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Aquatic Plant Control Research Program

Flowering Rush Control in Hydrodynamic Systems

Part 1: Water Exchange Processes

Bradley T. Sartain, Kurt D. Getsinger, Damian J. Walter,
John D. Madsen, and Shayne Levoy

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Flowering Rush Control in Hydrodynamic Systems

Part 1: Water Exchange Processes

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Abstract

In 2018, field trials evaluated water-exchange processes using rhodamine WT dye to provide guidance on the effective management of flowering rush (*Butomus umbellatus* L.) at McNary Dam and Reservoir (Wallula Lake, 15,700 ha). Additional evaluations determined the effectiveness of BubbleTubing (hereafter referred to as *bubble curtain*) at reducing water exchange within potential flowering rush treatment areas. Dye readings were collected from multiple sampling points at specific time intervals until a dye half-life could be determined. Whole-plot dye half-lives at sites without bubble curtain ranged 0.56–6.7 h. In slower water-exchange sites (≥ 2.6 h dye half-life), the herbicide diquat should have a sufficient contact time to significantly reduce flowering rush aboveground biomass. Other sites demonstrated very rapid water exchange (< 1.5 h dye half-life), likely too rapid to effectively control flowering rush using chemical treatments without the use of a barrier or curtain to slow water exchange. At one site, the use of the bubble curtain increased the dye half-life from 3.8 h with no curtain to 7.6 and 7.1 h with a bubble curtain. The bubble curtain's ability to slow water exchange will provide improved chemical control and increase the potential for other chemical products to be effectively used.

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Preface

The work reported herein was conducted as part of the Aquatic Plant Control Research Program (APRCP) under Project Number 611102AH68, “Flowering Rush Control in Hydrodynamic Reservoirs.” The APRCP is sponsored by Headquarters, US Army Corps of Engineers (HQUSACE), and is assigned to the US Army Engineer Research and Development Center (ERDC) under the purview of the Environmental Laboratory (EL), Vicksburg, Mississippi. Funding was provided under 96x3122. The APRCP is managed under the Civil Works Environmental Engineering and Sciences Office, Dr. Jen-Seiter Moser, EL, technical director. Dr. Christine VanZomeren, EL, was assistant technical director, and Michael Greer was program manager for the APRCP.

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This work was performed under the general supervision of Dr. Edmond J. Russo Jr., director, EL; Mark Farr, chief, Ecosystem Evaluation and Engineering Division; and Alan Katzenmeyer, chief, EEA.

At the time of publication of this report, Dr. David W. Pittman was director of ERDC. COL Christian Patterson was ERDC commander.

1 Introduction

1.1 Background

Flowering rush (*Butomus umbellatus* L.), a perennial monocot native to Eurasia, was first documented in North America in 1897, and by the early 1900s, it was reported to be established in the northeastern United States (Core 1941; Bellaud 2009). Currently found in all states bordering Canada and the Great Lakes, flowering rush has been documented in Connecticut, Iowa, Massachusetts, Nebraska, Oregon, and South Dakota (Cao, Berent, and Fusaro 2018). Flowering rush is dynamic in its ability to become established in northern lakes and rivers and can thrive in the littoral zones of both quiescent and flowing water systems. It can grow as an emergent plant along shorelines or as a submersed plant in deeper water (up to 6 m), or both (Countryman 1970; Madsen, Wersal, and Marko 2016). Once established, flowering rush can form 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). Potential impacts to salmonid species are a major concern, because dense stands of flowering rush may physically block key migration routes 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 in the Flathead River, Montana (Muhlfeld et al. 2008).

Currently, no reliable strategies provide long-term and selective control of flowering rush, particularly in hydrodynamic systems. Since both emergent and submersed forms create nuisances, each morphological type requires independent control strategies. Attempts to mechanically harvest flowering rush in Detroit Lakes, Minnesota, during the 1990s and 2000s were ineffective and likely resulted in its spread throughout the watershed because of rhizome and rhizome bud displacement. Rhizomes and rhizome buds are important propagules for flowering rush dispersal (Hroudova et al. 1996). At present, there are no biological control agents available for flowering rush control, and chemical management of flowering rush is still

in the formative stages of field development and implementation. Few areas in the United States are conducting operational control of this species, and therefore field studies are limited.

Small-scale studies have shown various levels of control using quick-acting aquatic herbicides alone and in combination with slower-acting systemic herbicides (Poovey et al. 2012, 2013; Wersal et al. 2014; Madsen, Wersal, and Marko 2016). Poovey et al. (2012) reported subsurface applications of endothall (7-oxabicyclo [2.2.1]heptane-2,3-dicarboxylic acid) provided ~75% control, and diquat dibromide [6,7-dihydro-dipyrido (1,2-a:2',1'-c) pyrazinediium dibromide] provided ~95% control of plant shoots at 12 h and 24 h exposure times. In addition, Poovey et al. (2013) reported that subsurface applications of endothall alone and in combination with triclopyr provided >60% control of flowering rush aboveground biomass under experimental conditions. Foliar applications of triclopyr, triclopyr + 2, 4-D, and imazapyr + glyphosate reduced above- and belowground biomass of flowering rush $\geq 70\%$ and 65%, respectively (Wersal et al. 2014). Madsen, Wersal, and Marko (2016) reported that treatments of diquat alone and in combination with fluridone reduced flowering rush aboveground biomass 71% and 96%, respectively, and belowground biomass 85% and 97%, respectively. Field demonstrations in Minnesota using subsurface applications of diquat and endothall for control of submersed flowering rush showed diquat treatments were effective at reducing flowering rush aboveground biomass, whereas endothall did not reduce above- or belowground biomass (Madsen et al. 2012). Additional field demonstrations in Detroit Lakes, Minnesota, in 2012 showed that diquat controlled aboveground biomass and reduced belowground biomass and rhizome bud density with minimal adverse effects on native plant communities (Madsen et al. 2013).

Variable results between studies in an experimental versus field setting is not surprising considering the number of factors that can be attributed to the success or failure of a submersed herbicide application in the field. Most notably, the two elements most responsible for submersed herbicide applications are (1) the concentration of herbicide that comes in contact with the target plant and (2) the length of time a target plant is exposed to dissipating concentrations of herbicide in the water column (Getsinger and Netherland 1997). In most cases, unsuccessful submersed herbicide treatments result from rapid off-target movement of treated water caused by

gravity flow, wind, thermal stratification, tidal movement, and other hydrodynamic processes (Getsinger, Fox, and Haller 1996). Large reservoirs and flowing water systems, where a high rate of water exchange can occur over a relatively short time, present a unique challenge for the operational management of aquatic plant species using submersed herbicide applications—even more so when trying to manage small, newly established populations that require spot treatments or the partial treatment of larger water bodies (Getsinger et al. 1996). Water exchange may be too rapid to maintain adequate herbicide concentrations in potential treatment areas; thus, it is beneficial to identify efficient methods to increase herbicide concentration exposure times (CETs) within these 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 was initially developed for commercial fishing (Kuznetsov 1971) and to mitigate fish intrusion at power generation facilities (Taft 2000; Michaud and Taft 2000). They are relatively inexpensive, require minimal maintenance, and can be repositioned or removed if needed (Zielinski et al. 2014).

1.2 Objective

This study sought to (1) analyze water-exchange patterns within multiple sites along the Columbia River where aquatic plant communities, including flowering rush, occur and (2) evaluate the effectiveness of bubble curtains at reducing water exchange within potential flowering rush treatment areas in the McNary Pool of the Columbia River. To date, no other studies have documented the use of bubble curtains as a potential method for reducing water exchange and increasing herbicide CETs.

1.3 Approach

To provide guidance on the management of submersed flowering rush (*Butomus umbellatus* L.), field trials evaluated water-exchange processes at five sites in McNary Dam and Reservoir using rhodamine WT (RWT)

dye. Water exchange information from the field can be used to develop herbicide concentration and exposure time (CET) relationships to predict levels of control following herbicide exposure to target plants at various concentrations. In addition, BubbleTubing (hereafter referred to as *bubble curtain*) was evaluated as a potential method for reducing water exchange within probable flowering rush treatment areas.

2 Materials and Methods

2.1 Evaluation site

McNary Dam and Reservoir (Wallula Lake, 15,702 ha) is 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 km¹ (65 miles)² along the Columbia River, 16 km along the Snake River, and 9.7 along the Yakima River. McNary is a run-of-the-river reservoir, and as such acts as a hydrodynamic system with constantly flowing water. Since 2008, flowering rush has spread throughout the Columbia River watershed, including the McNary Pool near Kennewick, Washington. It was first reported in the upper portion of the reservoir at the mouth of the Yakima River in 2008. As of 2017, the plant has been documented in numerous locations within the reservoir, primarily small, isolated patches and in stands <1 ha in size. Observations indicate that most flowering rush populations in these locations never break the water surface and remain submerged. In shallow areas (1–2 m), flowering rush grows in mixed stands of aquatic species (for example, milfoils [*Myriophyllum* spp.], elodea [*Elodea canadensis* Michx], and pondweeds [*Potamogeton* spp.]); however, in deeper areas (2–6 m) there is reduced competition from other plants. This dynamic reservoir system presents a complex matrix to determine treatment options that work best for control of flowering rush—particularly using herbicides in short CET settings.

2.2 Site selection and evaluation methods

Five sites were chosen within the Columbia River to evaluate water exchange (figure 1). These sites were chosen to represent varying water-exchange patterns according to visual observations. One of the five sites was established to evaluate the effectiveness of bubble curtains for reducing water exchange. The sites ranged 0.68 to 3.02 ha and were spaced ≥1.9 km

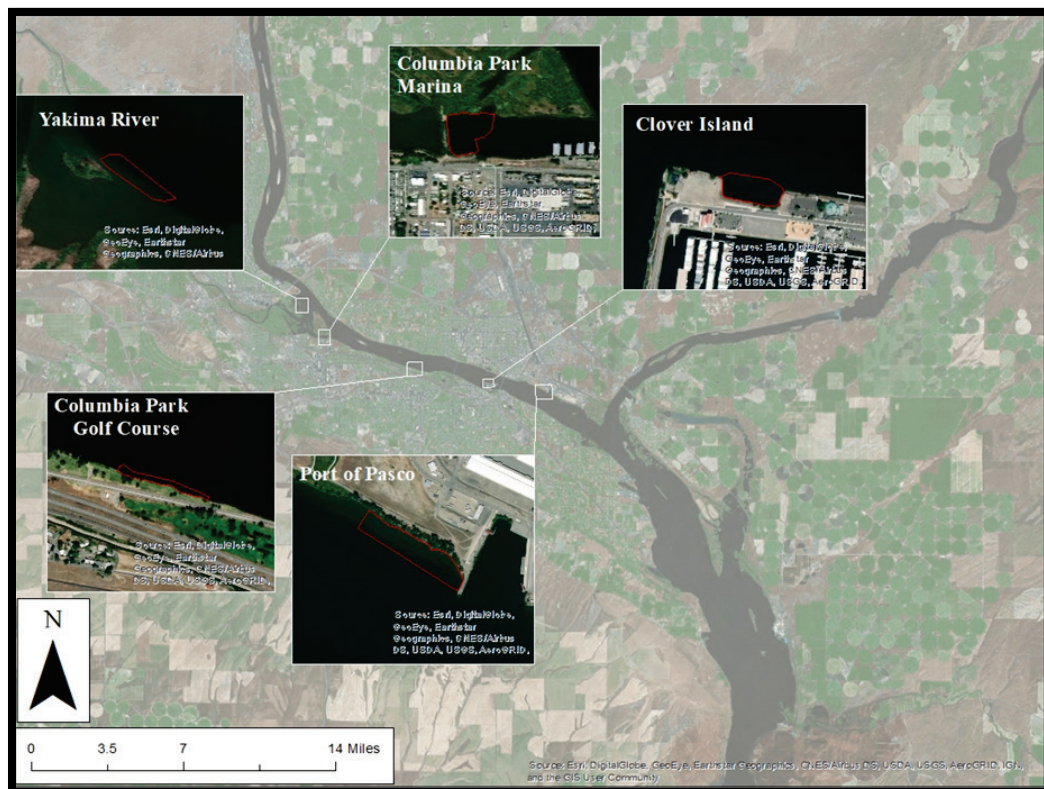
1. For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

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to prevent aqueous drift of dye into adjacent sites. Area and average depth were determined within each site prior to dye application.

Rhodamine-WT (RWT) dye was used to assess water-exchange patterns within each of the five sites. The dye resists absorption by plants and sediments (Smart and Laidlaw 1977; Turner, Netherland, and Getsinger 1991, Turner, Getsinger, and Netherland 1994), and research has demonstrated significant correlations between dissipation patterns of aquatic herbicides and RWT fluorescent dye (Fox, Haller, and Getsinger 1991; Fox, Haller, and Getsinger 1992; Fox, Haller, and Getsinger 1993; Turner, Getsinger, and Netherland. 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 (Fox, Haller, and Getsinger 1992; Fox, Haller, and Getsinger 1993; Turner, Getsinger, and Netherland 1994; Getsinger and Netherland 1997; Getsinger et al. 2000; Poovey et al. 2004; Getsinger et al. 2013).

Figure 1. Location of the water-exchange sites within the McNary Pool of the Columbia River, Washington, evaluated in August 2018.



Dye was uniformly applied throughout the water column at all sites using a boat-mounted spray boom affixed with eight equally spaced, weighted hoses to achieve an aqueous target concentration of $10 \mu\text{g L}^{-1}$. This inert fluorescent dye was developed specifically for water tracing and can be monitored and quantified in situ using a fluorometer at detection limits of $0.1 \mu\text{g L}^{-1}$ (Turner, Getsinger, and Netherland 1994). Dye measurements were collected in situ at predetermined sampling stations within each plot (figure 2 and 3) using a handheld Cyclops-7 submersible fluorometer (Turner Designs, Sunnyvale, California) and a Turner Designs field fluorometer (Turner Designs, Sunnyvale, California). At site #5, dye was also measured using an unattended data sonde (HYDROLAB HL4 Sonde, Ott HydroMet, Kempton, Germany) that was positioned near the center of the plot 0.5 m below the water surface and set to collect data at 10 min intervals. Dye concentrations were measured in the plot for 24 h or until dye readings were ≤ 1 .

Figure 2. Points sampled for rhodamine-WT (RWT) dye at Yakima River Site #1 (*left*) and Columbia Park Marina Site #2 (*right*).

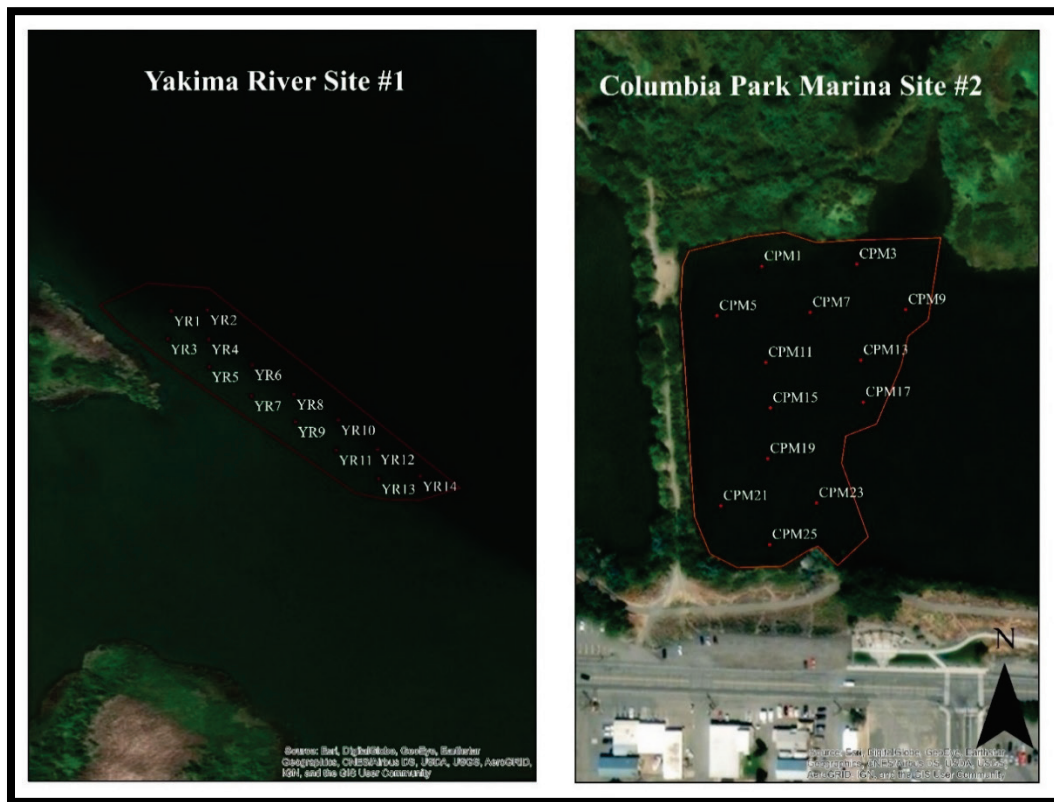


Figure 3. Points sampled for rhodamine-WT (RWT) dye at Columbia Park Golf Course Site #3 (*left*) and Port of Pasco Site #4 (*right*).



Water turbidity, temperature, pH, and dissolved oxygen (DO) were collected using a handheld water-quality measurement device (HYDROLAB DSX5, Ott HydroMet, Kempton, Germany). Water-quality measurements were taken from a boat at 1/3 depth and 2/3 depth ranges at three to five points (depending on site area) within each site prior to dye application. Water-quality data for all sites are presented in table 1. Quantitative vegetation assessments were also conducted by navigating to predetermined points within each site and deploying a two-sided rake head (Madsen and Wersal 2017). These assessments were used to determine the condition of the plant community in the treated plots. All plants attached to the rake were identified by species, and plant density was estimated on a 0–5 scale, where 0 = species not present; 1 = trace material present; 2 = 1%–25% plant coverage; 3 = 25%–50% plant coverage; 4 = 50%–75% plant coverage; and 5 = 75%–100% plant coverage.

