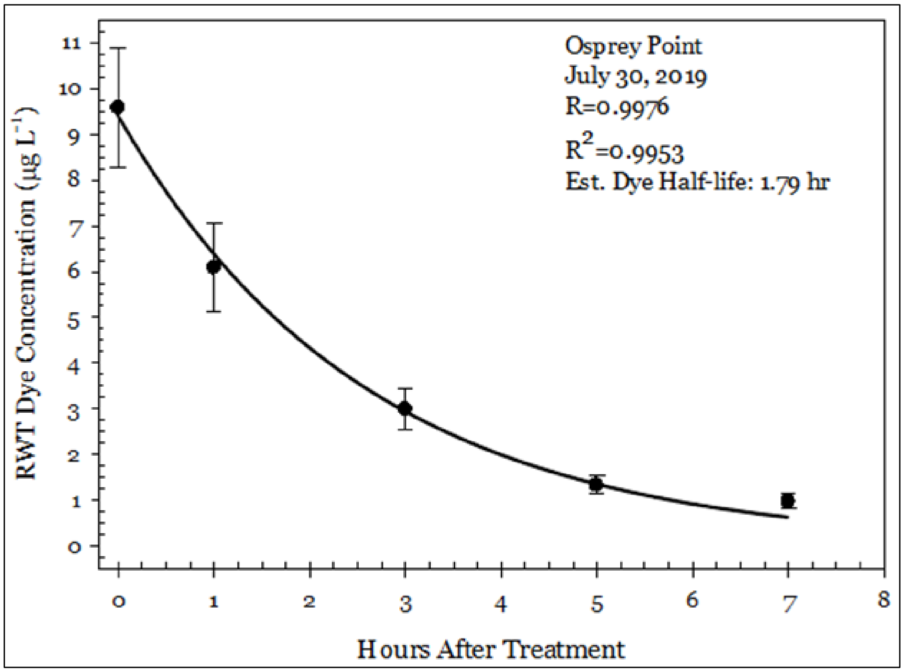
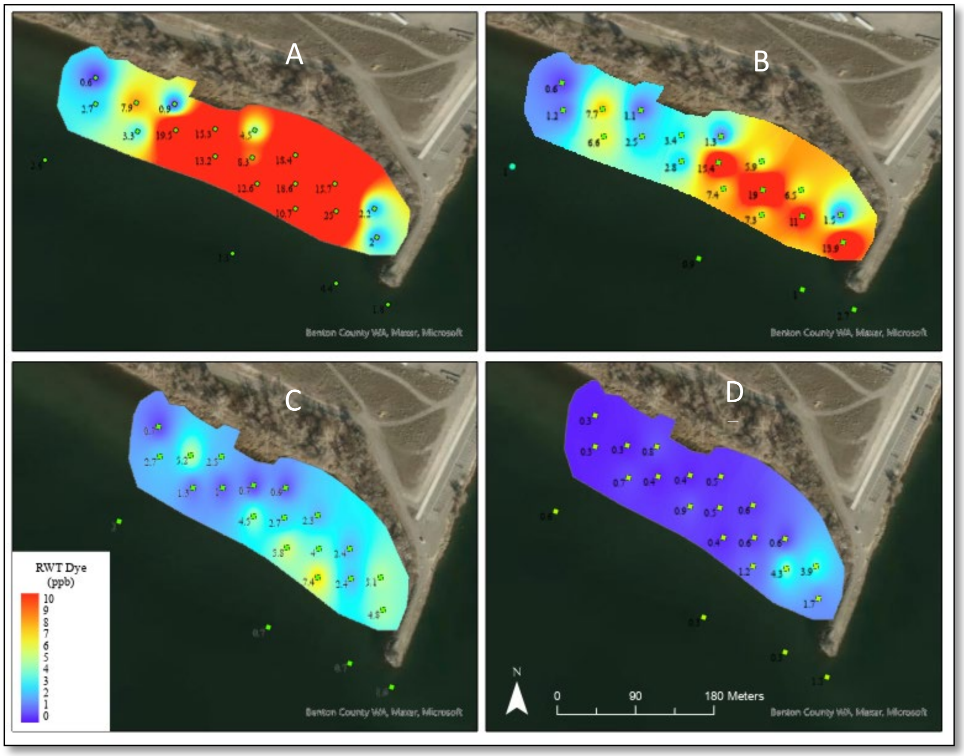


Figure 16. Estimated RWT dye concentrations at Oprey Point: (*A*) 0 HAT, (*B*) 1 HAT, (*C*) 3 HAT, and (*D*) 6 HAT. These data were estimated using inverse distance weight modeling of mean in situ RWT dye measurements recorded throughout the water column. Direction of river flow is northwest to southeast.



4 Field Demonstrations 2020

4.1 Water Exchange: Discussion and Results

No devices (e.g., bubble or barrier curtains) were deployed to mitigate bulk water exchange during the 2020 evaluation. RWT dye was applied 22 July 2020 (start: 0600 hours, end: 0625 hours) under clear, sunny skies and light winds from the west-southwest at 1.6–11.3 kmh (1–7 mph). Immediately following application, dye concentrations were measured at three locations throughout the water column: 15 cm below the water surface (top), mid-depth (middle), and 15 cm above the sediment-water interface (bottom). A weighted electric bilge pump affixed to a 5 m hose was used to obtain water samples from the middle and bottom of the water column. The dye concentrations within and outside the treatment plot were measured immediately following treatment (0), 1, and 3 HAT using a handheld Turner Designs field fluorometer at the same predetermined sampling points visited in the 2019 evaluations (see Figure 2). Total outflow and forebay elevation at McNary Dam were 185.8 KCFS and 339.1 ft at 0600 hours and 195.6 KCFS and 339.1 ft at 0900 hours.

The water-exchange process at Osprey Point on 22 July 2020 was extremely rapid and resulted in a RWT dye half-life of 0.75 hours (Figure 17). The whole-plot dye concentration immediately following treatment was 15.5 ± 2.9 $\mu g\ L^{-1}$ with higher concentrations being detected in the mid to downstream portion of the plot. Measurements 1 HAT indicated whole-plot dye concentrations had decreased an estimated 53% to 6.65 ± 1.6 $\mu g\ L^{-1}$. The average concentration measured at sampling points in the upstream portion of the plot failed to exceed 3.3 $\mu g\ L^{-1}$, whereas elevated levels (greater than or equal to 10 $\mu g\ L^{-1}$) were still being detected at sampling locations on the downstream end, indicating that the applied dye was rapidly dissipating downstream. Three hours after treatment no dye was detected at nine of the 18 sampling locations within the plot, and locations where dye was detected were less than 1.1 $\mu g\ L^{-1}$. Dye distribution throughout the water column remained relatively consistent across sampling periods, with slightly higher concentrations being detected at the bottom compared to the upper and middle portion of the water column (Figure 18). During this study period, pool elevation at McNary Dam forebay remained relatively consistent (Figure 19). Pool elevations remained consistent with normal summertime operations since increased volumes of water needed to be discharged from McNary Dam to accommodate the influx of water coming into McNary Reservoir. Compared to previously collected water-exchange data at Osprey Point, McNary Dam average daily discharge was at a minimum 30,000 ft^3/s greater in 2020 compared to 2018 (Sartain et al. 2022) and 2019.

Figure 17. Mean RWT dye concentration (±SE) for each sampling period during the RWT dye treatment at Osprey Point on 22 July 2020. Dye dissipation and dye half-life was estimated using nonlinear regression (exponential decay, $f = a \exp[-b x]$).

