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Study of the Efficacy of UV Light To Treat Aquatic Vegetation in an Unlined Canal

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14. ABSTRACT

Among irrigation canals of the U.S.'s semi-arid west, dense growths of aquatic macrophytes are a persistent issue – slowing water delivery and decreasing canal capacity. The aim of this project was to design and test the efficacy of a novel ultraviolet (UV) tool for controlling nuisance aquatic plants and determine the environmental constraints on macrophyte density and composition are driven by macrophyte abundance in irrigation canals in Fallon, Nevada. Inventive Resources, Inc. provided a UV-C Treatment device that was designed to provide a lethal dose of ultraviolet light in the range of 254 nm, killing and controlling the invasive aquatic plants in the unlined canal by damaging the aquatic plant cell structure and DNA that prevents it from replicating. The UV treated plants should collapse within a few days and begin the decomposition process in a few weeks depending on water temperature and other

environmental factors. The testing of the tool was hampered by drought and the dewatering of the canal in the first year and the rapid decline of plants in the reference and treatment reaches of the canals in the second and final year of treatment perhaps due to large disturbances from wildfire smoke emissions in the region or other conditions. We found that total suspended solids were the primary driver of macrophyte density, suggesting that light availability within the water column drives macrophyte growth.

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Ultraviolet light treatment; macrophytes; unlined canals

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S&T — Study of the Efficacy of UV Light to Treat Aquatic Vegetation in an Unlined Canal

Final Report No. 2022-PROJECT-ID (20041-REPORT NUMBER (01)

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Peer Review

Bureau of Reclamation
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Study of the Efficacy of UV Light to Treat Aquatic Vegetation in an Unlined Canal

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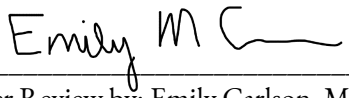

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Contents

Executive Summary

Canal conveyance capacities are dependent upon the boundary material between the bed and banks as well as the number of obstructions in the waterway. Plants decrease the conveyance capacity of rivers and canals; the losses are dependent upon the height, density, and location of the macrophyte communities within the channel. The Newlands Project is a large irrigation project in Western Nevada and contains a system of canals. The Truckee Canal is a primary conveyance of water within the Newlands Project and stretches from Derby Dam to Fernley and over to Lahontan Reservoir. Within the Truckee Canal, canal conveyance is reduced by upwards of 50% when Eurasian milfoil is in full bloom. Chemical and mechanical methods are used for macrophyte management. Management efforts to extract or eradicate macrophytes are costly. A new tool using ultraviolet light has been developed to control plants. Successful pilot studies have been completed in the laboratory, Lake Tahoe, and the central valley. The objectives of this study are to:

1: Determine the efficacy of Ultraviolet-C (UV) light to treat aquatic vegetation in unlined canals
2: Determine the optimal treatment time during the growth cycle of an aquatic macrophyte
3: Construct a UV treatment time to macrophyte density relationship within unlined canal
4: Quantify aquatic vegetation regrowth rates following UV treatments of varying exposure times

We implemented UV control tests and set up a monitoring program to quantify the plant and chemical water dynamics in the canals associated with the Newlands Project. Implementing tests occurred during the COVID19 pandemic leading to the series of adjustments as the managers and local community dealt with the pandemic. In short, protocols for safe operations needed to be developed at each implementing party's institutions. In the first year of UV treatment, the canal sections did not grow plants as anticipated by observations in previous years. The parties had to pivot quickly and move to another section of the canal requiring significant adjustment for pre and post monitoring and redesign of the treatment vessel. The adaptive approach led to the treatment of plants but the canal was partially dewatered due to drought conditions and operational management. In the following year, learning from the implementation in the first year and after discussions with the participating partners, Bureau of Reclamation (BOR), Truckee-Carson Irrigation District Irrigation District), University of Nevada, Reno (University), and Inventive Resources, we moved the treatment sections to another "main" section of canal known to have significant plant growth by the Irrigation District. The treatment occurred and post monitoring of the plants in the control section did not show growth. This lack of plant growth is not explainable but during this time there were significant changes in the air and light conditions due to regional wildfires. It may also be possible that chemical treatments were carried out by the local community to control plants. It is not clear however why these plants did not grow in the control section. Thus the findings from the scientific investigations are not conclusive for the second year. Laboratory and field trials from other ecosystems carried out during this time period did show the UV light treatment can reduce plants by up to 100% with targeted impacts to multiple plant taxa. Finally, the monitoring data from many canal reaches for plants and water quality indicates that plant biomass in these irrigation canals peaks in July suggesting the best timing for intervention to reduce plants would be during the initial growth of the plants earlier in the season (June). Ditchgrass is the most abundant plant type during this study. The importance of total suspended solids (an indicator of light availability) in driving macrophyte density indicates that creating