Table 1. Water-quality measurements collected at each site in the McNary Pool of the Columbia River.

	Shallow ^a				Deep ^b				
	TEMP ^c (°C)	PH	DO ^d (mg/L ⁻¹)	SCOND ^e	TEMP ^c (°C)	PH	DO ^d (mg/L ⁻¹)	SCOND ^e	TURB ^f
Yakima River Site #1									
YR1	20.21	8.59	7.9	133.2	20.23	8.54	7.8	133.9	N/A
YR5	20.13	8.61	7.86	133.3	20.17	8.6	8.02	133.4	N/A
YR8	20.21	8.59	7.88	133.4	20.15	8.56	7.86	133.8	N/A
YR11	20.16	8.66	8.04	133.5	20.19	8.62	8.04	133.5	N/A
YR14	20.19	8.59	7.84	133.1	20.21	8.56	7.86	133.4	N/A
Columbia Park Marina Site #2									
CPM3	21.16	8.75	7.94	151.7	21.15	8.78	8.08	150.9	12.8
CPM7	21.17	9.15	9.48	149.9	20.6	8.29	8.25	151.5	15.9
CPM11	21.17	9.27	9.77	149.9	20.58	8.35	4.03	151.7	5.3
CPM15	21.17	9.26	9.89	149.7	20.28	8.19	1.06	157.1	5.5
CPM19	21.18	9.28	10.07	149.4	20.34	8.09	2.17	156.2	4
Columbia Park Golf Course Site #3									
CPGC1	19.92	8.49	7.98	140.3	19.96	8.55	7.97	140.3	0.33
CPGC3	19.92	8.61	7.93	141.4	19.9	8.6	7.92	142.3	0.5
CPGC5	19.92	8.64	7.96	N/A	19.93	N/A	N/A	N/A	0.53
Port of Pasco Site #4									
PP3	20.39	8.74	9.04	149.1	20.43	8.97	9.17	150.0	0.26
PP9	20.39	8.9	9.06	148.5	20.44	8.84	9.09	149.3	0.54
PP13	20.97	9.24	10.53	152.9	20.77	9.2	10.53	152.3	0.45
PP21	21.17	9.38	11.18	152.1	20.99	9.36	11.15	151.4	0.33
PP27	21.29	9.45	11.88	154.7	20.8	9.4	11.86	153.2	0.21
Clover Island Site #5									
CI 4	20.9	9.19	9.66	141.3	20.7	9.1	9.5	141.8	15.5
CI 6	20.4	9.01	8.64	146	20.42	8.83	8.17	146	13.9
CI 8	20.6	9.13	9.13	143.5	20.64	9.07	9.08	143.7	11.7

Note: Letters and numbers below each site name represent the points sampled at each site.

^a *Shallow* indicates measurements collected at the top portion of the water column.

^b *Deep* indicates measurements collected from the bottom of the water column.

^c temperature

^d dissolved oxygen

^e specific conductivity

^f turbidity

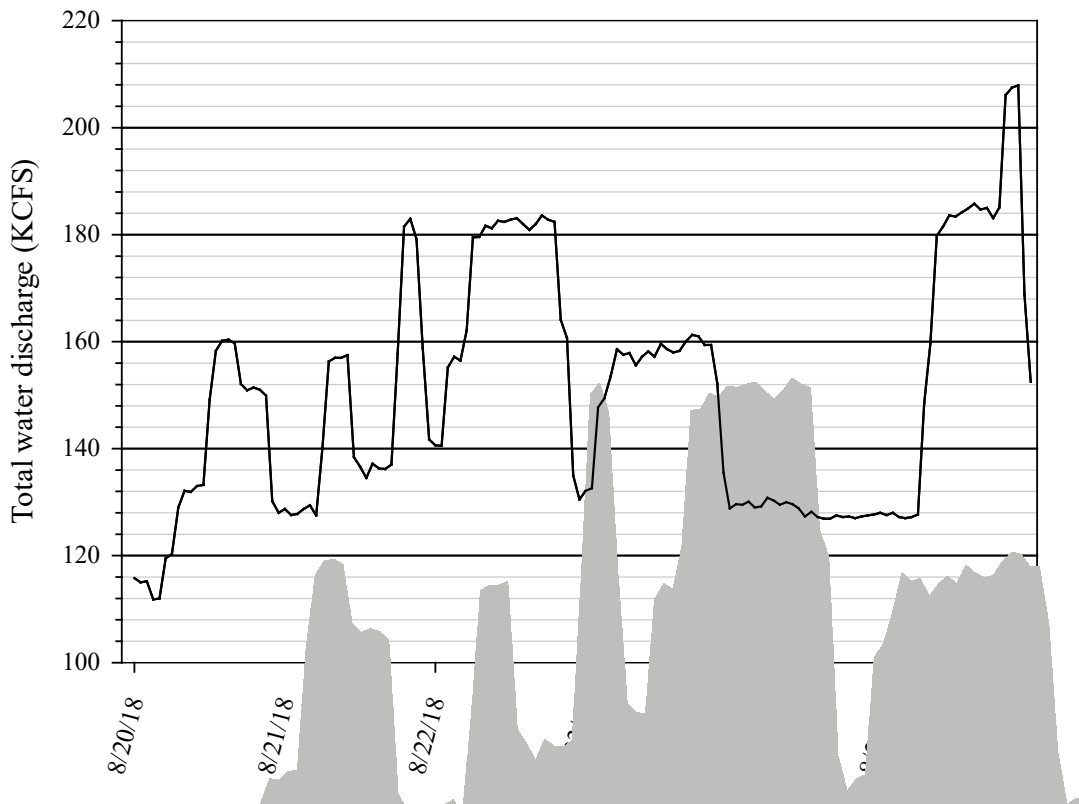
RWT dye measurements were subjected to a nonlinear exponential decay regression using SigmaPlot 11.0 statistical software (Systat Software, San Jose, California) to calculate shallow-, mid-, bottom-, and whole-plot dye half-lives within each site. Two-dimensional (2D) illustrations of dye concentrations were modeled for surface, middle, and bottom of the water-column measurements within each site at select times after treatment. Model inputs included field-derived dye concentrations at permanent dye-sampling points within each plot at surface, mid, and bottom depths. Using the ArcGIS Spatial Analyst extension's tools in ArcMap 10.3.1 (ESRI, Redlands, California) a raster surface-layer representative of dye concentrations throughout the treatment area was spatially interpolated from point data using an inverse-distance-weighted (IDW) technique.

2.3 Site characteristics

2.3.1 Yakima River Site #1

Yakima River Site #1 (lat 46°15'14.61" N, long 119°14'17.99" W) was a 1.42 ha plot located in the Yakima River Delta. The site was positioned parallel to the northeast side of a small island, approximately 0.57 km west-northwest of the confluence of the Yakima and Columbia Rivers and 0.57 km southwest of the main channel of the Columbia River in between river mile 335 and 336 (figure 1). The average depth of the site was 2.1 m, and it was relatively shallow (<1.5 m) near the island. Depth increased gradually moving away from the island to a maximum depth of 3.6 m. The submerged plants flowering rush, coontail (*Ceratophyllum demersum* L.), elodea, sago pondweed (*Stuckenia pectinata* (L.) Börner), clasping-leaf pondweed (*Potamogeton perfoliatus* L.), Eurasian water milfoil (*Myriophyllum spicatum* L.), curly-leaf pondweed (*Potamogeton crispus* L.), and water star grass (*Heteranthera dubia* (Jacq.) MacMill.) were documented within the site. RWT dye was applied on the morning of 22 August 2018 (start: 0750, end: 0800) under favorable weather conditions with light north winds at 0–1.6 kmph. Readings were collected at 1, 2, 3, 4, and 7 hours after treatment (HAT). Total water discharge at McNary Dam was 179.5 thousand cubic feet per second (KCFS) at treatment and 182.0 KCFS at 7 HAT (figure 4).

Figure 4. McNary Dam total water discharge in thousand cubic feet per second (KCFS) 20 August 2018 to 25 August 2018.



2.3.2 Columbia Park Marina Site #2

Columbia Park Marina Site #2 (lat 46°14'20.72" N, long 119°13'27.55" W) was a 1.81 ha plot located at the back of a dead-end canal bordered by Bateman Island to the north and a small gravel levee to the west (figure 1). It had the deepest average depth (3.4 m) compared to the other sites and was positioned 0.32 km from Columbia Park Marina and 0.82 km from the center of the Columbia River main channel. It had a shallow shoreline (≤ 3 m) along the site perimeter, and depth increased substantially moving away from the shoreline to a maximum depth of 7.5 m and minimal depth variation in the center of the plot. Sparse flowering rush was documented along the shoreline of the site; however, coontail, elodea, and sago pondweed were abundant. Dye was applied on the morning of 22 August 2018 (start: 1127, end: 1137) under favorable weather conditions with light easterly winds at 1.6–4.8 kmph. Dye measurements were recorded at 0.5, 1.5, 2.5, 4, and 21 HAT. Total water discharge at McNary Dam was 182.6 KCFS at treatment and reached a maximum discharge of 183.6 KCFS at 1800, 6.5 HAT (figure 4).

2.3.3 Columbia Park Golf Course Site #3

Columbia Park Golf Course Site #3 (lat 46°13'31.57" N, long 119°10'0.93" W) was a narrow strip positioned on the western shoreline of the Columbia River main channel (figure 1). It was the smallest site, at 0.68 ha, with an average depth of 2.9 m. Water depth along the shoreline ranged 1.5–2 m and increased to 3.5–4.3 m along the outer edge of the plot. Flowering rush, coontail, elodea, curly-leaf pondweed, Eurasian water milfoil, and water star grass dominated. Dye was applied on the morning of 25 August 2018 (start: 0740, end: 0750) with south winds at 16 kmph. Dye measurements were recorded at 0.5, 1, 1.5, and 2 HAT. Total water discharge at McNary Dam was 159.7 KCFS at treatment and 179.8 and 181.5 KCFS at 1 and 2 HAT, respectively (figure 4).

2.3.4 Port of Pasco Site #4

Port of Pasco Site #4 (lat 46°12'48.66" N, long 119°4'33.91" W) was positioned along the shoreline on a narrow flat (average depth 1.7 m) that ran east to west parallel to the main channel of the Columbia River (figure 1). It was the largest site evaluated, at 3.02 ha, and was located just upstream from a loading dock at the Port of Pasco Industrial Park, Washington. The north edge of the site was bordered by a rip-rap shoreline and a small peninsula on the downstream end that extended out into the river channel. Water depth increased quickly from 1.2 m along the shoreline to upwards of 3 m along the plot edge towards the main channel. The peninsula on the downstream end provided a current break that allowed multiple plant species to establish along the shoreline. Flowering rush occupied over 50% of the sampling site and had the greatest occurrence and density compared to the other evaluation sites. Additional plant species present included coontail, elodea, sago pondweed, curly-leaf pondweed, Eurasian water milfoil, and water star grass. Dye was applied on the 25 August 2018 (start: 1230, end: 1240) with south winds at 24 kmph. Dye measurements were recorded at 0.5, 1.5, 2.5, and 4 HAT. McNary Dam total water discharge at treatment was 184.2 KCFS and was maintained between 184 and 185 KCFS throughout the sampling period (figure 4).

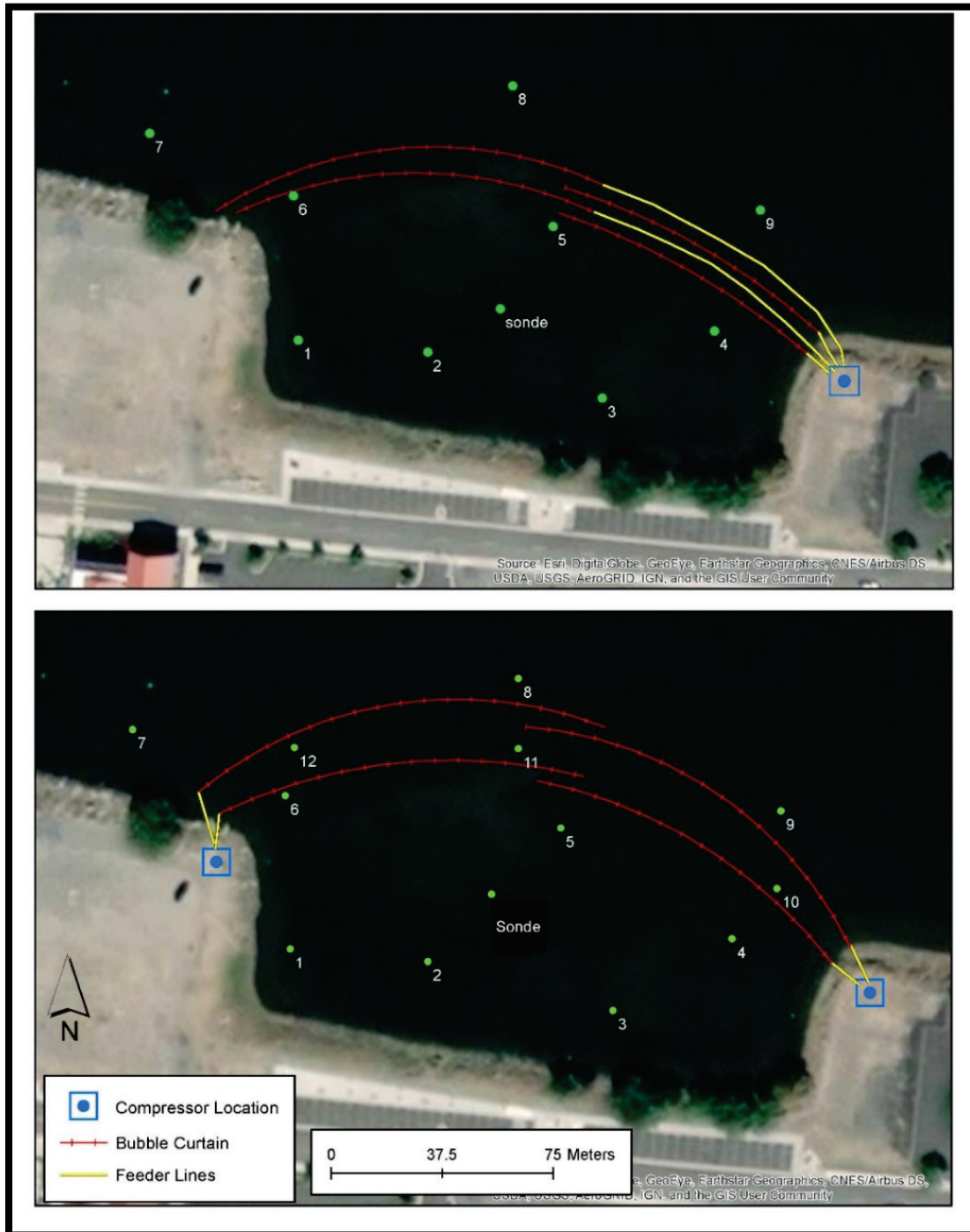
2.3.5 Clover Island Site #5

Clover Island Site #5 (lat 46°13'4.30" N, long 119°6'49.38" W) was a small (0.73 ha), artificial shallow bay with an average depth of 1.3 m. It was located on the north side of Clover Island, a 6.5 ha, fully developed commercial property owned by the Port of Kennewick. It 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. It was heavily vegetated with elodea, coontail, water star grass, sago pondweed, clasping-leaf pondweed, small pondweed (*Potamogeton pusillus* L.), and Eurasian water milfoil. Sparse flowering rush was documented in several locations. Dye was applied on 21 August 2018 (start: 1326, end: 1337) under hazy skies with north winds at 16–24 kmph. Dye measurements were recorded at 0, 3, 6, and 16 HAT. Total water discharge at McNary Dam was 136.6 KCFS at treatment, where it remained relatively steady between 134 and 137 KCFS up to 6 HAT. Water discharge increased to 157.8 KCFS 7 HAT and reached a maximum of 183.0 KCFS at 9 HAT (figure 4). Because site #5 was relatively shallow, initial dye measurements were collected from the middle of the water column. Site #5 was also selected as the test site to evaluate the effectiveness of bubble curtains for reducing water exchange.

2.4 Bubble curtain assessment

Three water-exchange evaluations were conducted at Clover Island Site #5. The first evaluation was conducted without the use of a bubble curtain, while the second and third evaluations were conducted with a bubble curtain under different configurations and rates of airflow (figure 5). Each bubble-curtain configuration used 375.7 m of 2.54 cm inside diameter (ID) weighted BubbleTubing (Canadianpond.ca Products, Montreal, Canada) sectioned into four 91.4 m segments. BubbleTubing is a flexible, durable, linear-aeration tubing equipped with two rows of perforated holes, spaced 1.27 cm apart, which run the entire length of the tubing. It was weighted with a solid-core ballast along its entire length, allowing it to sink and remain in place along the river bottom.

Figure 5. Example of bubble-curtain configurations for Bubble Curtain Evaluation 1 (*top*) and Bubble Curtain Evaluation 2 (*bottom*), during August 2018 at Clover Island Site #5.