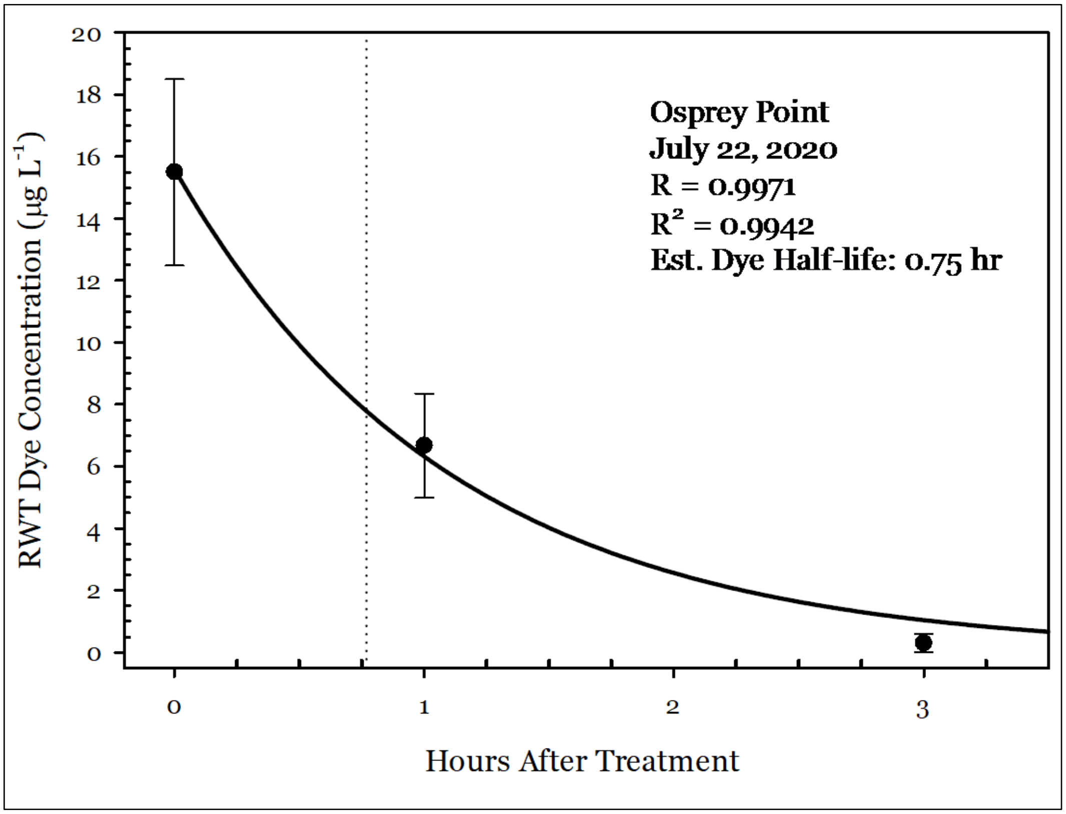


Figure 18. Mean RWT dye concentration measured at upper, middle, and bottom depths of the water column and mean across depths during each dye sampling event of the barrier curtain assessment at Clover Island in July 2019.

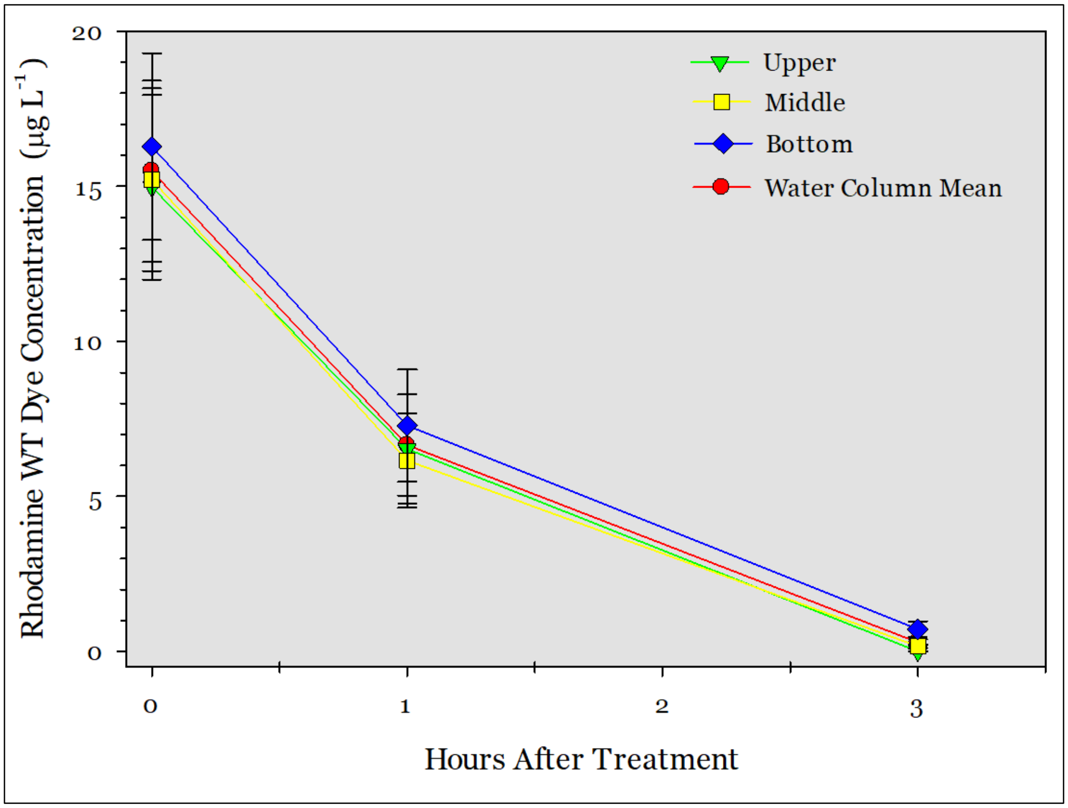
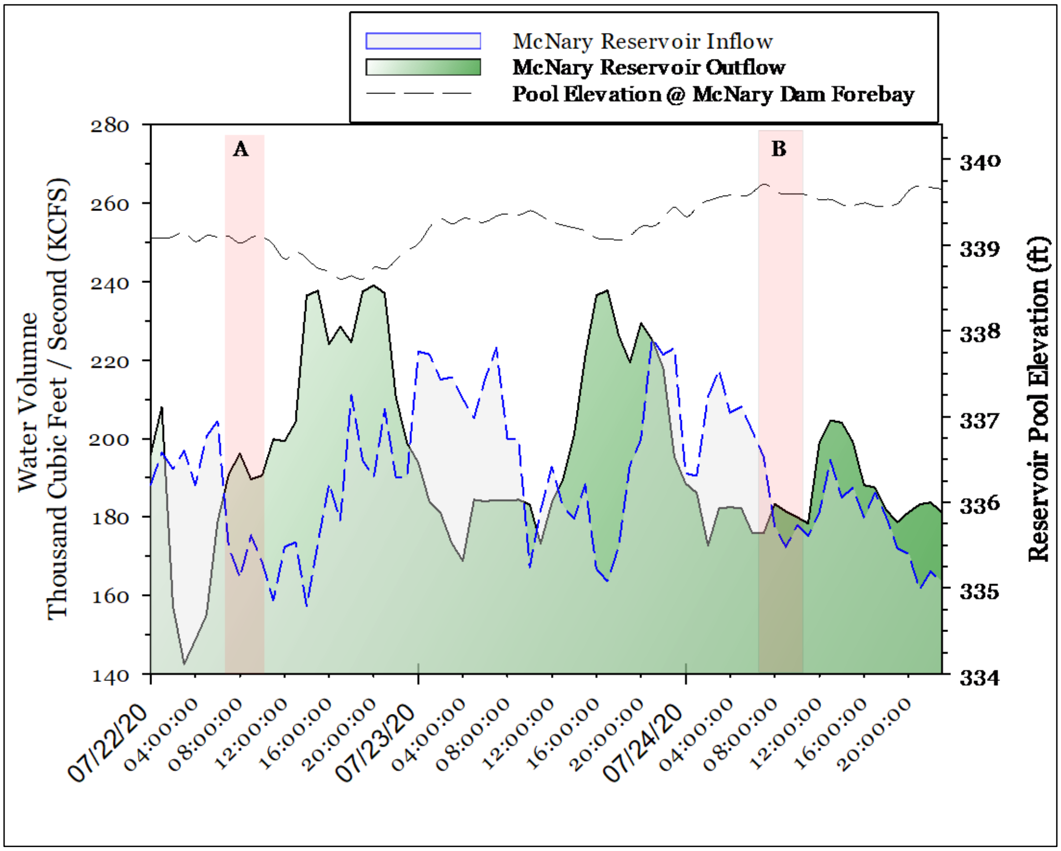