shading structures over the canals to reduce surface light availability may be a solution to limiting macrophyte growth. A refocused project during non-COVID pandemic periods coupled with examination of plant mortality from canals that are least likely to be dewatered would assist in testing the efficacy of UV light in canals managed by BOR.

Introduction

The presence of invasive aquatic macrophytes has been growing at an alarming rate (Leung et al. 2002; Rahel et al. 2008). The abundance and distribution of the invasive aquatic species are predicted to increase into the future (Hershner and Havens 2008), especially under changing climatic regimes (Hellmann et al. 2008; Rahel and Olden 2008; Rahel et al. 2008) and requires proactive management (Vander Zanden et al. 2010).

Canal conveyance capacities are dependent upon the boundary material between the bed and banks as well as the number of obstructions in the waterway (Pitlo and Dawson 1990; Nepf 1999). Macrophyte communities, such as Eurasian milfoil (*Myriophyllum spicatum*), decrease the conveyance capacity of rivers and canals (Pitlo and Dawson 1990; Bakry et al. 1992; Green 2005). Conveyance losses are dependent upon the height, density, and location of the macrophyte communities within the channel (Green 2005; Järvelä 2005; Aberle and Järvelä 2015). Within the Truckee Canal, canal conveyance is reduced by upwards of 50% when macrophytes are in full bloom. Macrophyte communities also artificially raise the water surface elevation within conveyance systems (Naden et al. 2006; Li et al. 2017). Risk of canal failure increases as water surface elevation increases (Paul and Slaven 2009; Taccari and Van Der Meij 2016). For example, five of the nine failures of the Truckee Canal took place following a water surface elevation increase (Paul and Slaven 2009).

Chemical and mechanical methods are used for macrophyte management. Management efforts to extract or eradicate macrophytes are costly (Eiswerth et al. 2000) and tend to be short-lived (Nichols 1991). Various active ingredients are present in herbicides for Eurasian milfoil eradication (Netherland and Getsinger 1992; Netherland et al. 1993; Poovey et al. 2002) (2,4-D; Diquat; Endothall; etc.). These chemicals can require long treatments, high concentrations (Netherland and Getsinger 1992; Netherland et al. 1993) and require irrigation delivery delays to protect irrigated crops. Mechanical harvesting methods range from underwater manual weed picking (Paoluccio 2018) to underwater mowing (Paoluccio, 2018; Jenson Lake Mower). Eurasian milfoil propagates through stem fragmentation (Evans et al. 2011; Martin and Valentine 2014) - meaning mechanical extraction, whether by hand or machine, leads to further propagation of milfoil (Paoluccio, 2018).

UV light has been used in the treatment of drinking water and wastewater (Betancourt and Rose 2004). Recently, UV treatment systems have also been tested to manage macrophyte communities in Lake Tahoe. Within Lake Tahoe, the UV system has successfully mitigated (i.e. killed and prevented future propagation) numerous invasive macrophyte communities including Eurasian milfoil with a single treatment; some of the plants treated were more than 10 feet tall and were successfully killed and removed from the water column. Bench-scale tests have also shown that the UV system can kill a broad variety of aquatic macrophytes species (https://www.youtube.com/watch?v=JYN75EtfxaE). While UV has been proven effective in lake systems, this system has been tested in a small segment of a concrete lined canal system with positive results.

In order to understand the efficacy of plant control, it is key to understand the recovery of the plants and the controls of plant production. In canals, plant reestablishment may come from upstream sources of plant fragment and "seeds", re-sprouting of the sediments, and plant production will be impacted by the hydrologic processes (dewatering) and land use and human activities adjacent to the canals. While we recognized we could

not understand all of the parameters and how they might influence plant production in the canal, we initiated this project to complete the following objectives AND gain a fundamental understanding of the determinants of plant dynamics in the canal. The objectives of this study are:

Objective 1: Determine the efficacy of ultraviolet light to treat aquatic vegetation in unlined canals,
Objective 2: Determine the optimal treatment time during an aquatic macrophyte's growth cycle,
Objective 3: Construct an ultraviolet light treatment time to macrophyte density relationship within unlined canal,
Objective 4: Quantify aquatic vegetation regrowth rates following annual rewetting of canals and ultraviolet light treatments of varying exposure times

The objective of this research is to answer the following questions:

- What is the efficacy of ultraviolet treatment systems in the management of aquatic macrophyte communities in unlined canals?
- When is ultraviolet treatment most effective (i.e. greatest mortality) in the aquatic macrophyte growth cycle?
- What are the relationships between ultraviolet light treatment time and aquatic macrophyte density within canals?
- What are the regeneration/regrowth rates of aquatic macrophyte communities within canals?

We initiated the work during the COVID19 pandemic, a series of strong drought years and wildfires. After discussions between the parties implementing this project (BOR, University, canal operators, and Inventive Resources, Inc.), we adjusted to the conditions to answer as many of the questions as possible.

Objectives 1-3: Design ultraviolet treatment system, treat sections of unlined canals, & monitor macrophyte responses to treatments

1. Site Overview & Initial Preparation Phase

We implemented ultraviolet treatments and monitored macrophyte responses in canal reaches in the Newlands Project, which is operated and maintained by the Truckee Carson Irrigation District (TCID). The Newlands project provides irrigation water through a series of canals to over 50,000 acres of cropland in western Nevada with water sourced by the Truckee and Carson Rivers (State of California, Resources Agency 1991). These canals generally deliver water during the irrigation season that spans from March to November and are dry the remainder of the year. Due to a drought, the irrigation season ended early and canals were drained prematurely (August) during our monitoring period in 2021 (see more details below). In 2020, the treated canal (R-line) was an unexpectedly drained mid-season following treatment. The studied canals have no canopy cover

and are in a region of the high desert (elevation: 1,207 m) with little rainfall (0.7 cumulative cm over the study period) and high average summer temperatures (average high of 34.7 degrees Celsius over the study period) (NOAA NOWData Online Weather, https://w2.weather.gov/climate, Fallon Experiment Station). Canals are unlined and sediment at the bottom of the canal is fine (i.e., silt and sand) with sparsely distributed cobbles and boulders. The land surrounding the canals is a mix of residential areas, commercial areas, cropland, and ranchland.

The original experimental reach for this study was located along the Truckee canal in Fernley, NV. Preparations for plant monitoring in the original study reach of the Truckee canal in Fernley (39.590973,-119.260096) began in February 2020. While the Truckee canal was still dry, we walked the reach and took preliminary canal dimension measurements. In March of 2020, field measurements were halted for COVID-19 restrictions. During this time the partners at each organization needed to work out protocols for accessing the canal and implementing the pre and post monitoring with minimal impact to the employees. Working virtually or with small teams, we continued to plan for plant monitoring in the summer for 2020. In July 2020, we sampled plants using a rake method in the Truckee canal, but only detected a minimal amount of plant material. This lack of detectable plant growth in the canal meant there was no reason to treat this section at this time.

Given the lack of plant growth in the Truckee canal by July 2020 and an unexplainable drying event at the end of July, we requested information about other sections of canals that had issues with excessive plant growth. Scott Fennema provided the locations of three canal sections in Fallon, the R-line, V-line, and S-line. The research team pivoted to collecting information from these new canals and set up transects for plant and hydrologic monitoring. In consultation with Inventive Resources Incorporated, the design-builder of the ultraviolet light tool, we determined that the R-line was the best location for ultraviolet light treatment. Treatment and sampling from 2020 informed the sampling design used in 2021, described in detail below.

2. Ultraviolet Treatment Boat Design & Development

In 2020, Inventive Resources Inc completed the Year 1 planned treatment for a 2,900-foot segment of the bottom of a 24-foot wide dirt lined canal (the R-line canal). This canal segment is along Reservoir Road between Stillwater Road/State Route 116 in Churchill County (39.486407, -118.663727) in Fallon, Nevada approximately 35 miles east of the original Fernley, Nevada site. The treatment vessel for the project had some modifications for this canal. The vessel was 30′ x 8′ with four (4) indexing wheels. Indexing wheels were used to position the vessel in the desired location of the canal (Figures, 1 and 2). The treatment vessel was comprised of the following:

- 6 Propane generators;
- 240 UV-C lamps 36 watts, 55 watts, 95 watts (size 8-ft x 20-ft)
- 10-inch castor wheels for easy removal on boat ramp; • 20-foot depth poles schedule 80;
- Propane tanks;
- 12-volt trolling motors;
- 15-foot winch system to lower array; and
- Outriggers with 48-inch floating wheels

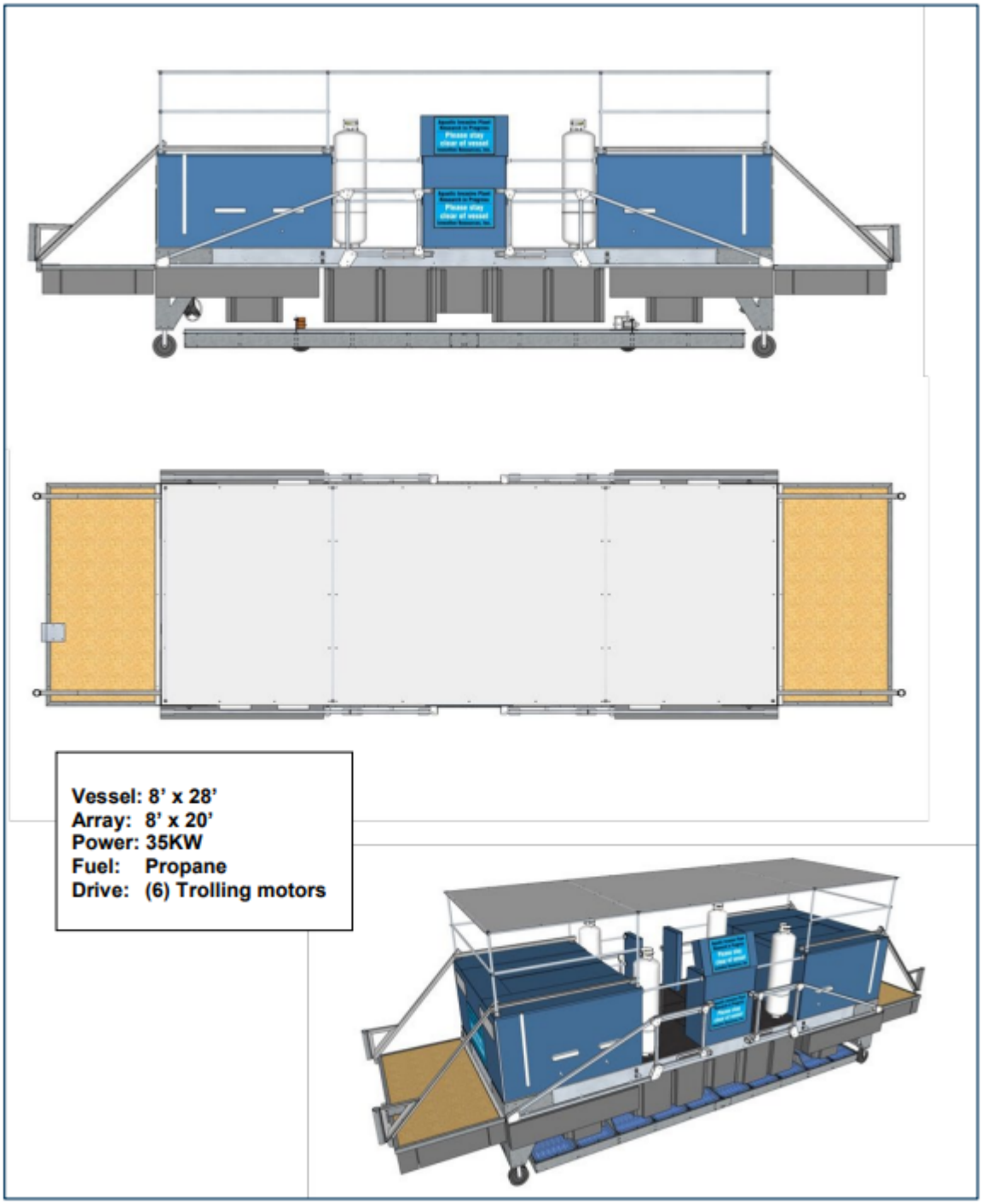

Figure 1. Treatment vessel designed and built for this project by Inventive Resources Inc. (IRI).