Both bubble curtain evaluations used a double-curtain arrangement, with two curtains operating parallel to the other. However, curtain spacing and rate of airflow varied between evaluations. Evaluation #1 used a Doosan

HP375 (Doosan Group, Seoul, South Korea) diesel air compressor (375 cubic feet per minute [CFM] rating, 150 pounds per square inch [PSI] [10.62 cubic meters per minute, 1034.21 kilopascal]) pressure rating to deliver a continuous stream of air at a flow rate of 0.31 CFM per foot. The mainline from the compressor was fitted to a six-valve manifold equipped with a pressure gauge and bleeder valve. Four feeder lines were affixed to the manifold and ran to the water's edge. Two of the four feeder lines were attached to the bubble curtain at the shoreline, and the additional two feeder lines extended to the midpoint of the plot and connected to the two additional bubble-curtain segments. This configuration, as shown in figure 5, maintained adequate, evenly distributed airflow throughout all four segments of bubble curtain and prevented air pressure loss at the upstream end. The two curtains in the double-curtain arrangement ran parallel and were spaced <2.5 m apart. To minimize the influence of gaps between segments at the mid-point of the plot, the bubble curtain was arranged so that each segment overlapped the adjacent segment by at least 4.5 m (figure 5). Dye was applied on the morning of 22 August 2018 (start: 0920, end: 0936) under calm north winds at 0 to 8 kph. Dye measurements were recorded at nine predetermined points, six inside the curtain and three along the outside edge of the curtain at 0, 1, 3, 6, 9, and 12 HAT. Dye readings were collected from the middle of the water column at each sampling station. Total water discharge at McNary Dam was 181.7 KCFS at treatment and remained relatively steady between 180 and 183 KCFS up to 11 HAT. Discharge decreased from 182.4 at 11 HAT to 164.1 at 12 HAT (figure 4).

Bubble Curtain Evaluation 2 used the same Doosan HP375 air compressor as in evaluation #1 plus an additional Doosan HP375WCUIQ (Doosan Group, Seoul, South Korea) diesel air compressor [375 CFM rating, 150 PSI pressure rating]. The Doosan HP375WCUIQ has the same CFM rating and PSI rating as the Doosan HP375 but is rated for continuous-duty operation. Either of the two models were sufficient for operating the bubble curtain. The additional compressor was stationed on the upstream end of the site, opposite of the compressor used in evaluation #1 (figure 5 bottom).

Each compressor was connected to two bubble-curtain segments, an inside segment and outside segment. The ends of the inside and outside segment, from each compressor, were placed parallel with a 4.5 m overlap, where they joined at the midpoint of the plot boundary to minimize gap effects in the curtain. Using dual compressors with simultaneous operation supplied

air evenly at 0.62 CFM per foot through all bubble-curtain segments. Spacing between the inside and outside segments was increased, compared to evaluation #1, so that a ≥ 2.5 m gap was present between the inside and outside curtains. Dye was applied on the morning of 23 August 2018 (start: 0947, end: 0958) under windy conditions (south-southwest at 24 to 32 kmph). Total water discharge at McNary Dam was 157.2 KCFS at treatment and remained relatively steady between 157 and 161.3 KCFS up to 12 HAT (figure 4). Three additional dye-sampling points were established between the inside and outside curtains, and measurements were recorded at 12 points total: 6 inside the curtain, 3 along the outside edge of the curtain, and 3 in between the curtains at 0, 1, 3, 6, 9, 12 and 14 HAT. Dye measurements were collected from 1/3 and 2/3 depths at each dye-sampling station.

3 Results and Discussion

3.1 Yakima River Site #1

The whole-plot half-life for RWT at Yakima River Site #1 was 2.6 h (figure 6). The whole-plot dye concentration at 1 HAT was $3.8 \mu\text{g L}^{-1}$ throughout, and measurements at shallow, medium, and deep depth ranges demonstrated that dye was concentrated in the upper and middle portions of the water column along the shallow edge of the plot. Deep measurements along the outer plot edge indicated that dye quickly became mixed and accumulated in these areas (figure 7). By 2 HAT, dye had become diluted near the water surface, and $>50\%$ of the sample points displayed concentrations $\leq 1.4 \mu\text{g L}^{-1}$ at the top of the water column. Mid-depth readings were slightly higher than surface readings at 2 HAT (figure 8) but overall displayed a similar pattern as the 1 HAT mid-depth readings. Bottom dye measurements 2 HAT indicated that dye had dissipated into deeper areas adjacent to high-concentration shallow areas 1 HAT. At 3 HAT, the bottom measurements on the downstream portion of the plot maintained the highest concentrations of dye with the exception of one sampling point, which consistently held dye at all sampling depths and intervals (figure 9). All sample points recorded measurements $\leq 3.3 \mu\text{g L}^{-1}$ by 7 HAT, with the exception of one point on the far upstream end of the plot, which registered a mid-depth dye reading of $5.9 \mu\text{g L}^{-1}$ (figure 10). This last reading was unexpected considering no points on the upstream end of the plot recorded a dye concentration $>5.9 \mu\text{g L}^{-1}$ (1 HAT) at any of the sampling intervals.

Figure 6. Mean RWT dye concentration (\pm SE) for each sampling period at Yakima River Site #1. Dye dissipation and dye half-life was estimated across depths (A), top of the water column (B), middle of the water column (C), and bottom of the water column (D) using nonlinear regression (exponential decay, $f = a \exp[-b x]$).

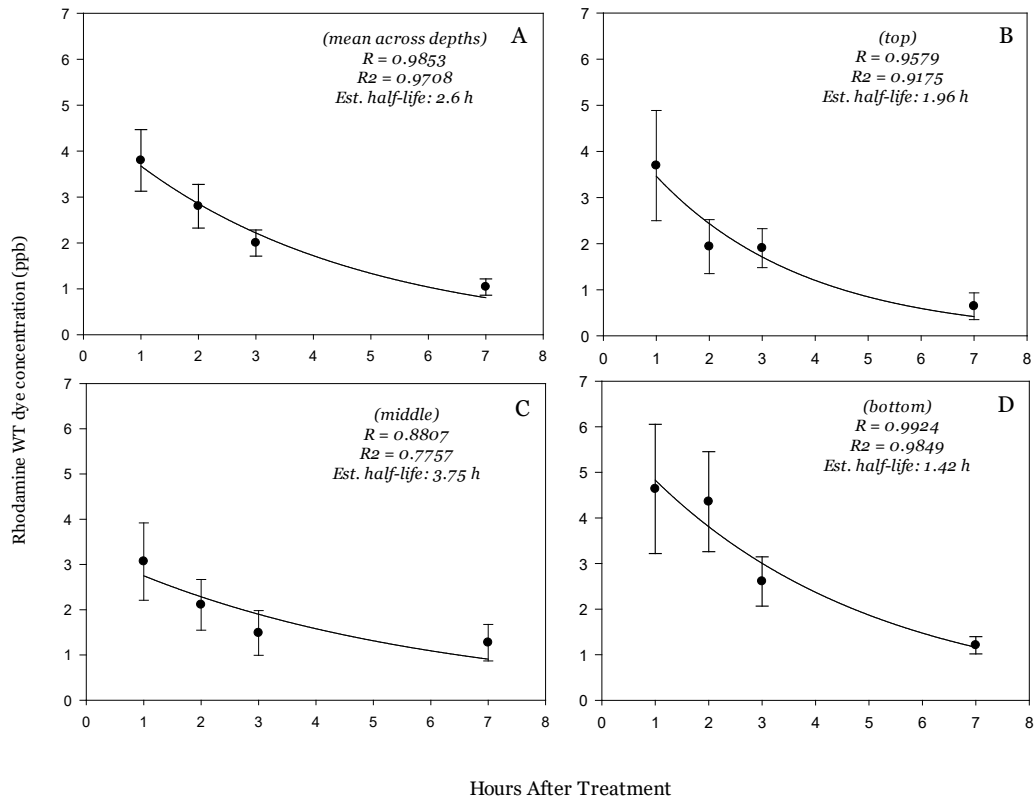


Figure 7. RWT dye concentrations predicted at Yakima River Site #1 at the top (A), middle (B) and bottom (C) of the water column 1 hour after treatment (HAT). The colors represent predictions, while the numbers at each point represent actual recorded dye measurements.

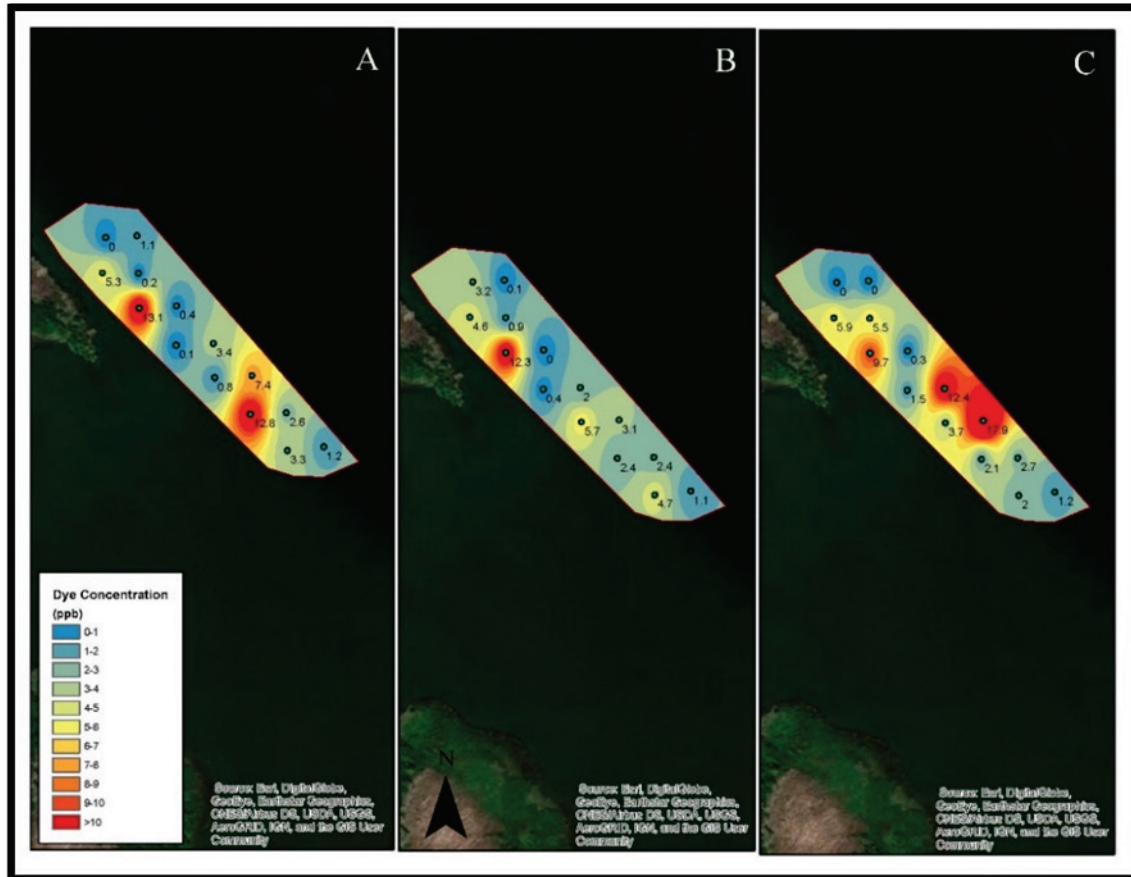


Figure 8. RWT dye concentrations predicted at Yakima River Site #1 at the top (A), middle (B) and bottom (C) of the water column 2 HAT. The numbers at each point represent actual recorded dye measurements.

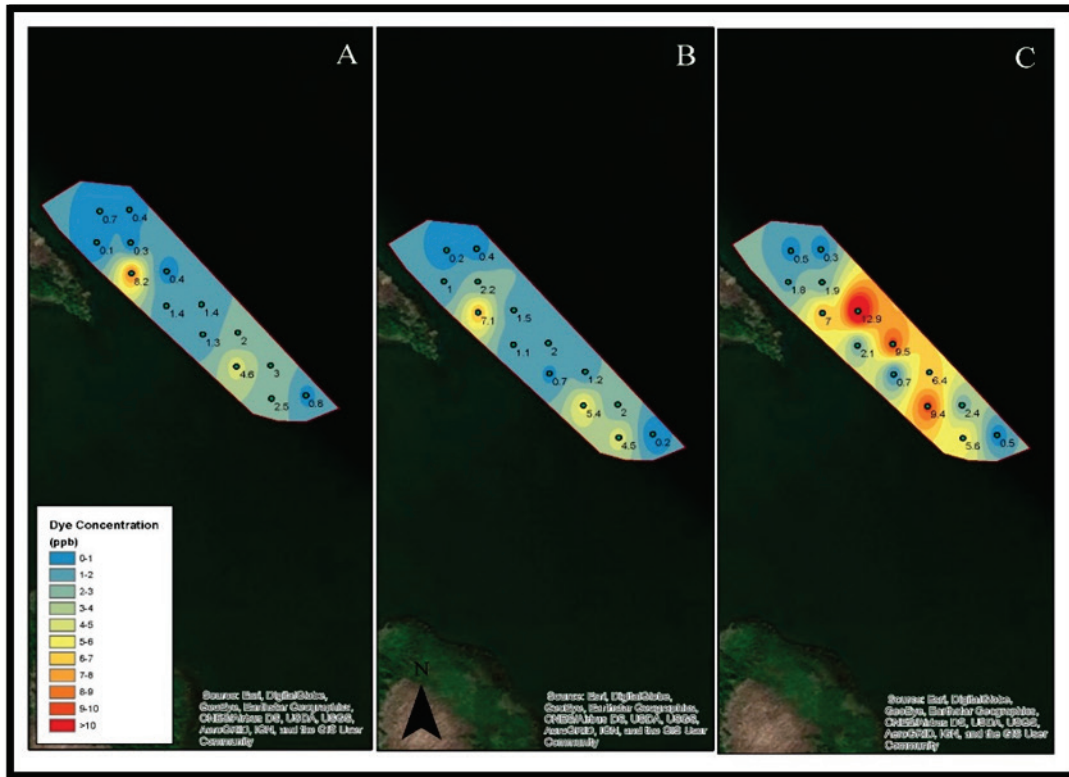


Figure 9. RWT dye concentrations predicted at Yakima River Site #1 at the top (A), middle (B) and bottom (C) of the water column 3 HAT. The numbers at each point represent actual recorded dye measurements.

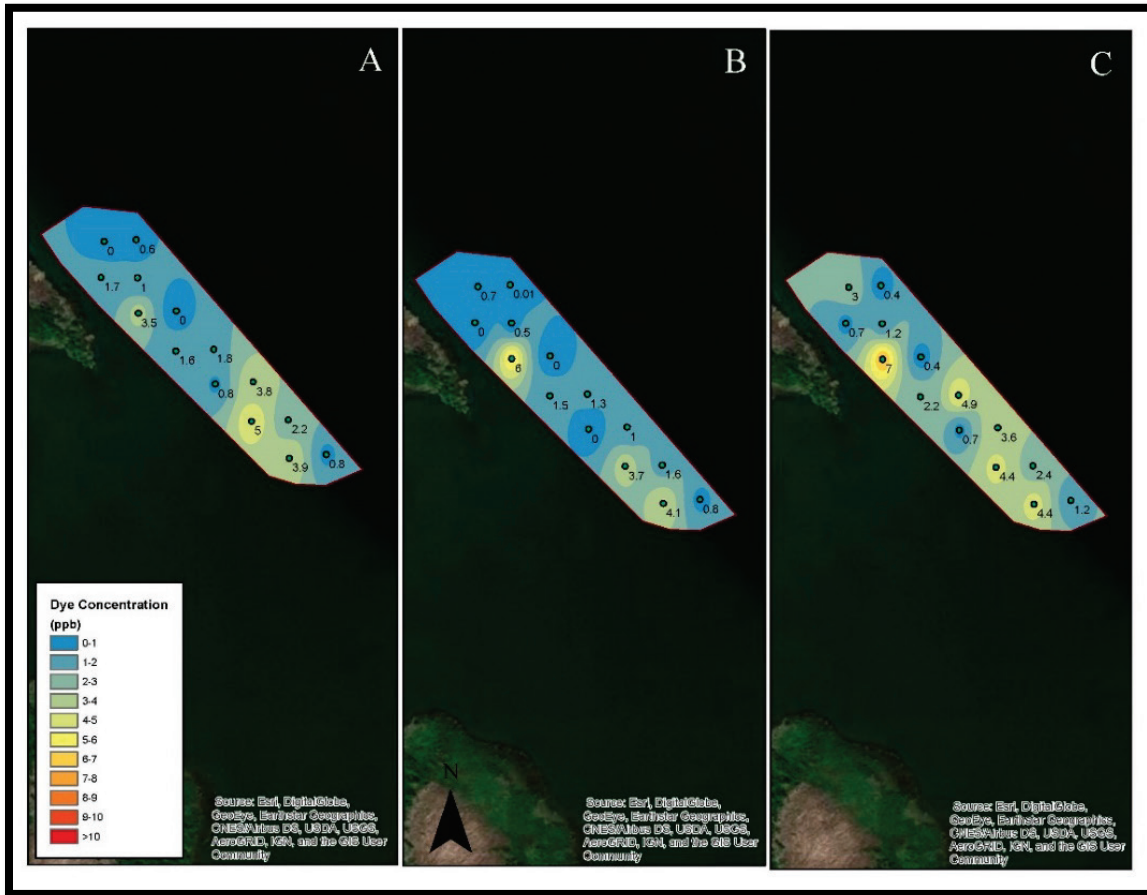
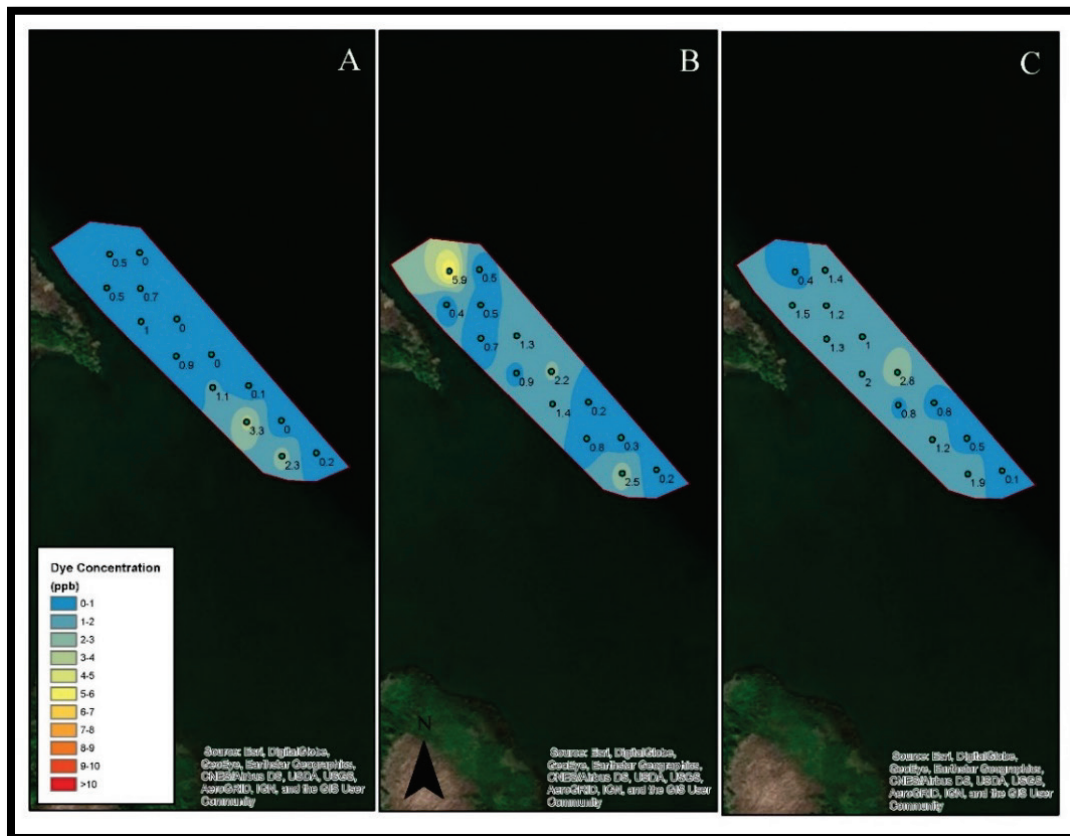


Figure 10. RWT dye concentrations predicted at Yakima River Site #1 at the top (A), middle (B) and bottom (C) of the water column 7 HAT. The numbers at each point represent actual recorded dye measurements.