Figure 19. Inflow and outflow of water at McNary Reservoir and pool elevation at the McNary Dam Forebay 22–24 July 2020. The *red transparent boxes* represent (*A*) RWT dye only treatment and (*B*) RWT dye plus diquat herbicide treatment. McNary Reservoir inflow is estimated based off discharge data at Priest Rapids Dam, Ice Harbor Dam, and the Yakima River. Priest Rapids, Ice Harbor, and McNary Dam discharge data are presented on an 18-, 8-, and 2-hour time of travel, respectively.



4.2 Herbicide and RWT Dye Application 2020: Discussion and Results

Prior to treatment, a request to McNary Dam operations was submitted and approved (see Appendix, Figure A-1) to maintain a stable pool elevation (339.5 ± 0.5 ft) throughout McNary Reservoir to evaluate bulk water exchange under a steady pool elevation. Diquat and RWT dye were uniformly applied throughout the Osprey Point site using an airboat boat equipped with five equally spaced nozzles on the morning of 24 July 2020 (start: 0600 hours, end: 0615 hours). Weather conditions at the time of treatment were fair with clear skies and southwest winds at 16 kmh (10 mph). RWT dye concentrations were measured using the same materials and methods as outlined in Section 4.1. Measurements were taken immediately after treatment and at 1 and 3 HAT intervals.

Water-exchange processes during the RWT dye plus herbicide application were extremely rapid and comparable to those documented during the dye only treatment two days prior. The initial whole-plot dye concentration immediately following treatment was 9.0 ± 0.3 µg L^{-1} and significantly decreased, approximately 76%, by the 1 HAT sampling interval (Figure 20). Dye sampling outside the downstream plot boundary at 1 HAT detected elevated levels (approximately 7.0 to 9.0 µg L^{-1}) of RWT dispersing from the treatment site at the mid and bottom portions of the water column. Consequently, the rapid dissipation of applied dye resulted in an estimated whole-plot dye half-life of only 0.5 hours and the average whole-plot dye concentration at 3 HAT did not exceed 1.0 µg L^{-1}. It should be noted that dye dissipation patterns in 2020 differed from those in 2019. In 2020, elevated concentrations of dye were recorded at locations parallel to the riverside plot boundary (Figure 21); whereas dye readings in 2019 indicated a uniform distribution of dye across the width of the plot that dissipated downstream over time.

Figure 20. Mean RWT dye concentration (±SE) for each sampling period during the RWT dye plus diquat herbicide treatment at Osprey Point on 24 July 2020. Dye dissipation and dye half-life was estimated using nonlinear regression (exponential decay, $f = a \exp[-b x]$).

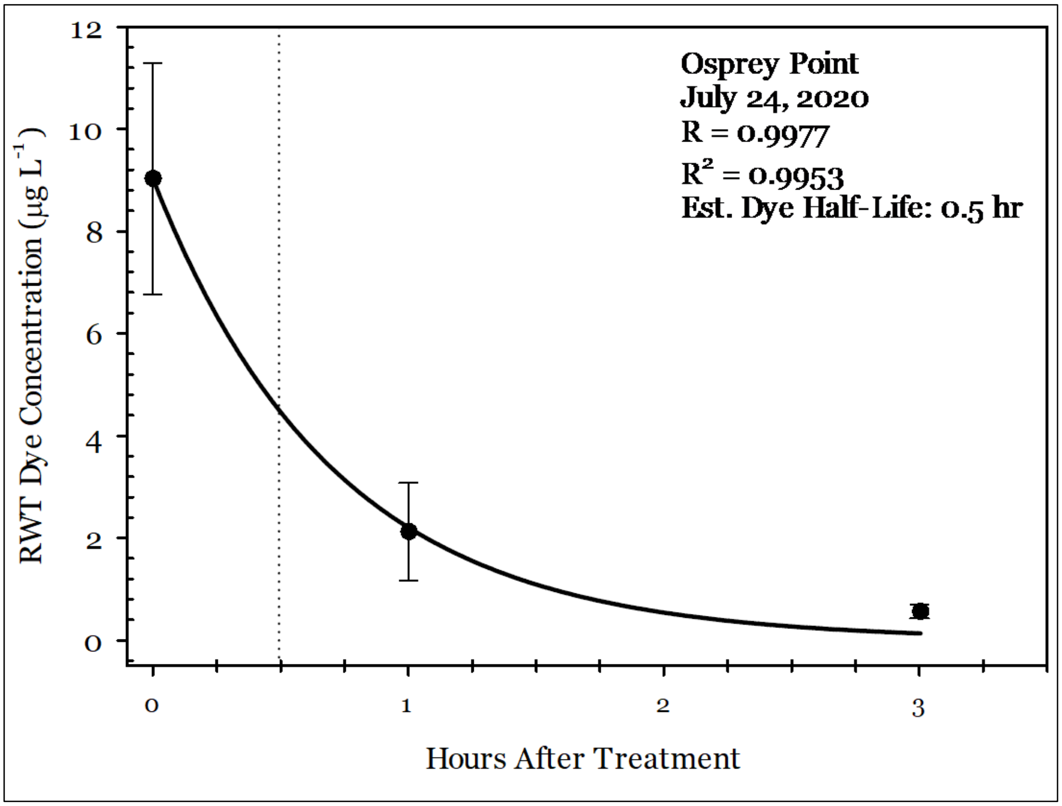
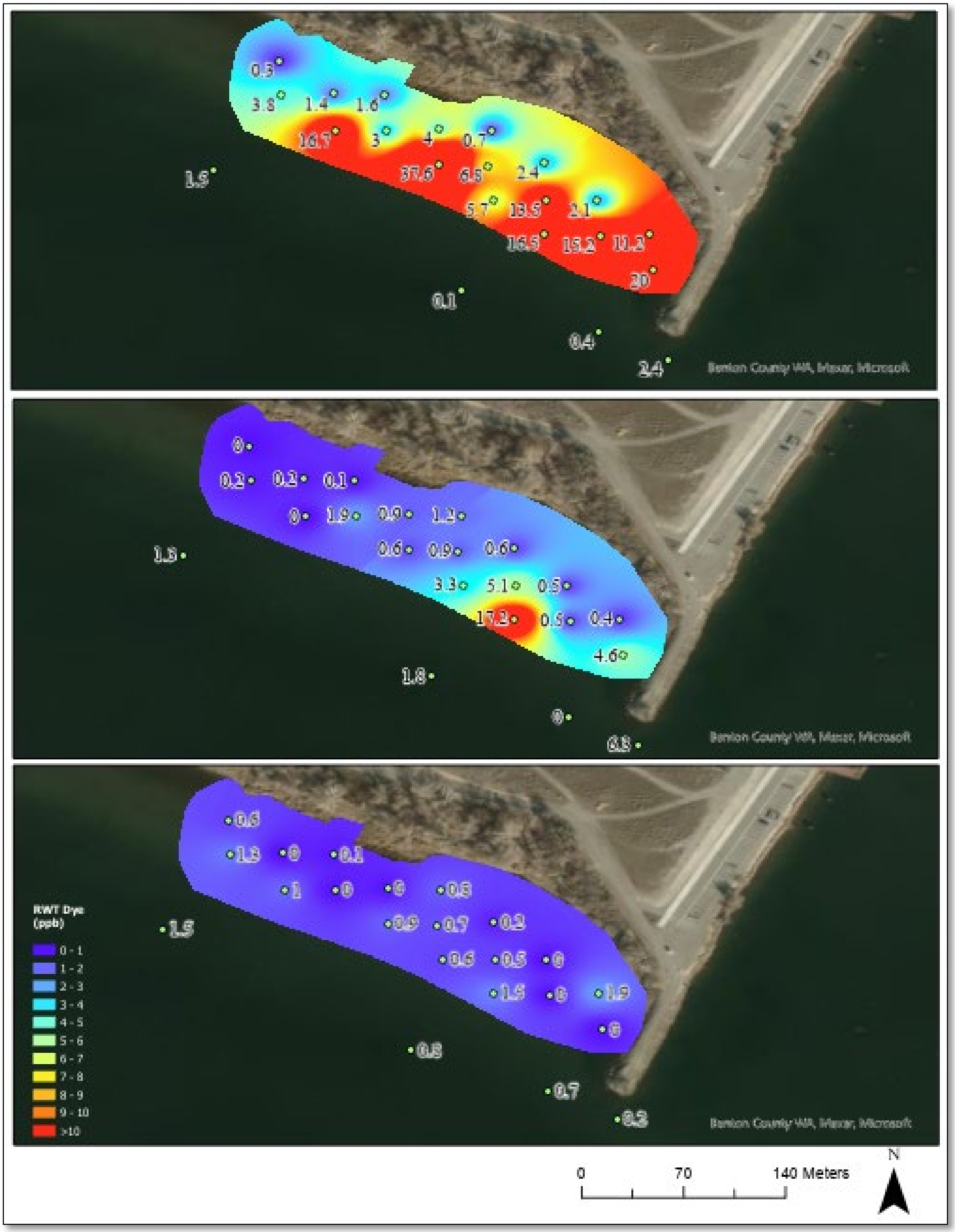