Figure 2. **Indexing wheels of the full Inventive Resources Inc. treatment vessel in the canals.**

The UV-C light treatment vessel was the first large scale UV-C treatment vessel made. This design was chosen to allow the operators to use propane as a fuel (Figure 1). Six (6) propane generators powered the lamps. The array was made up of a combination of 36, 55, and 95-watt UV-C lamps. The 8-foot by 20-foot array could slowly move over the plants and target larger infestations. A smooth rounded pipe system was added around the outer edge of the array to help deflect plants under the lamps.

The UV treatment device provided for 20 minutes of exposure to plants on the bottom of the canal. The light chamber under the vessel would be lowered to approximately 8 inches to 12 inches from the bottom. As the array was lowered it would deflect and concentrate the tall plants near the bottom in order to insure most of the plants would receive the desired treatment.

To position the vessel, ropes and trolling motors were used. The treatment patterns were done in linear movement. This allowed for proper overlap and 100 percent coverage. The vessel had four 55-watt electric motors for population and a winch system that pulled the vessel along the canal.

3. Year 1 (2020) Treatment Implementation & Macrophyte Monitoring

In 2020, we started by monitoring the Truckee Canal (as described above) but switched locations to where the project implemented its first treatment along Reservoir Road between Stillwater Road/State Route 116 in

Churchill County (39.486407, -118.663727) in Fallon, Nevada (R-line). This location is approximately 35 miles east of the original Fernley, Nevada site which required additional mobilization.

Sampling or scouting dates in Fernley (Truckee Canal original location):

1. 02/25/2020
2. 04/24/2020
3. 05/04/2020
4. 05/27/2020
5. 06/02/2020
6. 06/11/2020
7. 06/22/2020
8. 06/24/2020
9. 07/06/2020
10. 07/10/2020
11. 07/13/2020
12. 07/17/2020
13. 07/24/2020

Sampling dates in Fallon (R-line canal location):

1. 07/17/2020
2. 07/24/2020
3. 08/05/2020
4. 08/10/2020
5. 08/18/2020
6. 08/21/2020
7. 08/28/2020
8. 08/29/2020
9. 09/01/2020
10. 09/15/2020
11. 09/18/2020
12. 09/25/2020
13. 09/29/2020
14. 10/02/2020

From August 28-29th, 2020, we sampled the R-line for the pre-treatment monitoring measurements. To sample macrophytes, we raked from bank to bank, perpendicular to flow, at a random sampling location within each of the chosen canal segments. We used a double-headed garden rake for this method, consistent with accepted macrophyte sampling techniques (Parsons 2001; Yin and Kreiling 2011). We took pictures of the canal bed and sampled plants using a rake method from 12 randomly selected transects out of 20 transects. Half of the sampled transects were located in the "control" or reference reach and the other half were from the "treatment" reach at the R-line. The post-treatment sampling occurred on September 25th, in which we sampled plants

from all 20 transects. Inventive Resources Incorporated implemented a treatment over 6 days starting on September 3rd, 2020.

Figure 2. **IRI treatment of the R-line canal in Year 1 of the project.**

Near the end of the treatments, Inventive Resources discovered on September 15th that the canal had been drained of water. Drying the canals could have a significant impact on plant growth and we would not be able to determine whether the changes in plant growth following treatment were a result of canal drying or of the treatment by Inventive Resources. Therefore, we were unable to use the monitoring data to understanding the impacts of the treatments. In addition to the R-line sampling, the S-line was sampled on September 18th and the V-line was sampled on October 2nd. These locations did not have ultraviolet light treatment, but were sampled to provide additional context to the R-line plant growth given how variable it appears to be among canal reaches.

To conclude our field activities for 2020, on October 2nd, the V-Line canal in Fallon, Nevada was sampled to provide additional context to plant growth in the treated canal (the R-line) given how variable it appears to be among canal reaches. Plant monitoring included pulling a rake along the bottom of the canal to sample plant material. This plant material was sorted in the lab to separate different plant species and filamentous algae. Preliminary data for plant growth in the canals showed a lower biomass per area of plants in the treatment section as compared to the control section (Figure 3). Unfortunately, due to the draining of the R-Line canal in the two weeks following treatment, we were not able to conclusively state that this data reflects the effects of the UV-C treatment.