The Yakima River site displayed moderate water exchange in comparison to the other dye sites. A 2.6 h dye half-life indicates that the herbicide diquat should have sufficient contact time to significantly reduce flowering rush aboveground biomass; however, repeat applications to provide more complete control of the plants would likely be necessary. Dye studies in combination with herbicide trials for managing flowering rush in the Detroit Lakes, Minnesota, showed that diquat applications significantly reduced aboveground biomass when compared to the reference 4 weeks after treatment under an estimated half-life of 2 h (Madsen et al. 2012). Therefore, the whole-plot dye half-life within the Yakima River site indicates that diquat would be a suitable management tool for flowering rush under the water-exchange conditions that occurred during the evaluation period.

3.2 Columbia Park Marina Site #2

Columbia Park Marina Site #2 had the longest whole-plot dye half-life, at 6.7 h, in comparison to all other sites (figure 11). Measurements at 0.5 HAT indicated that dye was concentrated in the upper portion of the water column, and all surface measurements indicated concentrations $\geq 9.2 \mu\text{g L}^{-1}$, with the exception of one point located along the northern shoreline of the plot (figure 12). Middle and bottom depth readings indicated that dye concentrations were higher along the shallow shoreline areas and that uniform dye mixing was slower in deeper portions of the site. At 1.5 HAT, surface dye concentrations had begun to dissipate within the center of the plot; however, shoreline areas still maintained concentrations at or above the target concentration of $10 \mu\text{g L}^{-1}$ (figure 13). Middle and bottom depth measurements indicated that dye failed to mix uniformly throughout the water column, specifically in the deeper areas at the center of the plot (figures 14–16). During treatment and data collection, east winds were blowing into the site at 1.6–4.8 kmph, making it unlikely that wind currents were transporting dye across the water surface and out of the site. Dye dissipation was likely the result of water currents transporting dye just below the surface into nearby shallow areas or out of the treatment area, or both. In addition, water-quality measurements documented DO levels to be at or below 2.17 mg L^{-1} in deeper areas near the center of the plot (table 1), substantially lower than shoreline areas ($\geq 8.0 \text{ mg L}^{-1}$), indicating that stratification of the water column was preventing dye mixing.

An estimated dye half-life of 6.7 h indicates that diquat would be an excellent option for controlling flowering rush within this site or areas with similar water exchange. Research has shown that subsurface diquat applications with a contact time ≥ 6 h can provide a 95 % reduction of flowering rush aboveground biomass. In addition, a CET greater than 6 h opens up opportunities for additional products that require longer CETs. Under experimental settings, subsurface applications of endothall with a 12 h contact time reduced flowering rush aboveground biomass by 70%–75 % (Poovey et al. 2012), and field evaluations have also demonstrated some efficacy with contact times between 3 and 12 h (Madsen et al. 2012). Therefore, the whole-plot dye half-life within Columbia Park Marina Site #2 indicates that diquat and endothall could be potential management tools for flowering rush.

Figure 11. Mean RWT dye concentration (\pm SE) for each sampling period at Columbia Park Marina Site #2. Dye dissipation and dye half-life were estimated across depths (A), top of the water column (B), middle of the water column (C), and bottom of the water column (D) using nonlinear regression (exponential decay, $f = a \exp[-b x]$).

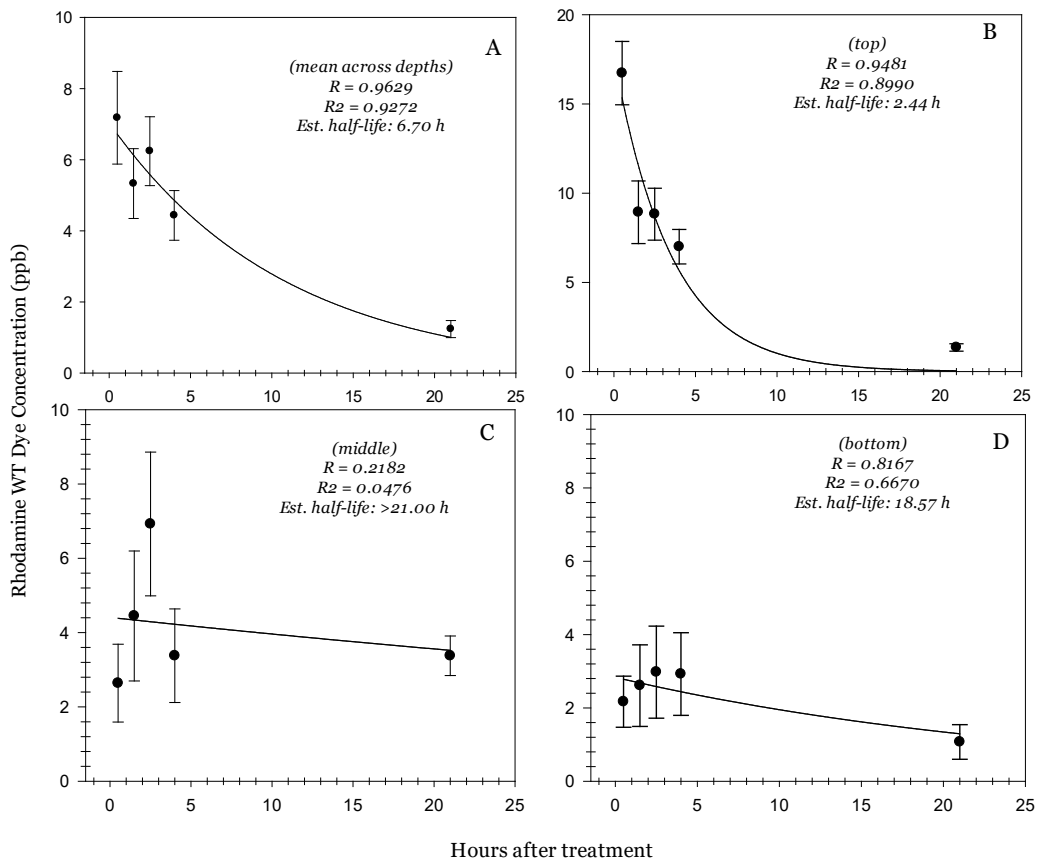


Figure 12. RWT dye concentrations predicted at Columbia Park Marina Site #2 at the top (A), middle (B) and bottom (C) of the water column 0.5 HAT. The numbers at each point represent actual dye measurements recorded.

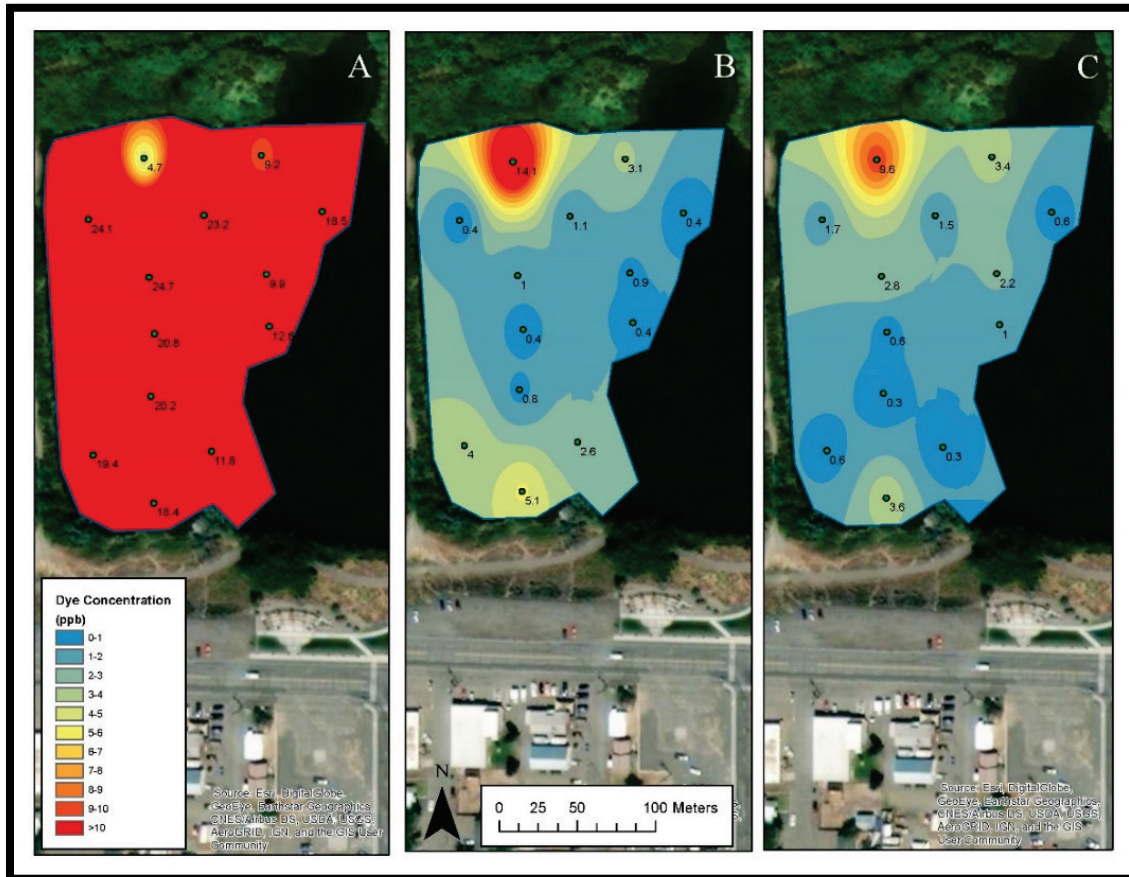


Figure 13. RWT dye concentrations predicted at Columbia Park Marina Site #2 at the top (A), middle (B) and bottom (C) of the water column 1.5 HAT. The numbers at each point represent actual recorded dye measurements

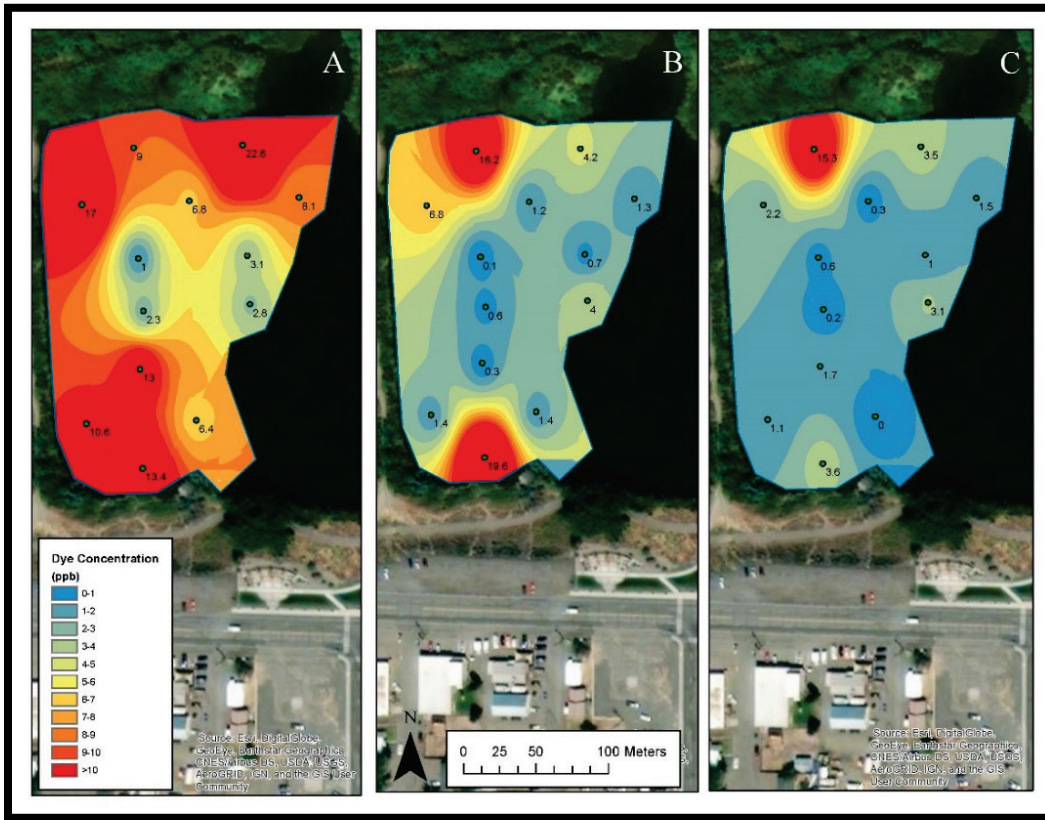


Figure 14. RWT dye concentrations predicted at Columbia Park Marina Site #2 at the top (A), middle (B) and bottom (C) of the water column 2.5 HAT. The numbers at each point represent actual recorded dye measurements.

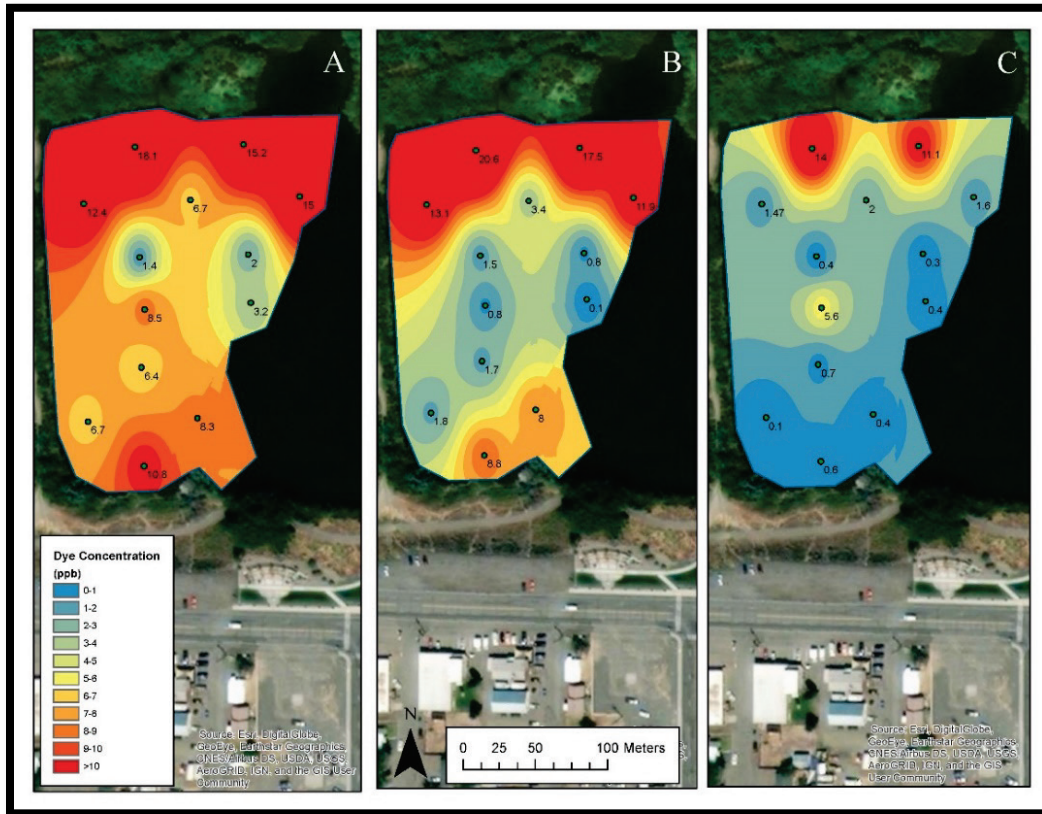


Figure 15. RWT dye concentrations predicted at Columbia Park Marina Site #2 at the top (A), middle (B) and bottom (C) of the water column 4 HAT. The numbers at each point represent actual recorded dye measurements.