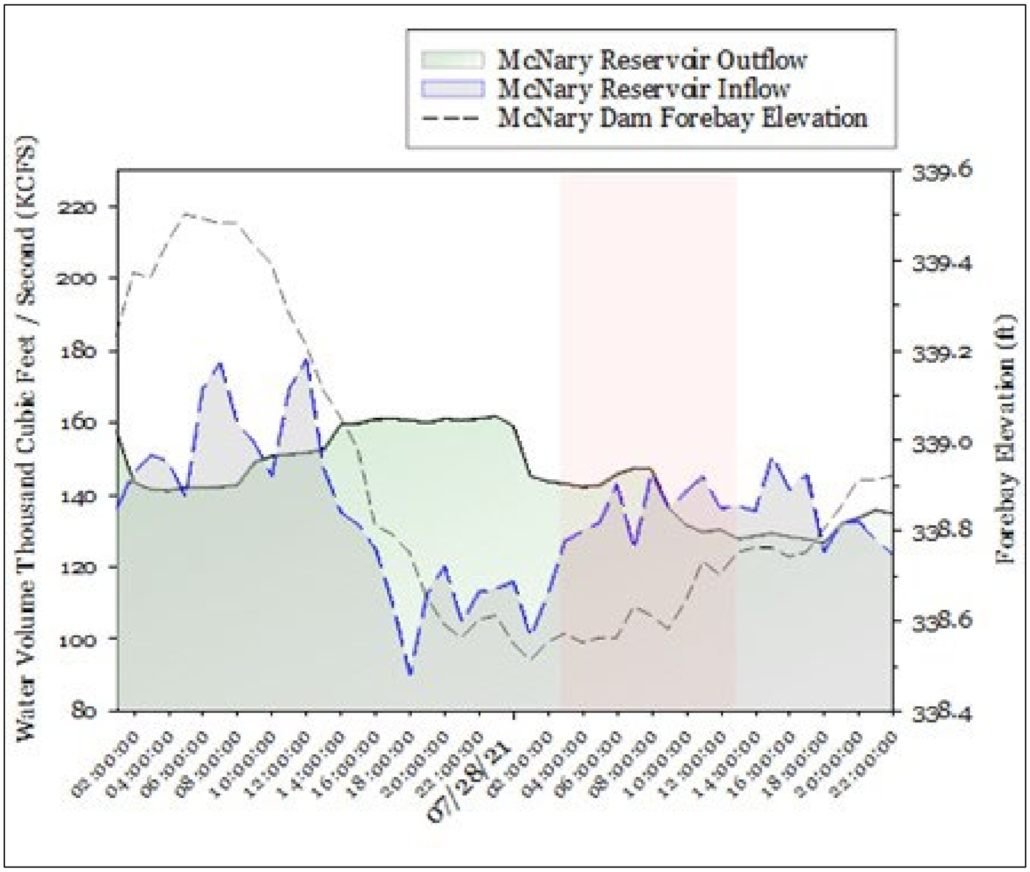
Figure 21. Estimated RWT dye concentrations at Osprey Point: *top*, 0 HAT; *middle*, 1 HAT; and *bottom*, 3 HAT. These data were estimated using the spatial analyst tool inverse distance weight technique of mean in situ RWT dye measurements recorded throughout the water column. Direction of river flow is northwest to southeast.



5 Field Demonstration 2021: Discussion and Results

Unlike the previous studies, water-exchange evaluations with RWT dye alone were not performed prior to the 2021 herbicide field demonstration. Using previously collected water-exchange data, the herbicide plus RWT dye application in 2021 was planned to coincide with a period of minimum McNary Dam discharge and an increasing pool elevation. This approach has been shown to significantly extend herbicide contact times in Noxon Rapids Reservoir, Montana (Wersal et al. 2022) and demonstrated promise following the 2019 water-exchange evaluations. Therefore, to extend potential herbicide contact time, the application of diquat plus RWT dye was administered during the early morning hours (treatment start: 0243, end: 0305) on 28 July 2021. Herbicide and dye were uniformly applied throughout the water column using a boat-mounted spray boom affixed with eight equally spaced weighted hoses. Immediately following application, dye concentrations were measured at 1/3 and 2/3 depth of the water column with a Turner Designs Databank handheld data logger equipped with a Cyclops-7F sensor with Rhodamine WT optics (Turner Designs, Sunnyvale, California) at 18 predetermined sampling points evenly distributed throughout the plot. Dye sampling points were also established outside the plot to track dye dissipation from the treatment area. Measurements were taken immediately after treatment and at 1, 3, 5, 8, and 10.5 HAT. Total water discharge and forebay elevation at McNary Dam was 142.4 KCFS and 338.57 ft at 0300 hours (at treatment) and 127.6 KCFS and 338.73 ft at 1100 hours (8 HAT). McNary Reservoir inflow, outflow, and pool elevation at McNary Dam (55 km downstream from study site) during the water-exchange evaluation are presented in Figure 22. McNary Reservoir inflow was estimated using discharge data at Priest Rapids Dam, Ice Harbor Dam, and the Yakima River. Priest Rapids Dam discharge data are presented on an 18-hour time of travel while Ice Harbor Dam discharge is presented on an 8-hour time of travel. Water discharge at McNary Dam is presented on a 2-hour time of travel.