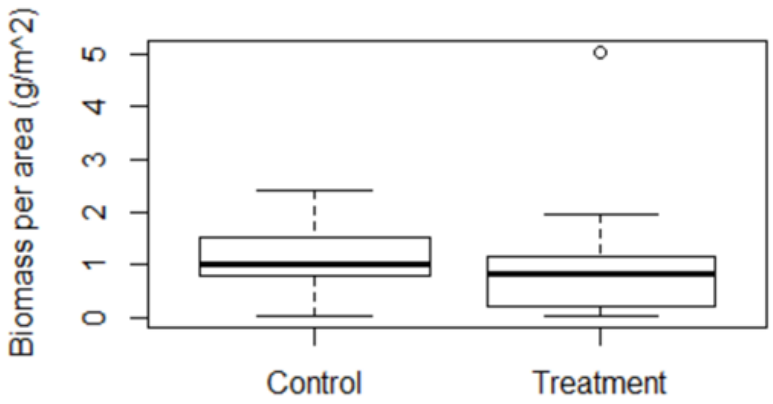

Figure 3. **Comparison of dried macrophyte biomass per area (g/m2) in the R-line in 2020 between the control and treatment sections of the canal after UV-C treatment occurred.**

After treatment and demobilization was completed in mid-September 2020, efforts were made in October and November for cleaning, servicing and storing ultraviolet lights for the season. After Year 1 treatment was completed, there were several team meetings and site visits for potential new treatment sites around the Fallon area.

We convened meetings with the project partners to prepare for treatments the following year and to focus our efforts in understanding the ecology of the plant growth in canals. To prepare for the next season of sampling and treatment, in the winter and spring of 2021, we reviewed literature on aquatic macrophyte growth in canals. In spring 2021, we developed a new sampling plan which attempted to address the dewatering issues from the previous year. We discussed options for treatment with the TCID to ensure that we would be in locations with lots of plant growth and where canal flow was sure to persist throughout the season. With those considerations in mind, representatives from the University and Inventive Resources Inc scouted potential treatment and sampling locations in Fallon, Nevada on February 15, 2021. As there was visible dead plant matter from the previous season on the bottom of the A-Line canal and it was accessible but somewhat remote, we determined that this was an appropriate location for treatment. While the canal was still dry, we walked the reach and took preliminary canal dimension measurements. We also determined a backup treatment location on the L-Line between Casey Road and Lattin Road. This will provide us with a known and monitored location for treatment in the event that we do not find aquatic plants in the A-Line. We also identified a further downstream location on the L-Line and a location on the V-Line for monitoring that would allow for a comparison between the effects of the UV-C treatment and the more traditionally used treatments – pre-emergent herbicide and mechanical chaining. All parties agreed on the site locations for the treatments that would allow for the efficacy testing of ultraviolet and minimize COVID exposure impacts to team members.

4. Year 2 (2021) Treatment Implementation & Macrophyte Monitoring

Year 2 (2021) Treatment Plan & Sampling Dates

In 2021, we monitored three canal sections located along two different canals in Fallon, Nevada. We chose these canal reaches because of their accessibility, consistent water flow throughout the irrigation season, and because the reaches were identified by TCID managers as problem areas where excessive macrophyte growth causes operational issues (e.g., lowered canal capacity, lower flow velocities). Water flow in these canals fluctuates based on irrigation demand so we chose primary canals to ensure that water flow would be relatively consistent. The three sections were: (1) A-Line (A): a ~1,463-meter length near the beginning of the A-Line canal surrounded by houses and ranches, (2) upstream L-Line (UL): a ~1,396-meter length near the beginning of the L-Line canal with cropland on one side and a residential area on the other, and (3) downstream L-Line (DL): a ~2,347-meter length of the L-Line canal in a residential area with a relatively busy road on one side.

Sampling or scouting dates in Fallon:

1. 2/15/2021
2. 4/7/2021
3. 4/23/2021
4. 5/7/2021
5. 5/17/2021
6. 5/24/2021
7. 5/31/2021
8. 6/1/2021
9. 6/7/2021
10. 6/8/2021
11. 6/14/2021
12. 6/15/2021
13. 6/21/2021
14. 6/28/2021
15. 6/29/2021
16. 7/6/2021
17. 7/12/2021
18. 7/19/2021
19. 7/26/2021
20. 7/27/2021
21. 8/2/2021
22. 8/9/2021
23. 8/10/2021
24. 8/16/2021
25. 8/30/2021

Inventive Resources Inc completed the Year 2 planned treatment on a 1,300-foot-long section of a 30-foot-wide canal in the A-Line. The treatment vessel for the project had some modifications for this canal. The vessel was 30-ft x 8-ft with four (4), 48-inch diameter indexing wheels that were modified to be adjustable as needed to provide proper overlap (Figure 4). Plant deflectors were added to the front and back of the vessel to guide plants underneath the ultraviolet light array. Field modifications were made on-site to adapt to the water level fluctuations. The treatment array was also upgraded with new ultraviolet lamps and indexing wheels in order to

keep the array from hitting sediment. The ultraviolet array was held off the ground approximately eight (8) inches. When the ultraviolet array hit an obstruction, the operator was able to lift the front side of the treatment array and adjust immediately after passing the obstruction.