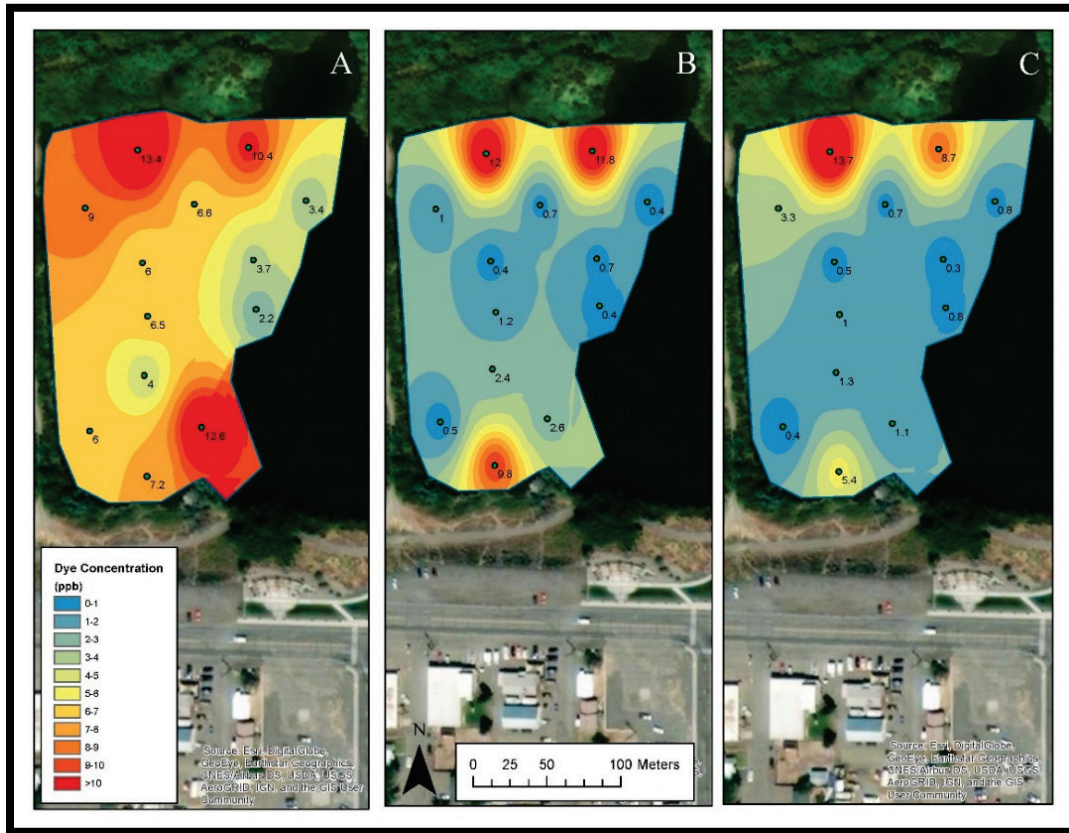
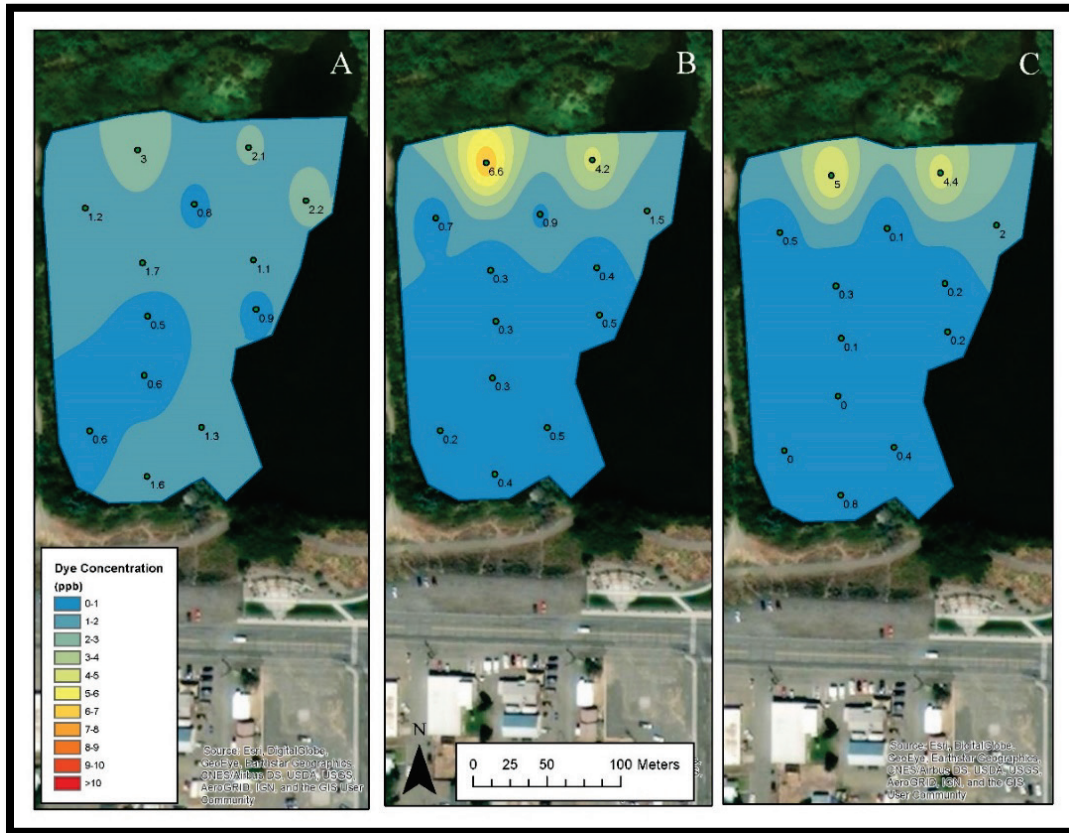


Figure 16. RWT dye concentrations predicted at Columbia Park Marina Site #2 at the top (A), middle (B) and bottom (C) of the water column 21 HAT. The numbers at each point represent actual recorded dye measurements.



3.3 Columbia Park Golf Course Site #3

RWT dye dissipation at Columbia Park Golf Course Site #3 was extremely rapid, with an estimated whole-plot half-life of only 0.6 h (figure 17). Rapid dissipation of dye was expected because of the narrow site's position along the shoreline of the Columbia River main channel. Currents most likely limited dye mixing, particularly on the upstream portion of the site, where only minimal traces of dye were measured at all sampling intervals. At 0.5 HAT, middle and bottom depth measurements on the downstream portion of the site provided the highest readings, of 4.3 and 3.6 $\mu\text{g L}^{-1}$, respectively (figure 18), while readings on the upstream end never exceeded 2 $\mu\text{g L}^{-1}$. Mid-plot readings indicated elevated dye levels compared to upstream sampling points and were likely the result of dye moving downstream and temporarily accumulating in these areas. By 1 HAT, no dye readings exceeded 2.7 $\mu\text{g L}^{-1}$, and the majority of traceable dye was measured at the middle and bottom of the water column (figure 19). At 1.5 HAT, all dye readings were $\leq 1.6 \mu\text{g L}^{-1}$ (figure 20), and by 2 HAT, all sampling points indicated dye concentrations to be less than 1 $\mu\text{g L}^{-1}$, except for middle and bottom depth readings on the downstream end of the site, which were 1.5 and 1.3 $\mu\text{g L}^{-1}$, respectively (figure 21). The rapid flushing of dye out of the Columbia Park Golf Course site severely limits the number of management options available, and sufficient CET requirements for controlling flowering rush with herbicides were not achieved. Therefore, herbicide applications targeting flowering rush within this site would not be recommended unless water exchange can be slowed through the use of some type of barrier.

Figure 17. Mean RWT dye concentration (\pm SE) for each sampling period at Columbia Park Golf Course Site #3. Dye dissipation and dye half-life were estimated across depths (A), top of the water column (B), middle of the water column (C), and bottom of the water column (D) using nonlinear regression (exponential decay, $f = a \exp[-b x]$).

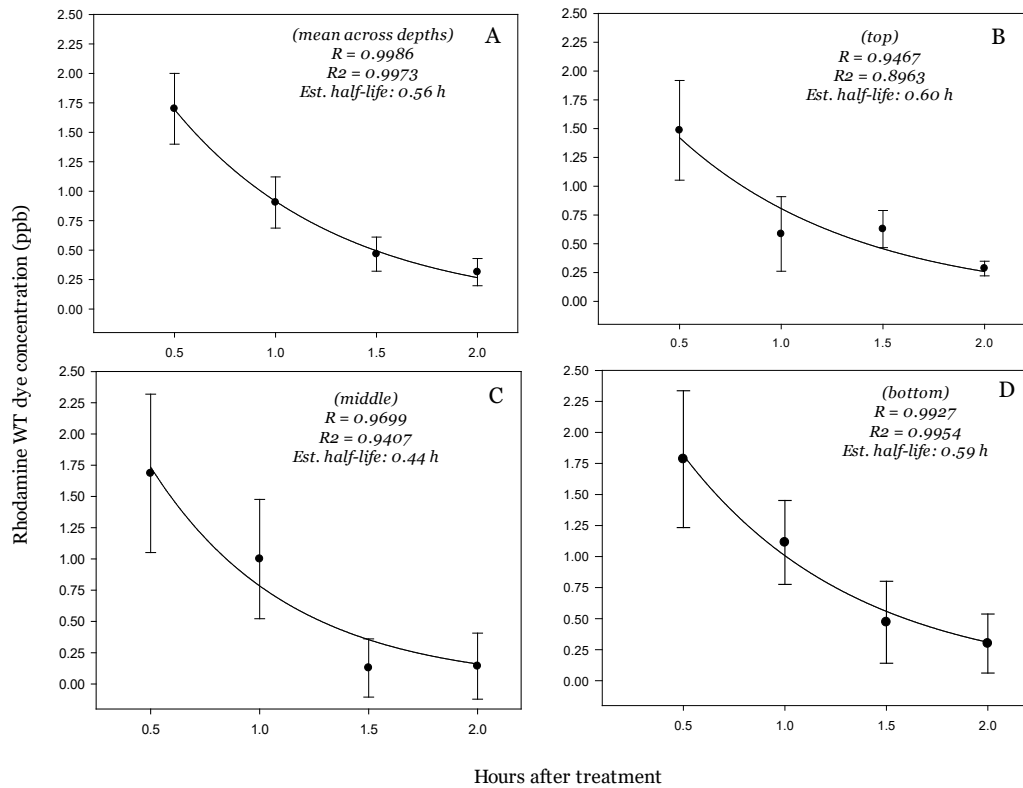


Figure 18. RWT dye concentrations predicted at Columbia Park Golf Course Site #3 at the top (A), middle (B) and bottom (C) of the water column 0.5 HAT. The numbers at each point represent actual recorded dye measurements.

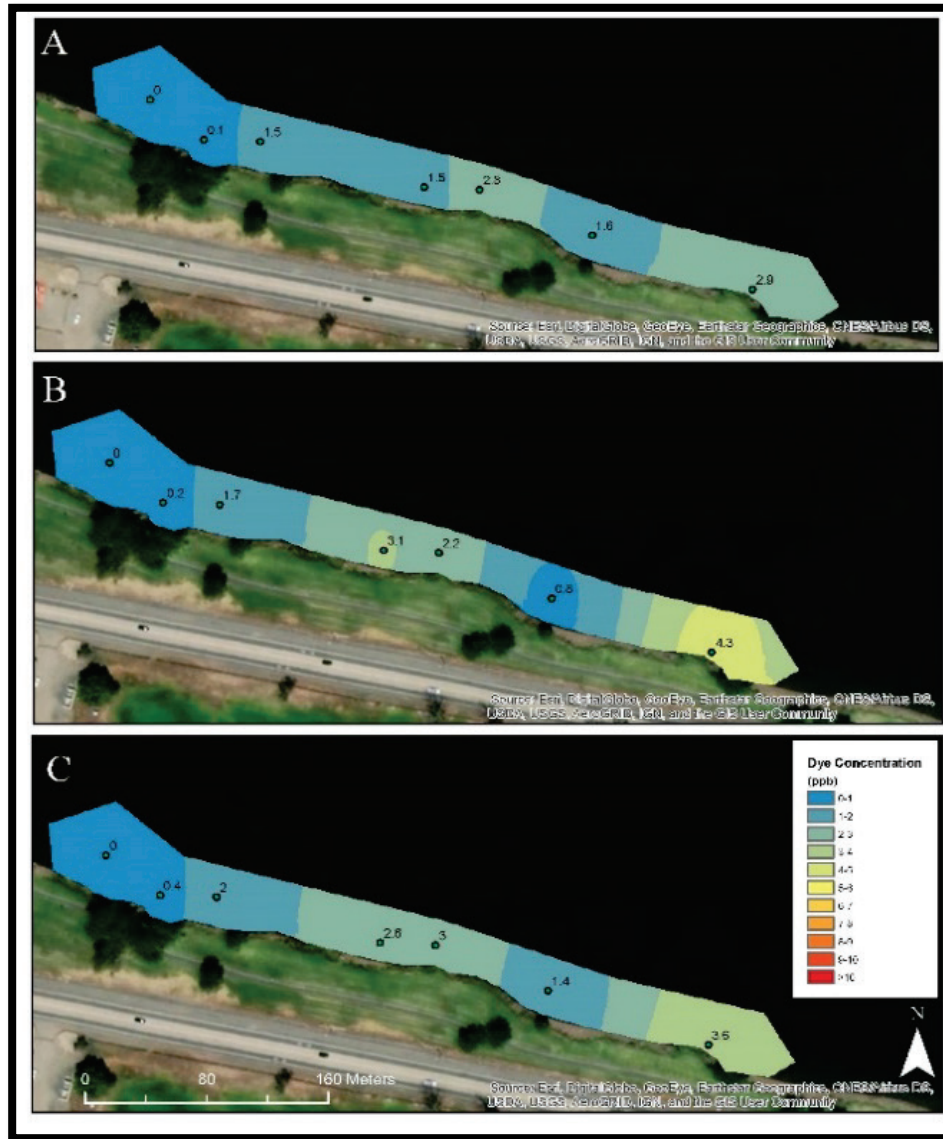


Figure 19. RWT dye concentrations predicted at Columbia Park Golf Course Site #3 at the top (A), middle (B) and bottom (C) of the water column 1 HAT. The numbers at each point represent actual recorded dye measurements.

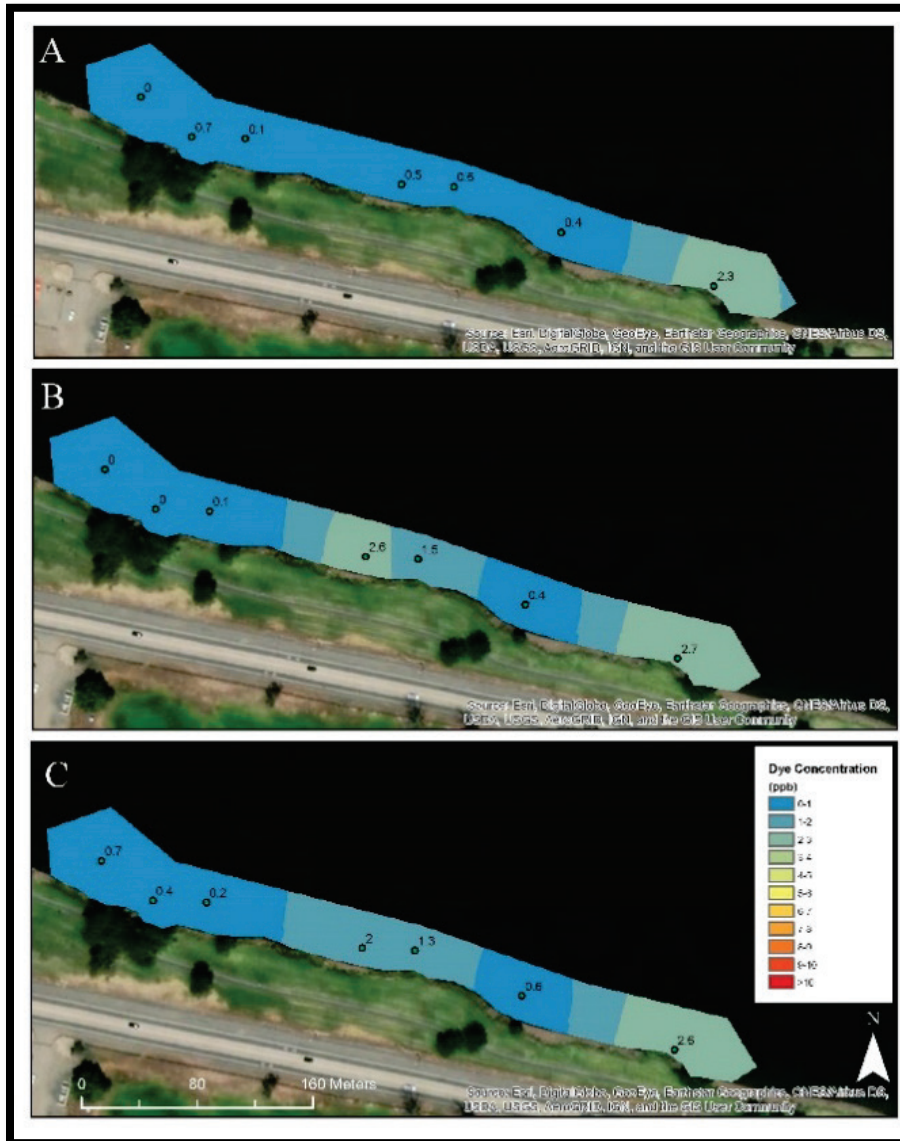


Figure 20. RWT dye concentrations predicted at Columbia Park Golf Course Site #3 at the top (A), middle (B) and bottom (C) of the water column 1.5 HAT. The numbers at each point represent actual recorded dye measurements.