Figure 22. Inflow and outflow of water at McNary Reservoir and pool elevation at the McNary Dam Forebay 27–28 July 2021. The *red transparent box* represents the sampling duration of RWT dye plus diquat herbicide treatment. McNary Reservoir inflow is estimated based off discharge data at Priest Rapids Dam, Ice Harbor Dam, and the Yakima River. Priest Rapids, Ice Harbor, and McNary Dam discharge data are presented on an 18-, 8-, and 2-hour time of travel, respectively.



The precise timing of the RWT dye plus diquat herbicide application resulted in an estimated dye half-life of 4 hours (Figure 23), which was a two-fold increase in the half-life of applied RWT compared with previous water-exchange evaluations at Osprey Point from 2018 to 2020 (Sartain et al. 2022). Immediately following treatment, the whole-plot dye concentration averaged 8.0 ± 0.6 µg L^{-1} and decreased by approximately 20% at 3 HAT. Distribution of RWT throughout the water column remained consistent from 0 to 3 HAT and ranged between 40% and 50% in the lower water column and 50%–60% in the upper water column (Figure 24). From the 3 to 8 HAT sampling interval, the most significant decrease in dye concentration was observed. Dye measurements indicated a reduction from 6.0 ± 0.3 to 1.0 ± 0.6 µg L^{-1} RWT at 3 and 8 HAT, respectively. At the 5 and 8 HAT samplings, greater proportions of dye were being detected in the upper water column compared with the lower water column.

Figure 23. Mean RWT dye concentration (±SE) for each sampling period during the RWT dye plus diquat herbicide treatment at Osprey Point 28 July 2021. Dye dissipation and dye half-life was estimated using nonlinear regression (exponential decay, $f = a \exp[-b x]$). The ▲ represent McNary Dam Forebay elevation at HAT.

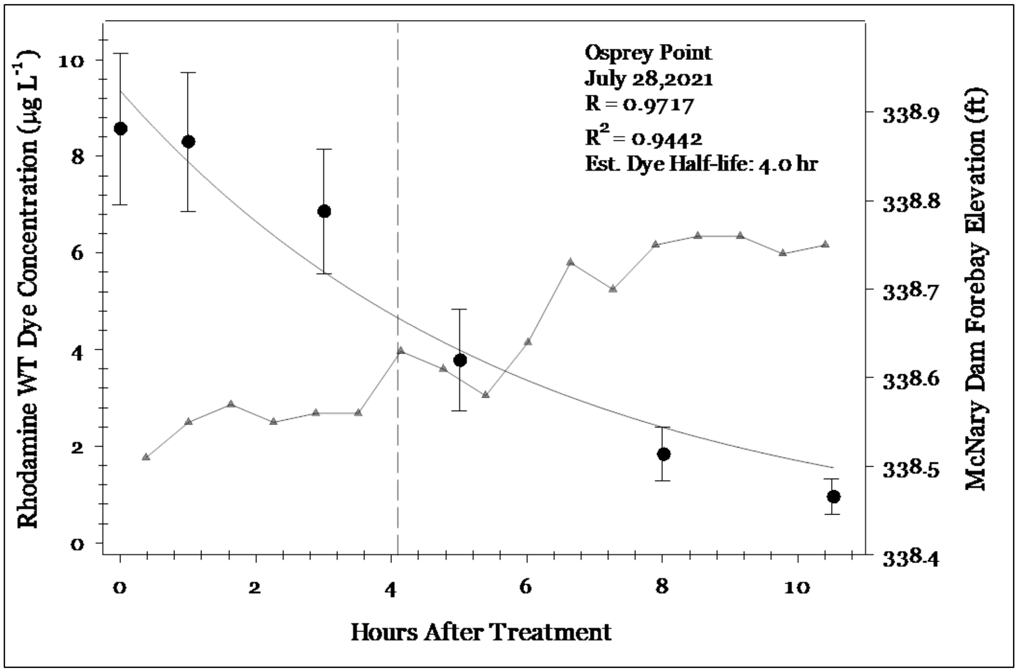
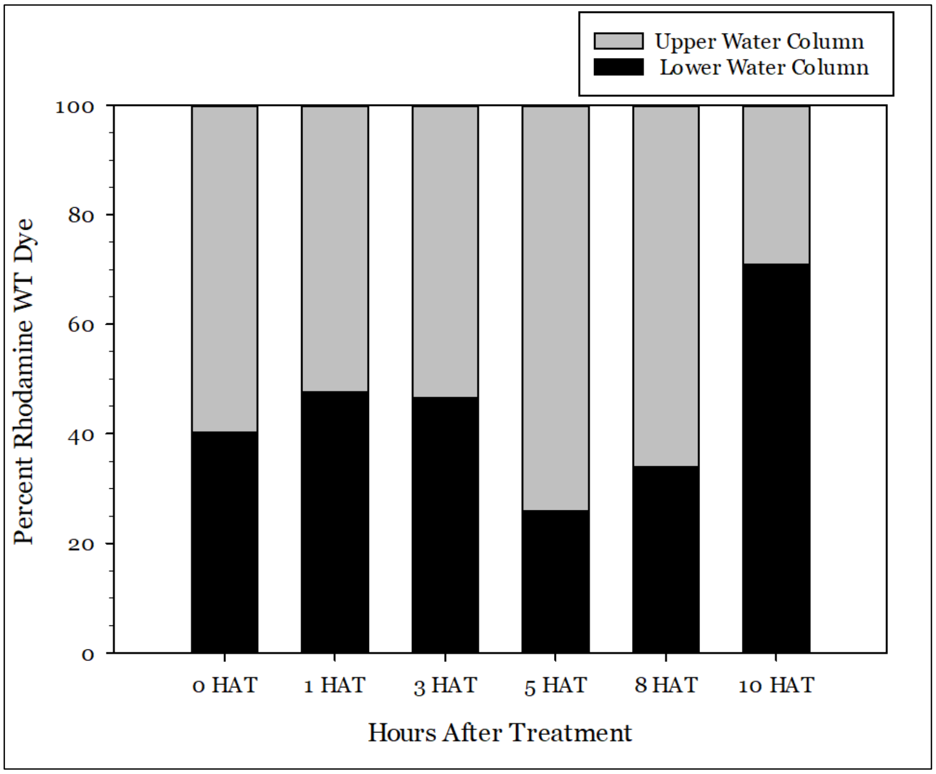
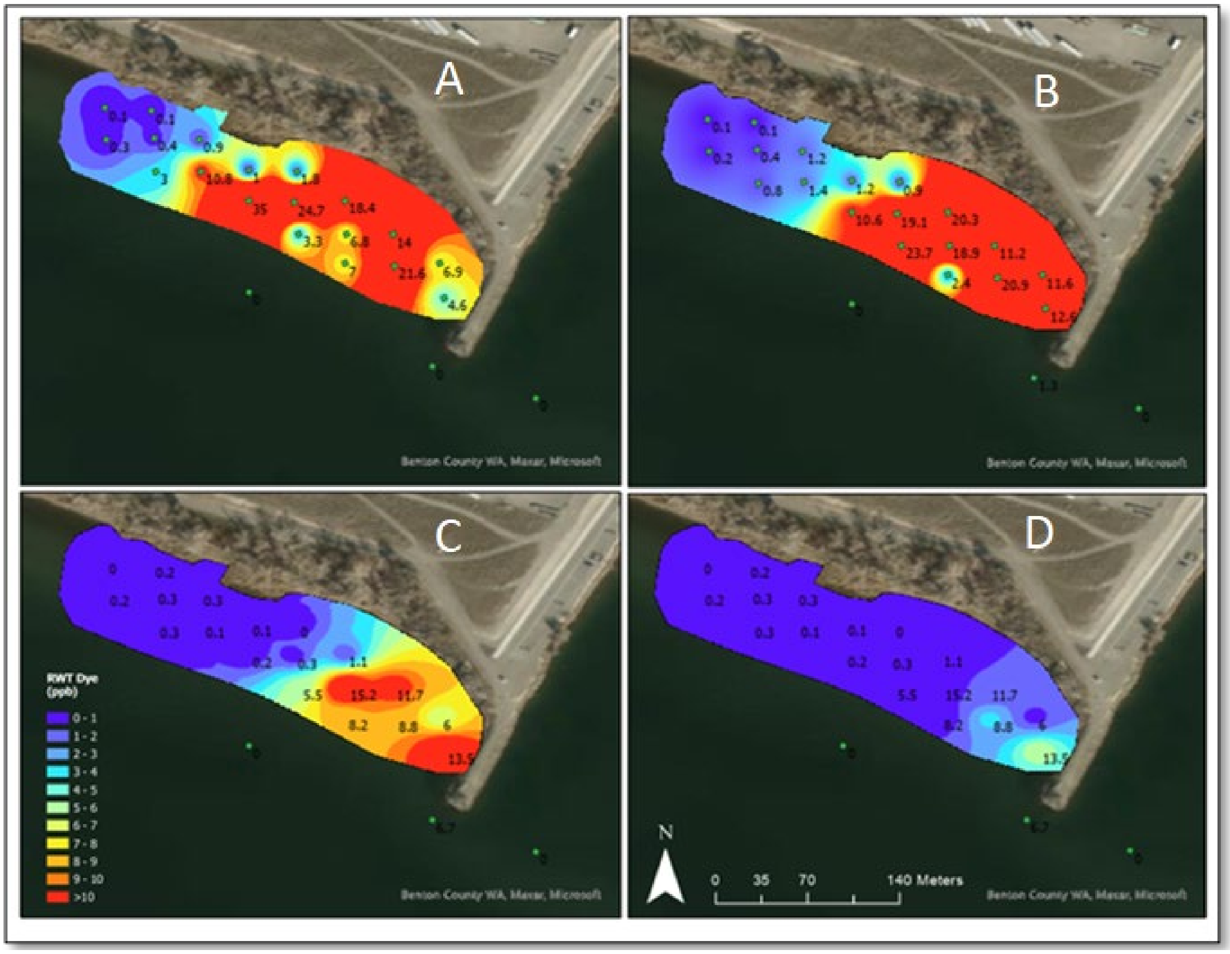