Figure 4. **IRI treatment boat on the A-line in 2021.**

In Year 2, Inventive Resources applied one treatment instead of two treatments but sections of the canal were split up into three phases (Figure 5). The middle section of the canal, an approximately 300-ft section, was treated twice. The other two sections of approximately 500-ft were treated one time. After treatment and demobilization was completed in mid-July, the ultraviolet vessel and lamps were inspected and tested for optimum ultraviolet output. No damage was visible on ultraviolet lights and light output was in the desirable limits.

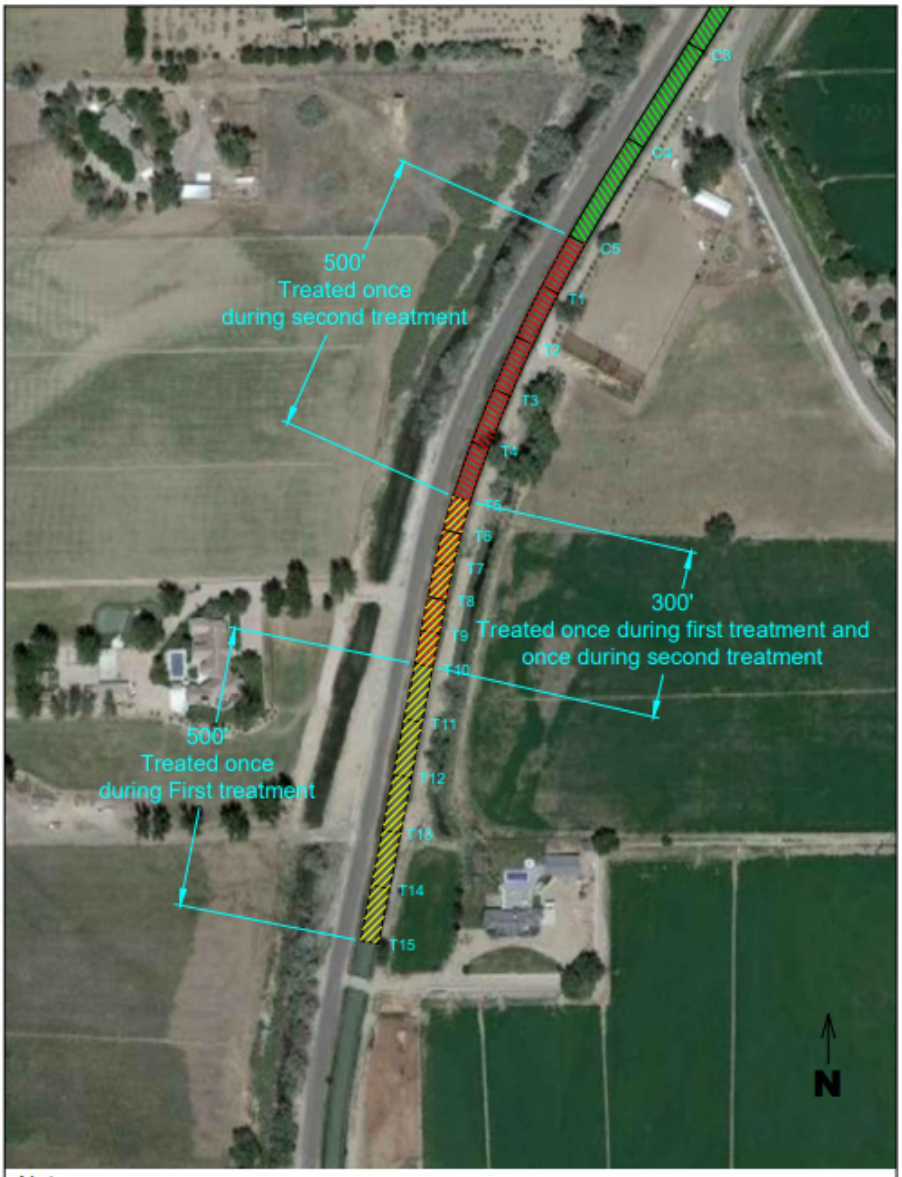

Figure 5. Year 2 treatment plan in the A-line canal. The green section corresponds to the control reach which was upstream from the treatment reaches.