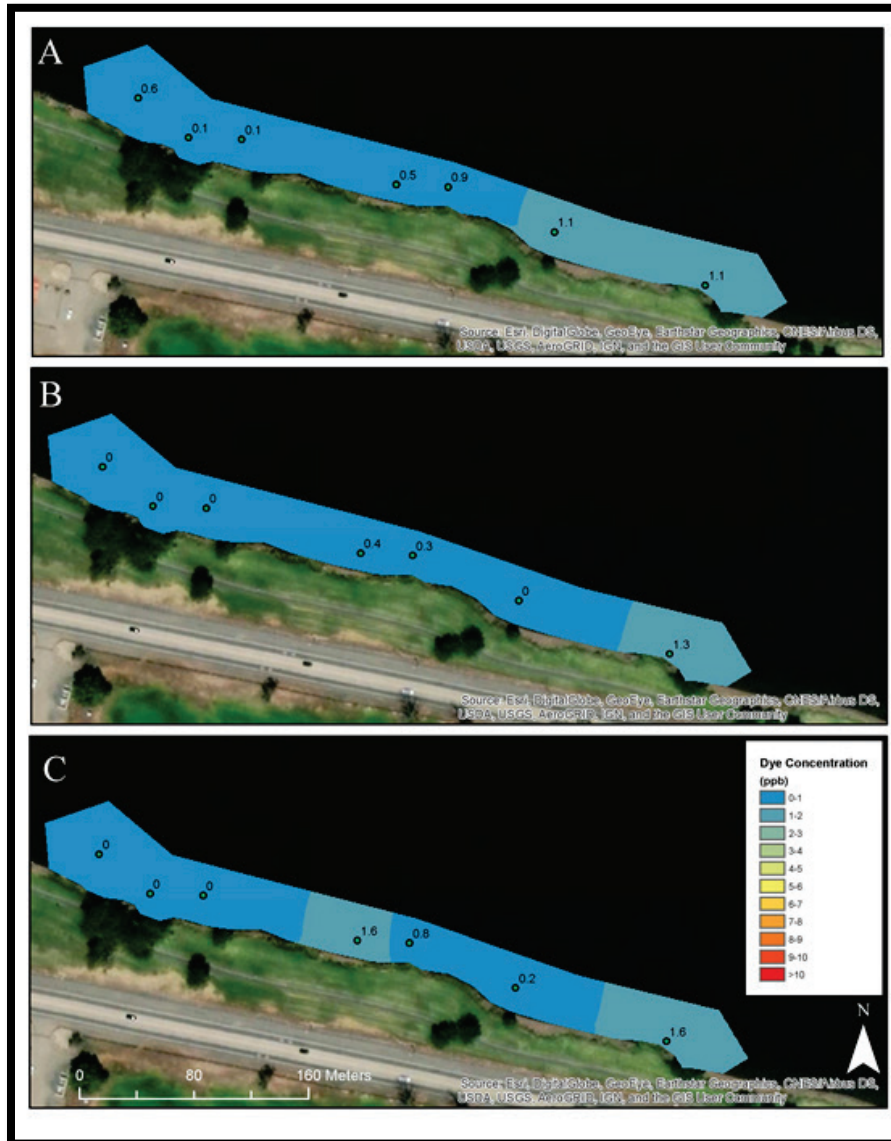
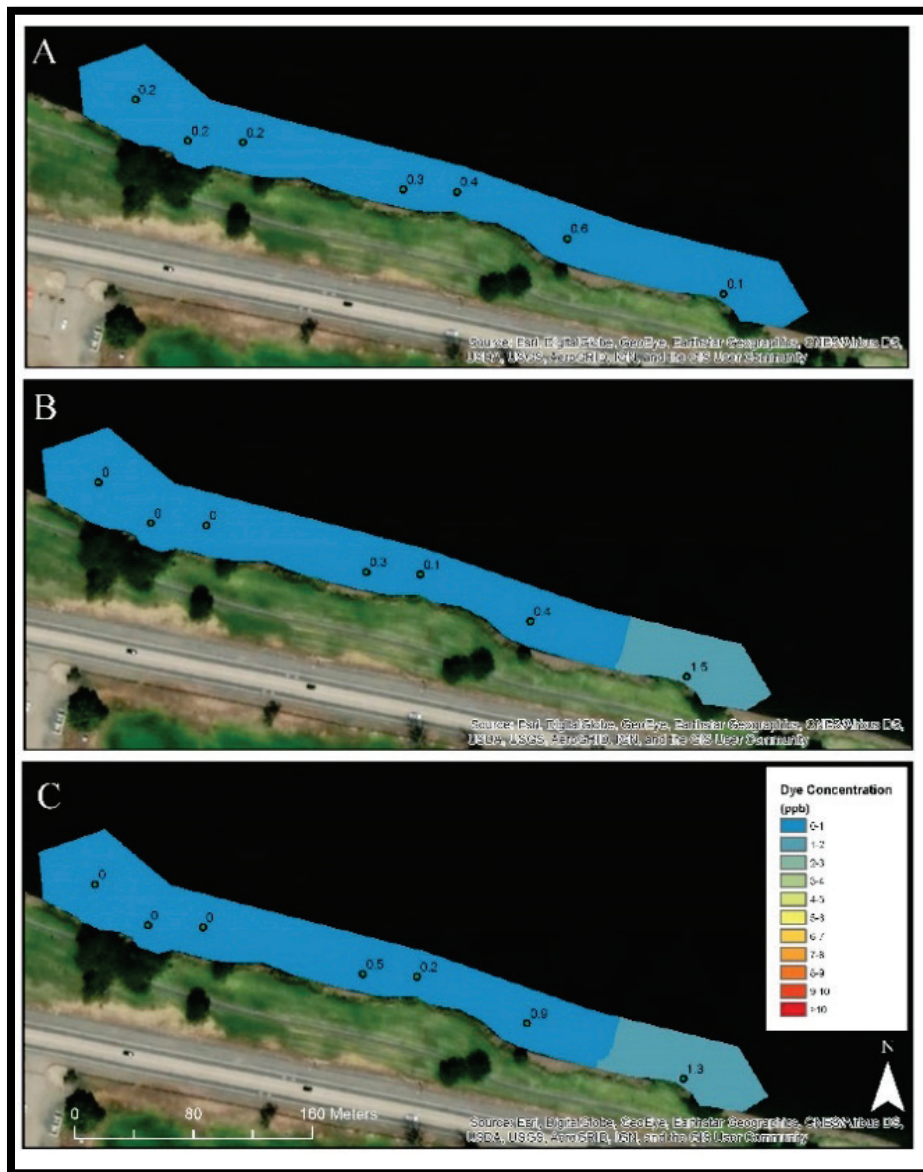


Figure 21. RWT dye concentrations predicted at Columbia Park Golf Course Site #3 at the top (A), middle (B) and bottom (C) of the water column 2 HAT. The numbers at each point represent actual recorded dye measurements.



3.4 Port of Pasco Site #4

RWT dye at Port of Pasco Site #4 followed a similar pattern to Columbia Park Golf Course Site #3, with dye on the upstream portion of the site dissipating more rapidly than the downstream end. The whole-plot dye half-life was estimated at 1.3 h, and dye half-lives at the top, middle, and bottom of the water column were 1.4, 1.1, and 1.4 h, respectively (figure 22). Dye measurements at 0.5 HAT demonstrated that the highest concentrations were found in the middle to downstream portions of the site, with

relatively little to no dye detected at the upstream end (figure 23). However, the dye mixed well throughout the water column, with top, middle, and bottom dye concentrations of 6.0, 5.3, and 4.1 $\mu\text{g L}^{-1}$, respectively. Measurements at 1.5 HAT indicated that dye had dissipated from the upstream half of the site but was still being maintained at concentrations $>10 \mu\text{g L}^{-1}$ on the downstream end (figure 24). By 2.5 HAT, all sampling points had dye concentrations $<10.7 \mu\text{g L}^{-1}$, with the highest concentrations found in the upper portions of the water column (figure 25). The majority of dye readings at 4 HAT were $\leq 1 \mu\text{g L}^{-1}$ (figure 26), except for three sampling points at the downstream end, which maintained readings between 1 and 3.8 $\mu\text{g L}^{-1}$. Although Port of Pasco Site #4 had a relatively short dye half-life (1.3 h), concentrations of dye (up to 10.7 $\mu\text{g L}^{-1}$) were recorded through the 2.5 HAT sampling period. Diquat would be the only chemical treatment option under such a rapid water exchange, and multiple treatments would be necessary to sufficiently control submersed flowering rush. Ideally, the use of a barrier curtain or bubble curtain that could slow water exchange and increase the half-life from 1.3 h to ≥ 3 h would greatly improve herbicide efficacy.

Figure 22. Mean RWT dye concentration (\pm SE) for each sampling period at Port of Pasco Site #4. Dye dissipation and dye half-life were estimated across depths (A), top of the water column (B), middle of the water column (C), and bottom of the water column (D) using nonlinear regression (exponential decay, $f = a \exp[-b x]$).

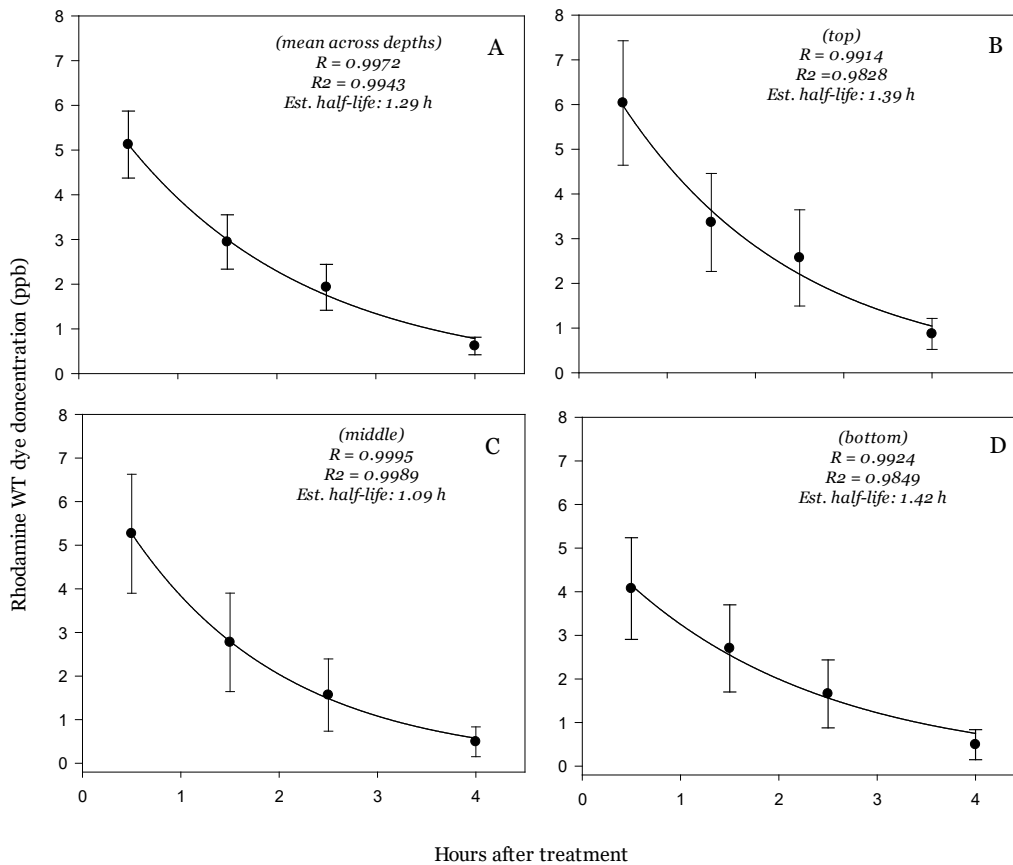


Figure 23. RWT dye concentrations predicted at Port of Pasco Site #4 at the top (A), middle (B) and bottom (C) of the water column 0.5 HAT. The numbers at each point represent actual recorded dye measurements.

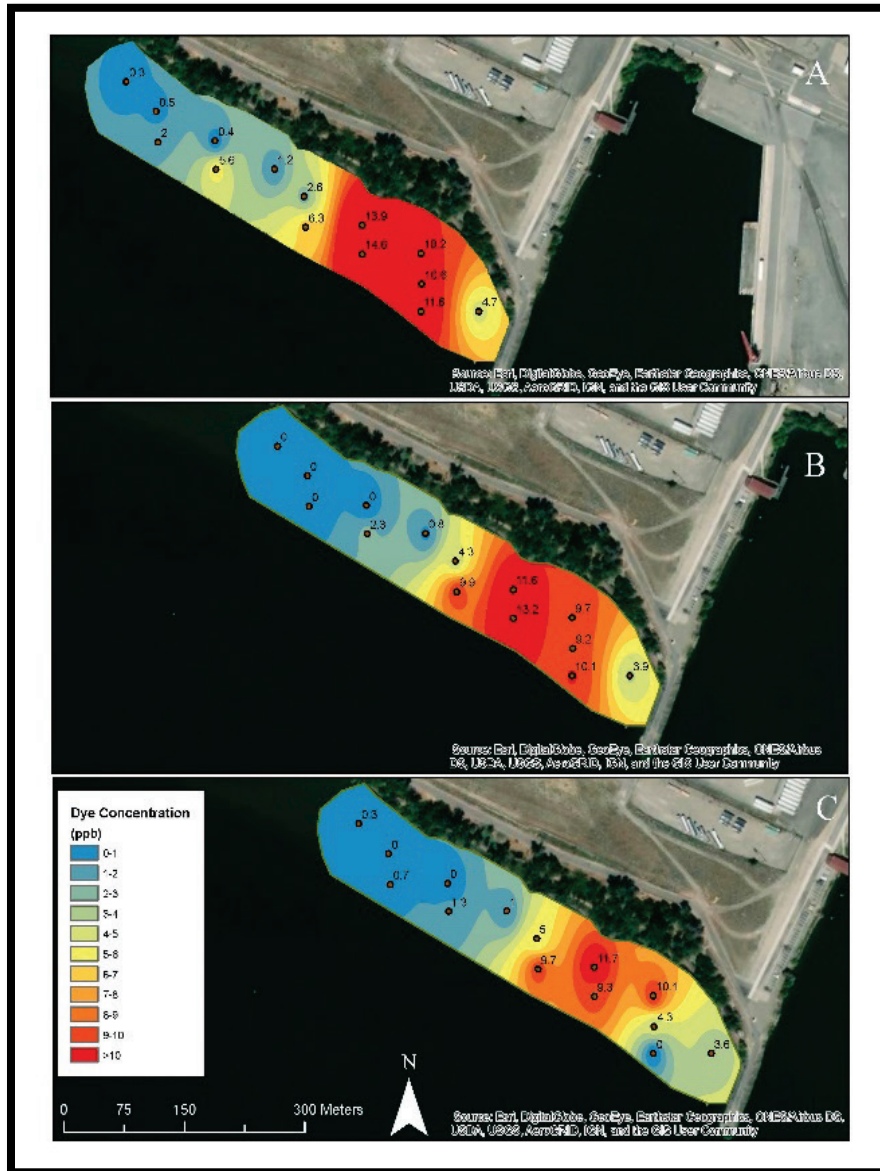


Figure 25. RWT dye concentrations predicted at Port of Pasco Site #4 at the top (A), middle (B) and bottom (C) of the water column 2.5 HAT. The numbers at each point represent actual recorded dye measurements.