Figure 24. Percent distribution of RWT dye in the water column at Osprey Point 28 July 2021; percentages were calculated from mean concentrations within the plot at the upper and lower water column.



Overall dye dissipation patterns closely resembled those observed in 2019, which indicated a uniform distribution of dye across the plot with lower concentrations detected at the upstream end, and downstream dissipation occurring over time (Figure 25). It should be noted that the precise timing of the treatment coincided with a period of decreasing dam discharge and water level increase, as shown in Figures 22 and 23. It is likely this combination of hydrologic factors led to the increased residence time of the applied dye in the treatment plot.

Figure 25. Estimated RWT dye concentrations at (*A*) 0 HAT, (*B*) 1 HAT, (*C*) 5 HAT, and (*D*) 8 HAT on 28 July 2021, data were estimated using mean in situ RWT dye measurements recorded throughout the water column and the Spatial Analyst Inverse Distance Weight tool in ArcMap Pro. Direction of river flow is northwest to southeast.



6 Vegetation Assessments and Water Quality 2019–2021

6.1 Vegetation Assessments

The 2019 pretreatment vegetation assessment at Osprey Point documented an 100% occurrence of flowering rush (see Table 1). Plants occurred as both the submerged and emergent growth forms, with emergent plants predominately occurring as a vegetation band that extended through the center of the plot (Figure 26). In addition to flowering rush, other nonnative aquatic plants like Eurasian watermilfoil and curly leaf pondweed were detected at a frequency of 58% and 53%, respectively. Four co-occurring native species, coontail, water stargrass, elodea, and leafy pondweed, were also documented at frequencies greater than 30%.

Visual observations 4 WAT indicated flowering rush plants exhibited typical diquat injury symptomology (e.g., chlorotic, and necrotic shoots), as shown in Figure 27. Herbicide injury was most prevalent along the upper portions of leaves, whereas green viable plant tissue persisted at the base of the plant near the sediment-water interface. Submersed plants occurring at greater depths greater than 1.5 m) did not appear to be as injured as emergent/submersed plants found in shallower waters (less than 1.5 m). Flowering rush remained at 100% occurrence at 4 WAT, since injured plants had not begun to deteriorate. However, all predominate co-occurring species displayed a decrease in percent occurrence (see Table 1). Injury to nontarget vegetation was not surprising, as diquat is a broad-spectrum contact herbicide and many of the co-occurring species are sensitive to the herbicide rate applied. By 8 WAT, flowering rush occurrence had decreased by 44%. While the herbicide treatment likely contributed to this decline, it is probable that the onset of fall senescence for flowering rush and other aquatic plant species (e.g., leafy pondweed) contributed, especially since plant occurrence rapidly decreased from 8 to 10 WAT. A similar trend was observed from 8 to 10 WAT for flowering rush and co-occurring species in the nontreated reference plot (see Table 2).

Figure 26. Emergent flowering rush occurring throughout the Osprey Point treatment plot prior to herbicide treatment in July 2019.

Figure 27. Diquat herbicide injury to submersed and emergent flowering rush 4 weeks after treatment (WAT) at Osprey Point in August 2019.

The 1 year after treatment (YAT) vegetation survey in 2020 indicated that flowering rush occurrence only slightly decreased (approximately 10%) following the 2019 herbicide application. Further, flowering rush remained the most frequently occurring species within the plot in 2020. Of the predominate co-occurring species, water star grass and elodea both showed increases in coverage compared to the 2019 pretreatment survey, whereas coontail, Eurasian watermilfoil, leafy pondweed, and curly leaf pondweed occurred at lower levels. Similarly, decreased coverage of flowering rush, coontail, water stargrass, and curly leaf pondweed were documented in the reference plot (see Table 2). Delayed plant growth, resulting from a prolonged spring and high-water flows, likely contributed to the decreased coverage of these species.

During the diquat treatment in 2020, water-exchange rates were extremely rapid (estimated dye half-life 0.5 hours), resulting in minimal herbicide to target-plant exposure. Because of high bulk water exchange, visual herbicide injury to flowering rush 4 WAT was expected to be negligible; however, moderate injury was noted to plants at the downstream end of the plot (Figures 28 and 29). It is likely that these plants were subjected to prolonged herbicide exposure. Like the 2019 study, flowering rush frequency of occurrence was 90% at 4 WAT in 2020 following a single diquat application, whereas coontail, Eurasian watermilfoil, and multiple pondweed species increased in occurrence (see Table 1). This trend was also observed at the reference plot where all co-occurring species, except for Eurasian watermilfoil, increased from July to August 2020 (see Table 2).

Figure 28. Aerial view of the Osprey Point treatment site 4 WAT in August 2020.

Figure 29. Submersed flowering rush documenting moderate diquat herbicide injury 4 WAT at Osprey Point in August 2020.

The pretreatment vegetation assessment prior to the 2021 treatment (1 year after and 2 years after the 2020 and 2019 treatments, respectively) indicated an 84% occurrence of flowering rush. Although plant occurrence was still greater than 80%, plant density had visually declined following 2 years of consecutive herbicide treatments. As a result, the occurrence of native pondweed species (*P. perfoliatus, P. foliosus, P. praelongus,* and *P. zostraformis*) showed an increase in occurrence (see Table 1). Most notably was the prolific growth of leafy pondweed that surged from 53% occurrence in 2019 to 84% occurrence in 2021 (see Table 1). The nonnative species Eurasian watermilfoil and curly leaf pondweed were also documented at lower levels prior to the 2021 herbicide treatment.

Precision timing of the 2021 RWT dye plus diquat herbicide treatment showed that herbicide exposure persisted longer than what was previously documented at Osprey Point during water-exchange evaluations and herbicide treatments that began in 2019 (see Figure 23). Because of the greater diquat residence in the water column, injury to flowering rush was observed as soon as 72 HAT (Figure 30). Rapid plant response to the 2021 dye plus diquat treatment is in-line with observations from small scale flowering rush studies evaluating diquat exposures between 3 and 12 hours (Sartain et al. 2021). By 6 WAT, flowering rush herbicide injury was prevalent in remaining plants (Figure 31), and frequency of occurrence decreased from 84% to 53% (see Table 1).

Figure 30. Flowering rush displaying diquat herbicide injury 72 HAT in July 2021.

Figure 31. Flowering rush displaying diquat herbicide injury 6 WAT in September 2021.

6.2 Water Quality

Water-quality measurements were taken from the middle of the water column at multiple locations throughout the treatment plot prior to each herbicide treatment and 5 days after treatment (DAT) in 2021. All measured parameters were relatively consistent across all treatment years (Table 3). Increased water turbidity was recorded in 2021 but was likely because of a larger, deeper drafting boat that may have increased suspended sediments in the water column while navigating to water-quality sampling stations. Even still, no interference from suspended sediments on diquat efficacy was anticipated with the low turbidity levels observed.

Table 3. Water-quality data collected prior to herbicide treatment at Osprey Point 2019–2021 and 5 days posttreatment in 2021 (Mean ±SD [standard deviation]).

Date	29 July 2019	23 July 2020	27 July 2021	1 August 2021[a]
Water Temperature (°C)	19.7± 0.2	20.8 ± 0.4	20.4 ± 0.1	21.6 ± 0.2
Dissolved O_2 (mg L^{-1})	9.6 ± 0.4	—	7.9 ± 0.6	7.6 ± 1.2
Turbidity (FNU)[b]	0.9 ± 1.0	0.5 ± 0.6	3.4 ± 3.4	5.6 ± 4.3
Sp. Cond (µS/cm)[c]	158.4 ± 5.0	—	155.4 ± 7.6	169.5 ± 10.8
pH	7.9 ± 0.2	8.52 ± 0.1	7.8 ± 0.1	7.8 ± 0.2

[a] Data collected five days post herbicide treatment.

[b] Formazin Nephelometric Unit (FNU).

[c] Specific Conductivity (micro siemens per centimeter).

7 Conclusions and Recommendations

Based off the results of these studies, the following conclusions and recommendations were developed to guide and continue to improve the chemical management of flowering rush in complex hydrological systems.

7.1 Conclusions

1. Water-exchange patterns in plant beds are influenced by inflow and outflow interactions and are driven by dam operations.
2. Bubble curtain effectiveness at minimizing water exchange is more sensitive to inflow and outflow interactions compared to traditional barrier curtains.
3. Precision timing of treatments during low flow and increasing pool elevations (e.g., inflows greater than outflows) can minimize water exchange in shoreline treatment plots and mitigation of complex hydrodynamic processes ultimately determines herbicide treatment success.
4. Diquat applications once annually in late-July for three successive years provided notable injury to standing flowering rush, but reductions in frequency of occurrence were minimal from year to year.
5. Diquat application once annually in late-July for three successive years did not negatively impact native nontarget plant populations within the treatment plot.
6. Label rates of certain tradename diquat products are limited by average depth of the treatment site; as such, achieving desired aqueous concentrations of diquat are limited in treatment sites where average depths exceed 1.2 m.
7. Water-quality parameters prior to treatment were relatively consistent between years, and turbidity was at low levels not conducive to affecting diquat efficacy. Water-quality data collected 5 DAT in 2021 did not indicate any significant reductions in dissolved oxygen, specific conductivity, or pH that would be expected to have a negative impact to sensitive fish species.

7.2 Recommendations

1. To extend aqueous herbicide contact times, treatments should be appropriately timed to correspond with dam operations where pool levels are increasing (e.g., inflows greater than outflows).

2. Water-exchange evaluations should continue to be conducted within McNary Reservoir to investigate the impact of dam operations and water level fluctuation at flowering rush sites that differ (e.g., open water) from the sites evaluated in the current study.
3. Within the current allowable treatment window, if conditions are suitable, two diquat treatments annually should be incorporated for the management of flowering rush.
4. Tradename diquat products whose allowable labeled rates are not limited by water depth should be added to the Project's operational management strategy for managing flowering rush in areas with average depths greater than 1.2 m.
5. Other fast-acting herbicides alone or in combination with diquat that allow for alternative application strategies (e.g., drip/metered treatments) should be evaluated for efficacy in high water-exchange treatment sites.