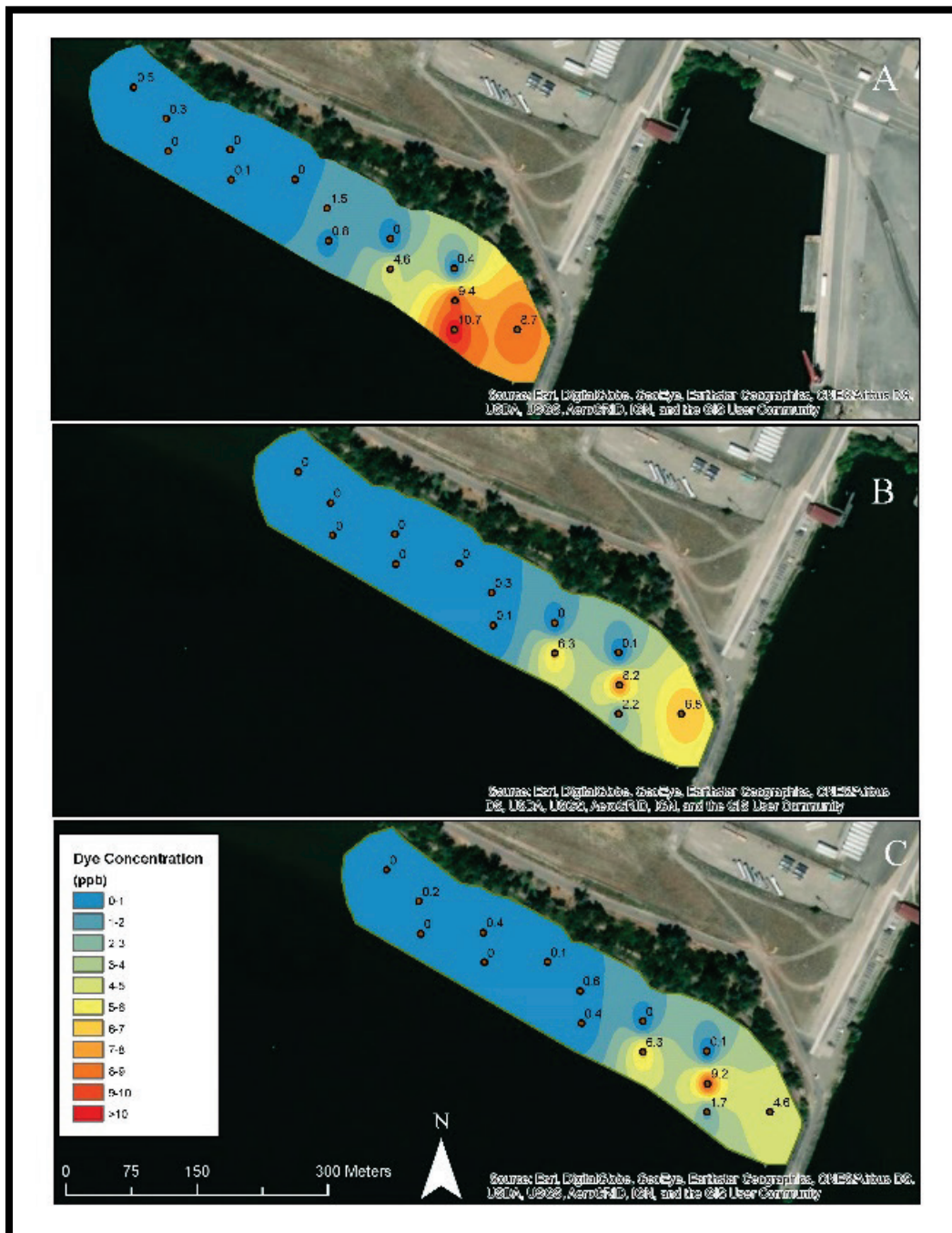
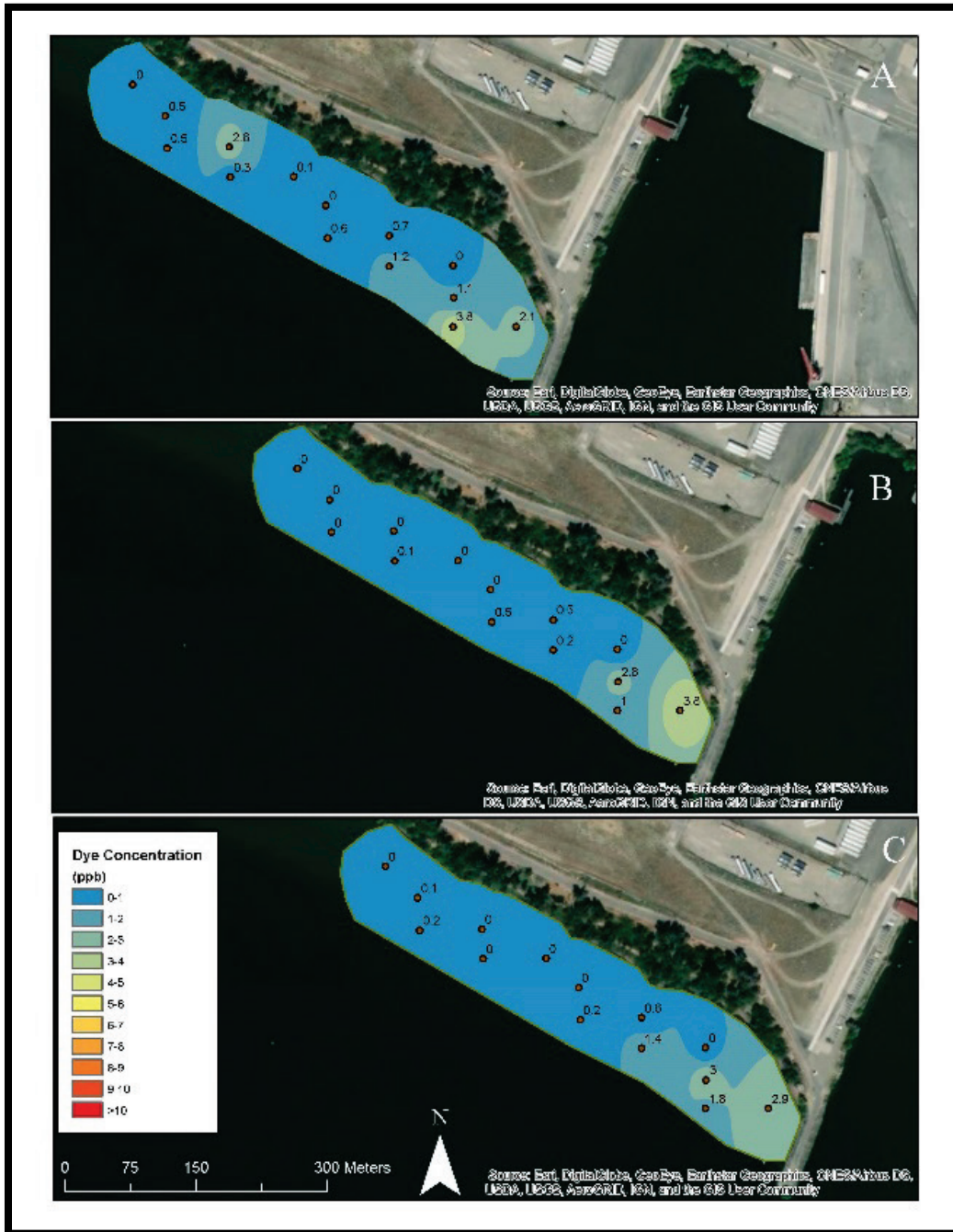


Figure 26. RWT dye concentrations predicted at Port of Pasco Site #4 at the top (A), middle (B) and bottom (C) of the water column 4 HAT. The numbers at each point represent actual recorded dye measurements.



3.5 Clover Island Site #5

3.5.1 No bubble curtain

The whole-plot, water-exchange half-life for RWT dye at Clover Island Site #5 with no bubble curtain was 3.8 h (figure 27). Throughout the evaluation, light, steady winds were blowing directly into the site, which likely increased dye-retention rates. The highest dye concentrations were measured 0 HAT at sampling points 2, 3, and 5 (figure 28). These three points were located in a densely vegetated area (that is, submerged vegetation at or near the water surface) near the middle portion of the plot, and dye dissipation was likely slowed because of the dense plant communities. At 3 HAT, sampling points 2, 3, and 5 still maintained the highest dye concentrations, at 10.2, 8.9, and 9.9 $\mu\text{g L}^{-1}$, respectively, and low concentrations of dye were detected just outside of the treatment plot at sampling points 7, 8, and 9, thus indicating that dye was dissipating into the deeper water adjacent to the plot. At sample point 6, on the upstream end of the plot, dye measurements decreased from 6.2 to 1.1 $\mu\text{g L}^{-1}$ by 3 HAT, and dye readings at sample point 4 decreased from 6.2 to 3.2 $\mu\text{g L}^{-1}$ 3 HAT, indicating that water flow was also causing dye to dissipate at the upstream and downstream ends of the plot albeit at a much slower rate in the heavily vegetated area. Sampling points 2 and 5 still maintained the highest dye concentrations, at 8.5 and 6.0 $\mu\text{g L}^{-1}$, respectively, at 6 HAT, and all other sampling points documented dye concentrations less than 5.0 $\mu\text{g L}^{-1}$. By 16 HAT, all dye measurements were $\leq 1.5 \mu\text{g L}^{-1}$. An estimated dye half-life of 3.8 h indicates that diquat would be the most effective option for controlling flowering rush within this site or areas with similar water exchange.

Figure 27. Mean RWT dye concentration (\pm SE) for each sampling period without the use of a bubble curtain at Clover Island Site #5. Dye dissipation and dye half-life were estimated for the whole plot using a nonlinear regression (exponential decay, $f = a \exp[-b x]$).

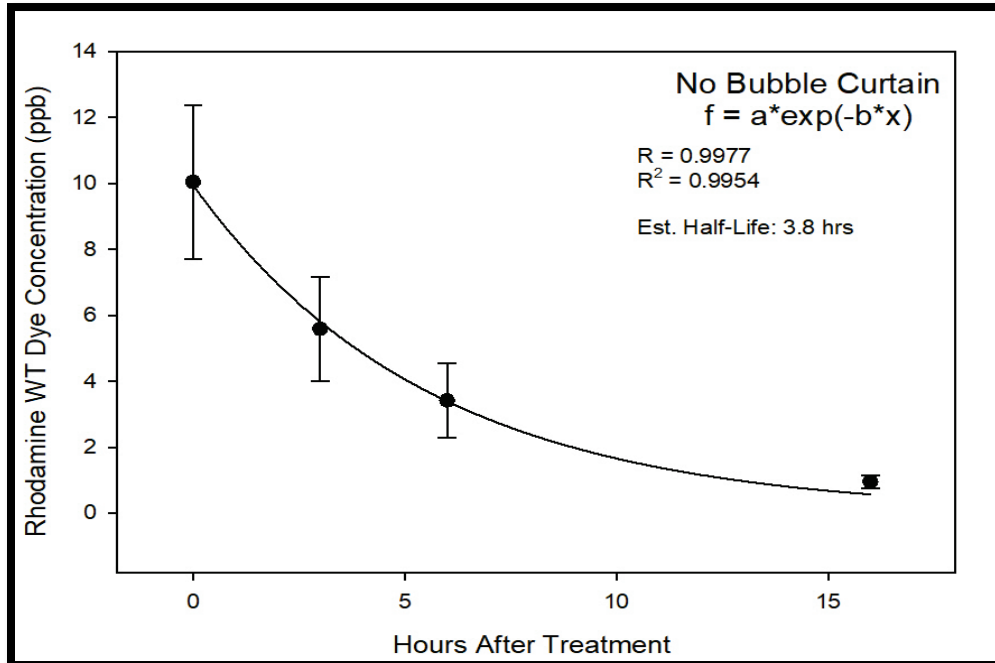
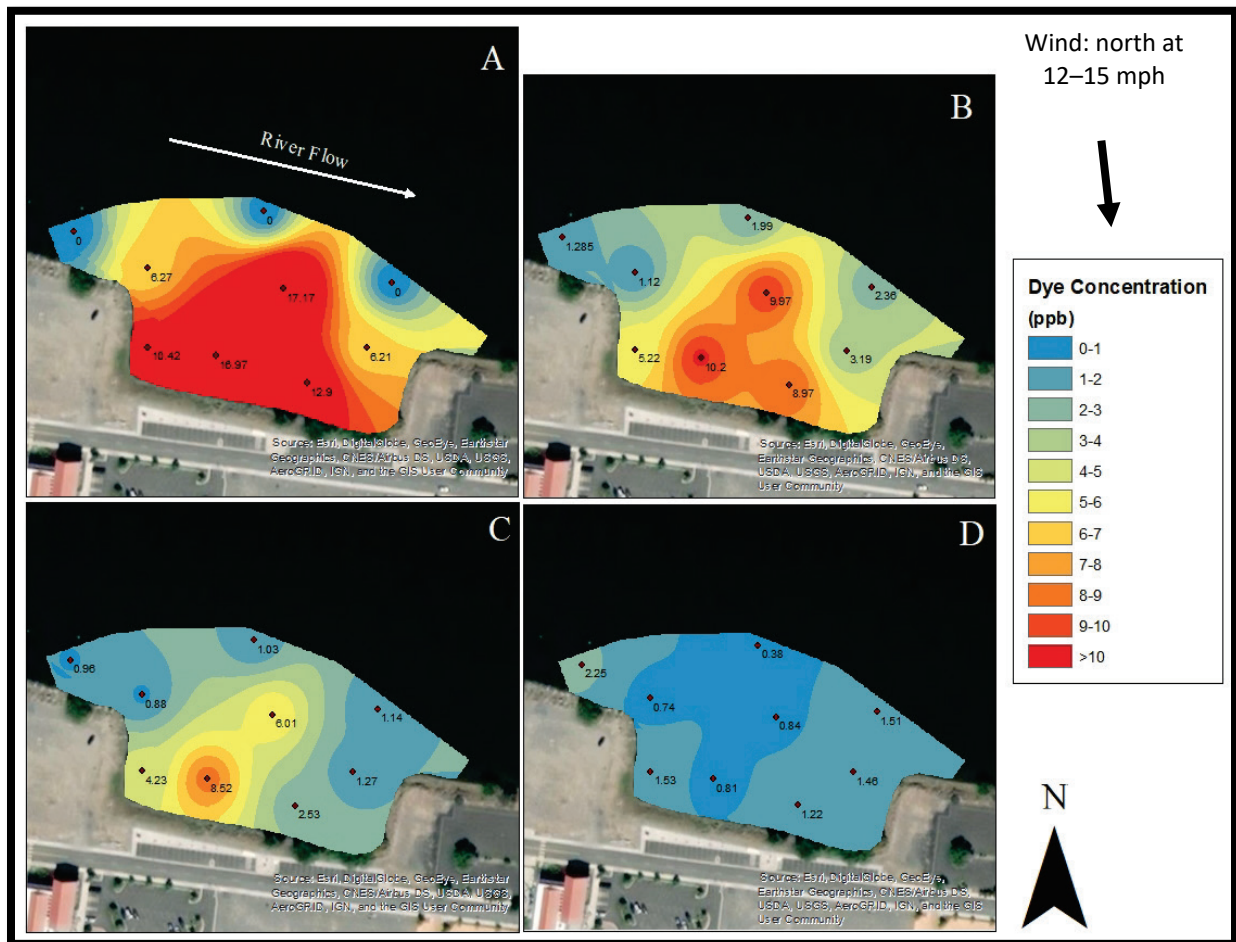


Figure 28. RWT dye concentrations predicted at Clover Island Site #4 with no bubble curtain at 0 HAT (A), 3 HAT (B), 6 HAT (C), and 16 HAT (D). The numbers at each point represent actual recorded dye measurements.



3.5.2 Bubble Curtain Evaluation 1

Dye half-life increased from 3.8 h without the bubble curtain to 7.6 h with the bubble curtain (figure 29). At 1 HAT, dye readings indicated that whole-plot dye concentration decreased from 10.4 to 9.0 $\mu\text{g L}^{-1}$ by 3 HAT. Dye measurements throughout the site became more uniform by 6 HAT, indicating that the dye had sufficiently mixed throughout the water column (figure 30). The southeastern portion of the site was significantly vegetated and slowed water flow, causing dye to remain at higher concentrations than the other areas of the site. Measurements recorded along the inside edge of the curtain on the upstream end showed minimal dye during all sampling periods, likely because of north winds and river currents. Minimal dye was also recorded outside of the bubble curtain, and the highest recorded measurement was 2.1 $\mu\text{g L}^{-1}$ 1 HAT on the downstream end.

Visual observations immediately following treatment determined that small portions of dye were being lost in shallow water areas at the upstream and downstream corners of the site. Because the bubble curtain needed full submersion to maintain adequate pressure, a small opening was present between the shoreline and bubble tubing; however, losses were minimal. At 12 HAT, dye remained at $4 \mu\text{g L}^{-1}$. The addition of the bubble curtain and its ability to slow water exchange at Clover Island Site #5 increases the number of chemical treatment options available. The increased half-life with the use of the bubble curtain would provide increased efficacy of diquat treatments as well as the option for endothall applications.

Figure 29. Mean RWT dye concentration (\pm SE) for each sampling period during Bubble Curtain Evaluation 1 at Clover Island Site #5. Dye dissipation and dye half-life were estimated for the whole plot using a nonlinear regression (exponential decay, $f = a \exp[-b x]$).

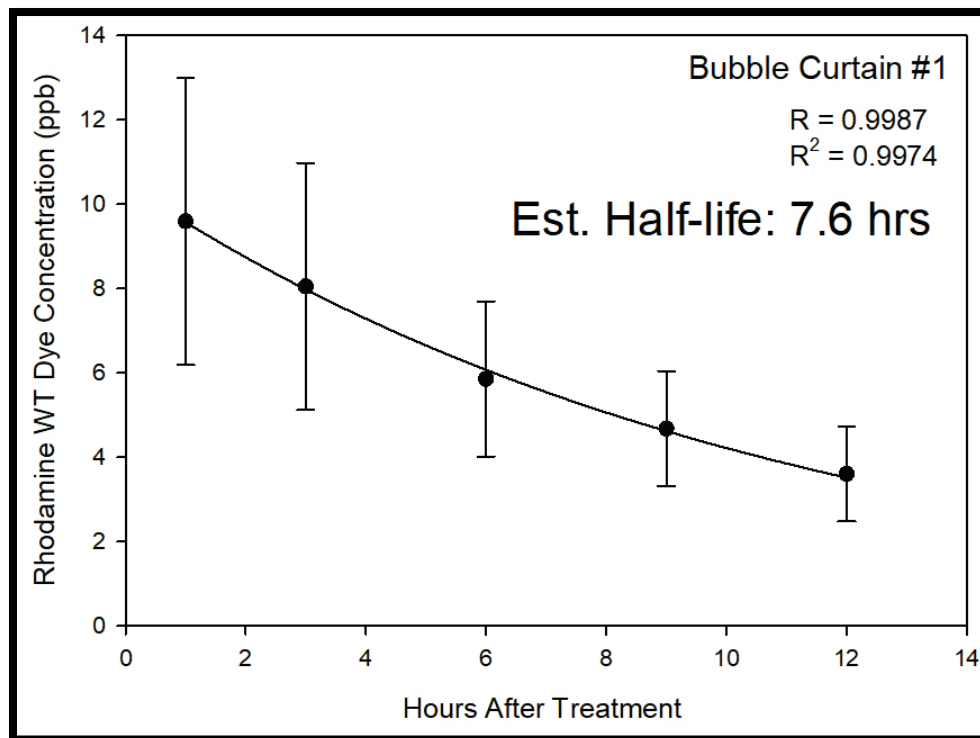
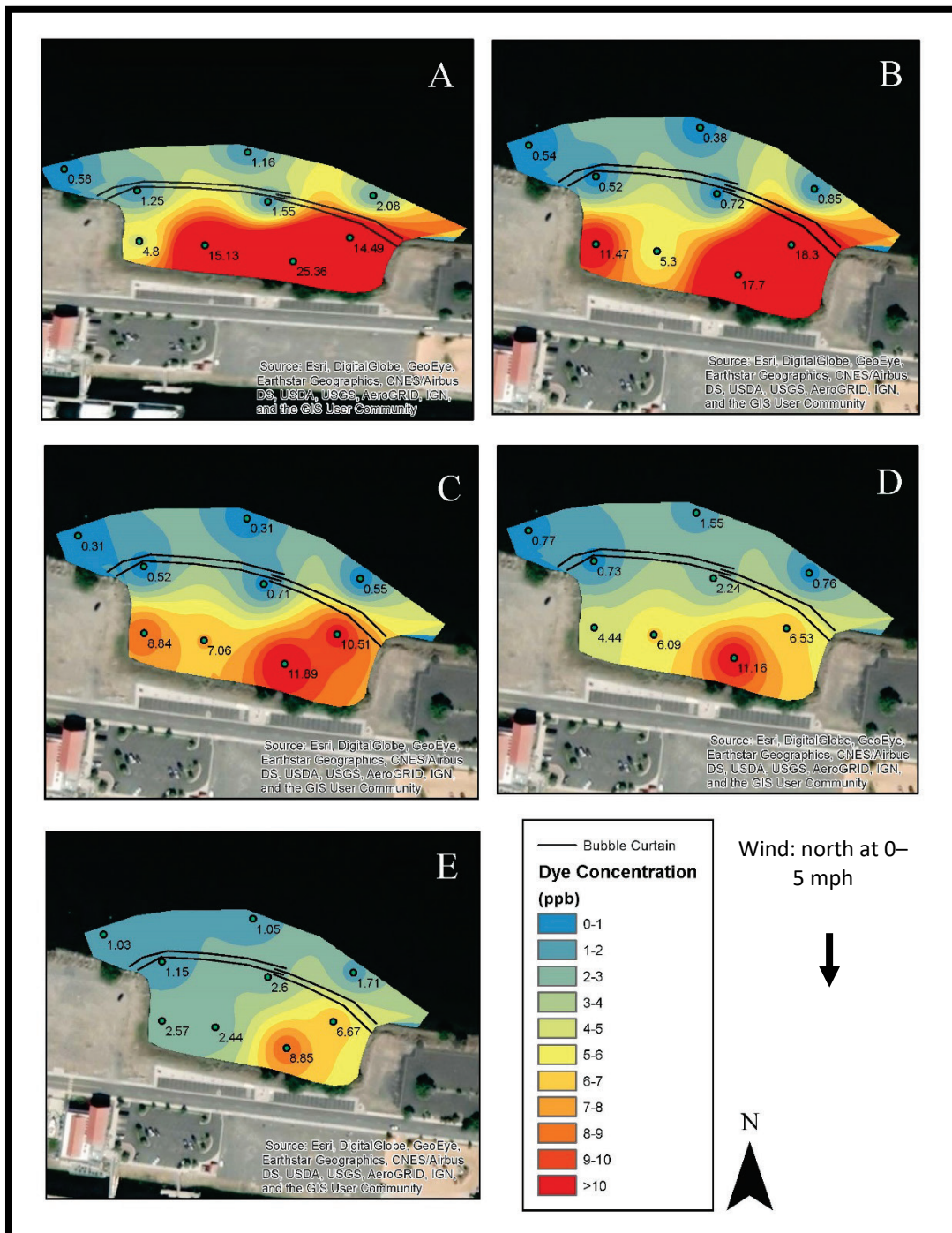


Figure 30. RWT dye concentrations predicted at Clover Island Site #4 during Bubble Curtain Evaluation 1 at 1 HAT (A), 3 HAT (B), 6 HAT (C), 9 HAT (D) and 12 HAT (E). The numbers at each point represent actual recorded dye measurements.



3.5.3 Bubble Curtain Evaluation 2

Like Bubble Curtain Evaluation 1, Bubble Curtain Evaluation 2 increased the whole-plot dye half-life (7.1 h, figure 31) compared to the no-curtain evaluation (3.8 h). As expected, dye concentrations were highest at 0 HAT, and the highest measurements were recorded in the densely vegetated portions of the site. Sampling points 1 and 6 had the lowest dye readings among the points located within the site during each sampling time (figure 32), likely caused by a strong wind (24–32 kmph) from the south-south-west that pushed portions of dye out of the plot before proper mixing could occur. Wind action created small waves that pushed dye over the top of the bubble curtain, leading to detectable amounts of dye along the outside of the curtain in these areas. At 3 HAT, estimated whole-plot dye half-life was $4.9 \mu\text{g L}^{-1}$ ppb, and measurements within the curtain ranged from 2.9 to $7.6 \mu\text{g L}^{-1}$. Minimal traces of dye ($<1.5 \mu\text{g L}^{-1}$) were recorded outside of the bubble curtain, and measurements in between the two bubble curtains ranged from 0.6 to $2.3 \mu\text{g L}^{-1}$. The estimated whole-plot dye half-life in Bubble Curtain Evaluation 2, with less-than-favorable conditions (for example, strong winds blowing directly away from the site that would likely postpone an operational herbicide treatment), was nearly $2\times$ longer than that observed with no bubble curtain. The decrease in water exchange with the use of the bubble curtain would provide increased efficacy of diquat treatments and allow for endothall applications even under less-than-optimal treatment conditions.

Figure 31. Mean RWT dye concentration (\pm SE) for each sampling period during bubble curtain evaluation #2 at Clover Island Site #5. Dye dissipation and dye half-life was estimated for the whole plot using a non-linear regression [Exponential decay ($f = a \cdot \exp(-b \cdot x)$)].

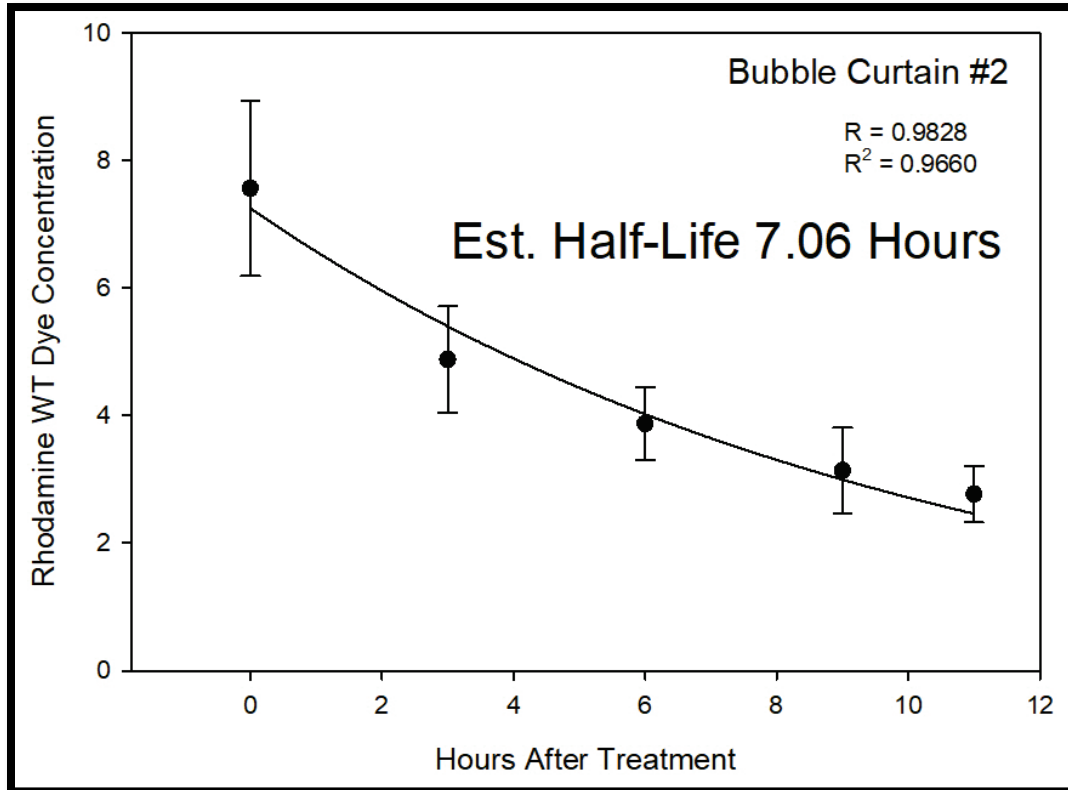
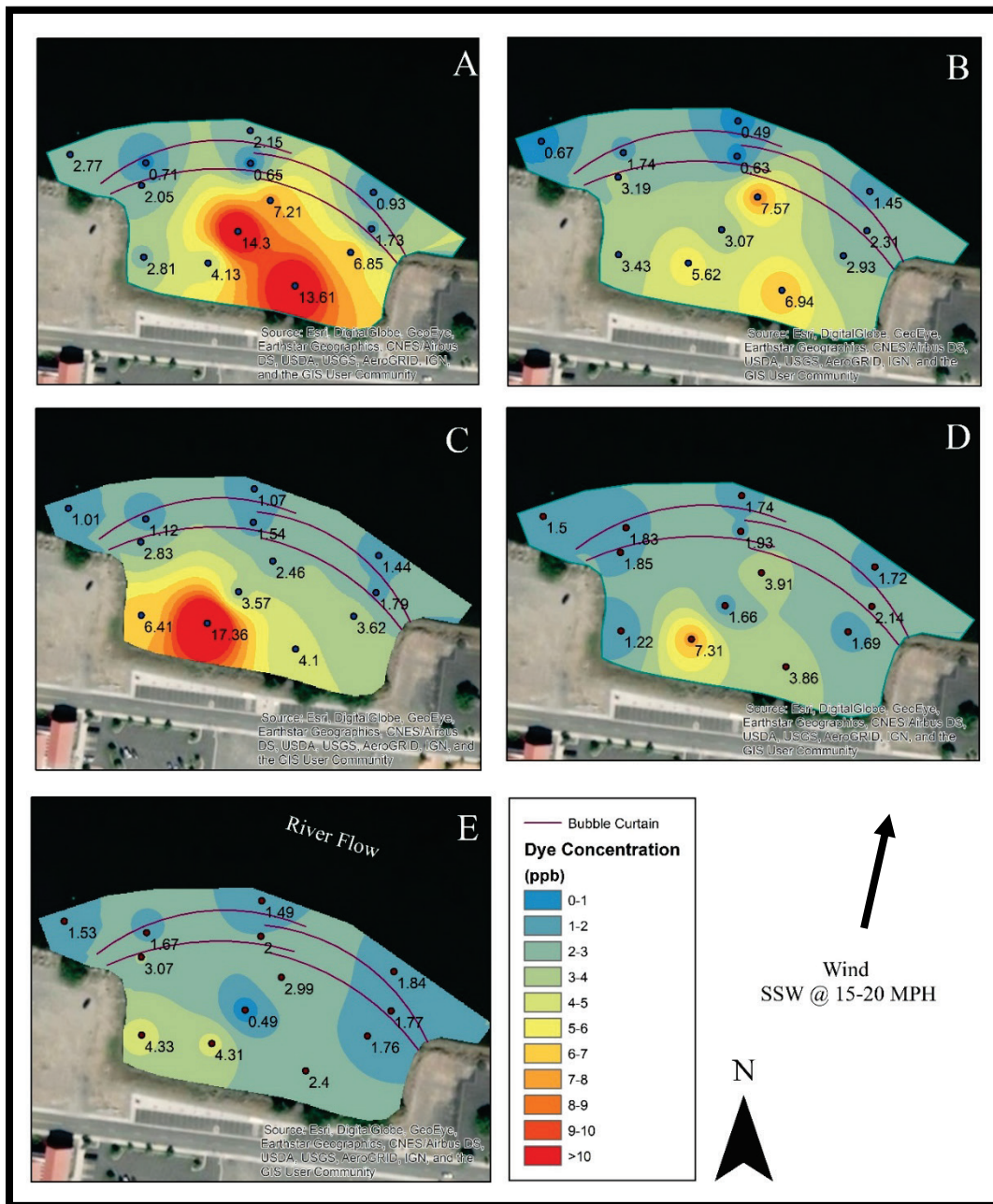


Figure 32. RWT dye concentrations predicted at Clover Island Site #4 during bubble curtain evaluation #2 at 0 HAT (A), 3 HAT (B), 6 HAT (C), 9 HAT (D) and 11 HAT (E). The numbers at each point represent actual dye measurements recorded.



4 Conclusion

Columbia Park Golf Course Site #3 and Port of Pasco Site #4 demonstrated very rapid water exchange, likely too rapid to effectively control flowering rush using chemical treatments without the use of a barrier or curtain to slow water exchange.

Diquat is a suitable management option in slower water-exchange sites, such as the Yakima River Site #1 (2.6 h half-life) and Columbia Park Marina Site #2 (6.7 h half-life).

Endothall might be a suitable management option in slow-flow, back-bay areas such as Columbia Park Marina Site #2, where dye half-lives are near the 6–8 h range.

Whole plot dye half-life was increased from 3.8 h with no curtain to 7.6 and 7.1 h for Bubble Curtain Evaluation #1 and #2, respectively. Successfully decreasing water exchange leads to more potential management options. Although a 3.8 h dye half-life with no curtain is suitable for a diquat application, doubling product half-life with the use of a bubble curtain will likely provide improved control and the potential for other products to be effectively used. In addition, the bubble curtain does not disrupt transportation by boat and personal watercraft and can act as a deterrent to prevent salmonids and other aquatic species from entering treatment areas.

5 Recommendations

On the basis of the information documented in this study, the following recommendations are presented to fully determine and increase the efficacy of herbicides to control flowering rush in the McNary Pool of the Columbia River:

- Perform additional small-scale herbicide CET studies for controlling flowering rush.
- Continue to evaluate bubble curtains using different configurations and under different water-flow regimes as a method to reduce water exchange and increase herbicide CETs.
- Compare bubble curtains to other barriers commonly used to reduce water exchange, such as turbidity and silt curtains.
- Link herbicide CET requirements of selected products and water-exchange processes through field-verification studies.
- Continue monitoring populations of flowering rush on the Columbia River to analyze expansion of existing infestations, new infestations, and potential infestation sites.

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Appendix: Clover Island Site #5

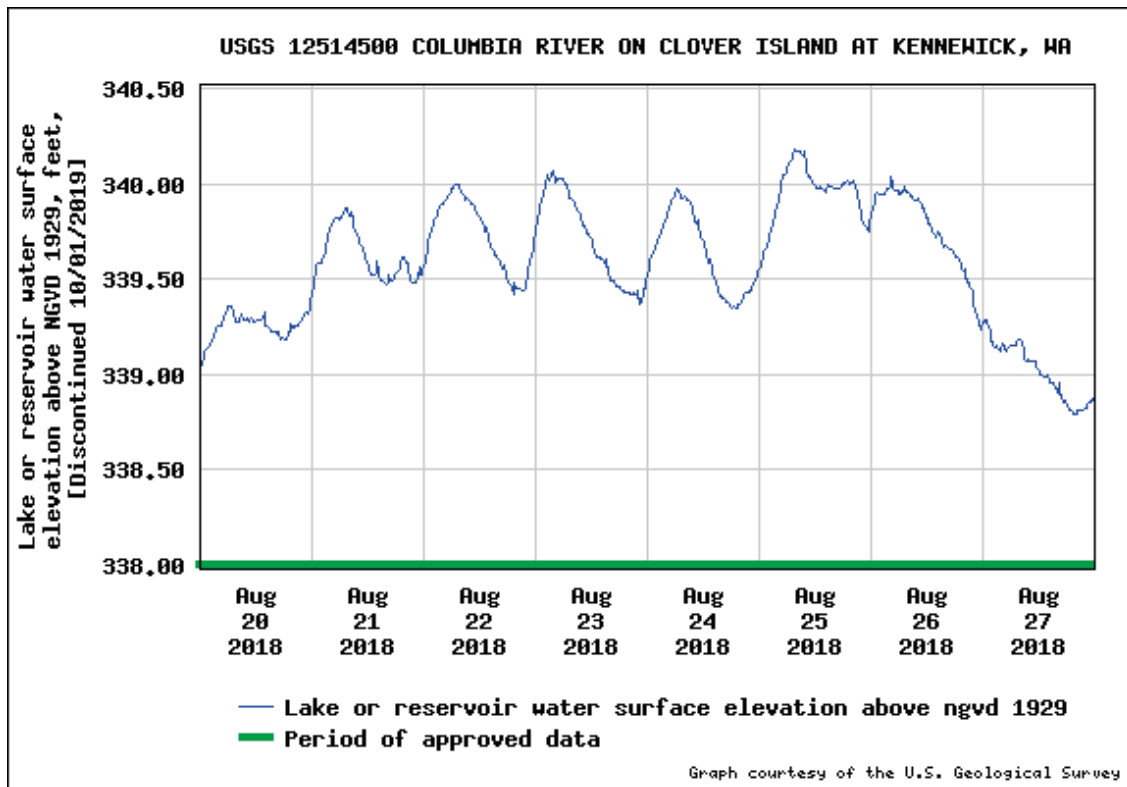
Figure A-1. Bubble curtain in operation at Clover Island Site #5 for Bubble Curtain Evaluation 1. Photo by John Madsen.



Figure A-2. Bubble curtain in operation at Clover Island Site #5 for Bubble Curtain Evaluation 2. Photo by Terry McNabb.



Figure A-3. Columbia River water surface elevation on Clover Island at Kennewick, Washington, 20–27 August 2018.



REPORT DOCUMENTATION PAGE

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