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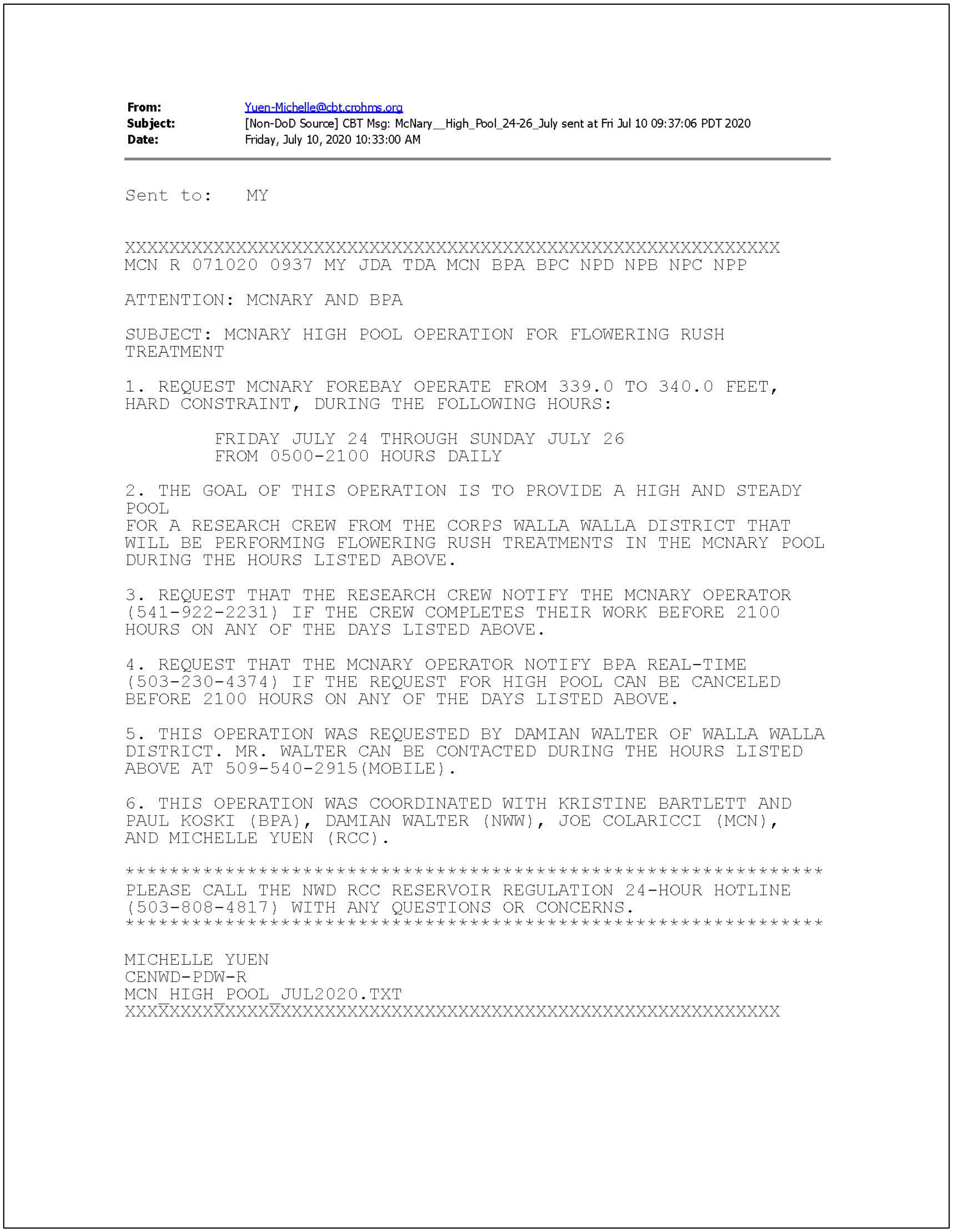
Appendix: Supporting Documents

Figure A-1. Correspondence letter to McNary Dam Operations requesting that the reservoir pool be consistently maintained between 339.0 and 340.0 ft from 0500 to 2100 hours daily on 24–26 July 2020.



From: Yuen-Michelle@cbt.crohms.org
Subject: [Non-DoD Source] CBT Msg: McNary__High_Pool_24-26_July sent at Fri Jul 10 09:37:06 PDT 2020
Date: Friday, July 10, 2020 10:33:00 AM

Sent to: MY

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
MCN R 071020 0937 MY JDA TDA MCN BPA BPC NPD NPB NPC NPP

ATTENTION: MCNARY AND BPA

SUBJECT: MCNARY HIGH POOL OPERATION FOR FLOWERING RUSH TREATMENT

1. REQUEST MCNARY FOREBAY OPERATE FROM 339.0 TO 340.0 FEET, HARD CONSTRAINT, DURING THE FOLLOWING HOURS:

FRIDAY JULY 24 THROUGH SUNDAY JULY 26
FROM 0500-2100 HOURS DAILY

2. THE GOAL OF THIS OPERATION IS TO PROVIDE A HIGH AND STEADY POOL FOR A RESEARCH CREW FROM THE CORPS WALLA WALLA DISTRICT THAT WILL BE PERFORMING FLOWERING RUSH TREATMENTS IN THE MCNARY POOL DURING THE HOURS LISTED ABOVE.

3. REQUEST THAT THE RESEARCH CREW NOTIFY THE MCNARY OPERATOR (541-922-2231) IF THE CREW COMPLETES THEIR WORK BEFORE 2100 HOURS ON ANY OF THE DAYS LISTED ABOVE.

4. REQUEST THAT THE MCNARY OPERATOR NOTIFY BPA REAL-TIME (503-230-4374) IF THE REQUEST FOR HIGH POOL CAN BE CANCELED BEFORE 2100 HOURS ON ANY OF THE DAYS LISTED ABOVE.

5. THIS OPERATION WAS REQUESTED BY DAMIAN WALTER OF WALLA WALLA DISTRICT. MR. WALTER CAN BE CONTACTED DURING THE HOURS LISTED ABOVE AT 509-540-2915(MOBILE).

6. THIS OPERATION WAS COORDINATED WITH KRISTINE BARTLETT AND PAUL KOSKI (BPA), DAMIAN WALTER (NWW), JOE COLARICCI (MCN), AND MICHELLE YUEN (RCC).

****
PLEASE CALL THE NWD RCC RESERVOIR REGULATION 24-HOUR HOTLINE (503-808-4817) WITH ANY QUESTIONS OR CONCERNS.
****

MICHELLE YUEN
CENWD-PDW-R
MCN_HIGH_POOL_JUL2020.TXT
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

Abbreviations

CET	Concentration and exposure time
DAT	Days after treatment
EL	Elevation
FNU	Formazin nephelometric unit
HAT	Hours after treatment
ID	Inside diameter
KCFS	Thousand cubic feet second
RWT	Rhodamine water tracing
SD	Standard deviation
SE	Standard error
WAT	Weeks after treatment
YAT	Years after treatment

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June 2024	Final Technical Report (TR)	**START DATE** FY2019	**END DATE** FY2022

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Part 2: Field Demonstrations for Chemical Control of Flowering Rush

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Washington, DC 20314
and
US Army Corps of Engineers–Walla Walla District
201 North Third Avenue
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14. ABSTRACT

A series of 10 water-exchange studies were conducted from 2019 to 2021 at two sites, Clover Island and Osprey Point, within the McNary Pool of the Columbia River on the Oregon-Washington border. Six of the studies incorporated a barrier curtain or bubble curtain, whereas the other four studies did not include any device to mitigate water exchange. Once annually, diquat aquatic herbicide was applied concurrently with rhodamine water tracing (RWT) dye at the Osprey Point site (2019–2021) to control flowering rush. An additional plot, Clover Island Reference, served as the nontreated control to the Osprey Point treatment plot. Pre- and posttreatment vegetation surveys were conducted in 2019, 2020, and 2021 to determine flowering rush control, treatment impacts to water quality, and nontarget species response. This study sought to (1) document the use of barrier curtains and bubble curtains as potential methods for reducing water exchange and increasing herbicide concentration exposure times within potential flowering rush treatment areas, (2) evaluate bulk water exchange and selective control of flowering rush under varying reservoir operations, and (3) use the results from these studies to provide guidance for managing submersed flowering rush infestations on the McNary Pool, Columbia River, and similar run-of-the-river impoundments.

15. SUBJECT TERMS

Aquatic herbicides; Aquatic plants; Introduced organisms; Invasive plants

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**
a. REPORT	**b. ABSTRACT**	**C. THIS PAGE**	SAR	65
Unclassified	Unclassified	Unclassified		

19a. NAME OF RESPONSIBLE PERSON	**19b. TELEPHONE NUMBER (include area code)**
Bradley Sartain	(601) 634-2516

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PREVIOUS EDITION IS OBSOLETE.

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