We sampled each of the three canal sections three times over the summer of 2021, always in the same order in consecutive weeks (UL → DL → A), resulting in a total of nine sampling events. Each canal section was chained to remove macrophytes in between the first and second samplings (UL and DL chained on June 9th and 10th; parts of A chained on June 16th and 23rd). The A canal section was treated using UV-C in between the second and third sampling events. At the UL and DL canal sections, we established ten evenly spaced segments of

approximately 140 and 235 meters in length respectively, each of which was sampled for macrophytes during sampling events. Due to further experimental design considerations, the A canal section was divided into twenty segments – five at 61 meters long (AC 1-5), five at 30.5 meters long (AT 1-5), five at 18 meters long (AT 6-10), and another five at 30.5 meters long (AT 11-15; Supplemental Figure 1). During the first sampling event, we sampled all segments within AC 1-5 and ten randomly chosen segments from AT 1-15. During subsequent events, we sampled three randomly chosen segments from each AC 1-5, AT 1-5, AT 6-10, and AT 11-15 for a total of twelve sampled segments.

Year 2 (2021) Macrophyte & Canal Monitoring Methods

To sample macrophytes, we raked from bank to bank, perpendicular to flow, at a random sampling location within each of the chosen canal segments. We used a double-headed garden rake for this method, consistent with accepted macrophyte sampling techniques (Parsons 2001; Yin and Kreiling 2011). We measured depth at one-meter intervals across the sampled transects to allow for calculation of biomass per area. We used a Ponar (Petite Ponar with 6" Scoops, Wildco Supply Company, Yulee, Florida, USA) to collect at least 150 g of wet sediment from six randomly chosen sampling locations at the UL and DL canal sections and at three randomly chosen sampling locations within AT 1-5 and three randomly chosen sampling locations within AC 6-10 at the A canal section. Of the six Ponar samples that were collected, two were located near the left bank, two were near the middle, and two were near the right bank. Macrophyte and sediment samples were stored in plastic resealable bags on ice until transported back to the lab where they were refrigerated at 4°C until processing.

For each sampling event, we filtered three surface water samples in the field through Whatman GF/F filters (Whatman, Piscataway, New Jersey, USA) into acid-washed 60 mL HDPE bottles. Filtered surface water samples were stored on ice until they were transported back to the lab and frozen at -20°C until chemical analysis. We also collected one unfiltered surface water sample in a clean 500 mL plastic bottle for analysis of total suspended solids (TSS).

We processed macrophyte samples within two days following collection. We sorted a randomly selected subset of collected macrophyte samples per sampling event, at least 30%. We sorted macrophytes to the genus level or further, apart from the many aquatic grasses. We combined these grasses into one category which we call ditchgrass. The components of ditchgrass are leafy pondweed (Potamogeton foliosus), horned pondweed (Zannichellia palustris), threadleaf pondweed (Stuckenia filiformis), sago pondweed (Stuckenia pectinatus), and widgeongrass (Ruppia maritima or cirrhosa). Non-grass species included curly leaf pondweed (Potamogeton crispus), Elodea, Nitella, and watermilfoil (Myriophyllum). In addition to macrophytes, we sorted all filamentous algae into a separate category. All macrophyte samples, including those that were not sorted, had non-macrophyte/filamentous algae (e.g., snails), terrestrial, and decomposing material removed, were washed in a sieve, and were placed into paper bags to be dried in an oven at 60°C for 48 hours. We calculated macrophyte and filamentous algae biomass per m^2 by dividing dried sample weights by the area that was sampled (calculated by multiplying rake width by length of sampling area determined from depth transect).

We measured bulk density, organic matter content, and pH for each Ponar-grab collected sediment sample. We weighed 50 mL of wet sediment to determine bulk density. We dried sediment samples at 60°C for 48 h and then combusted them at 440°C for 4 h to determine ash-free dry mass (AFDM) and percent organic matter (%OM = ((dry weight – AFDM)/dry weight) × 100). All organic matter content samples were run in triplicate with an average standard deviation of 0.1%. We used an Orion Star A211 Benchtop pH Meter (Thermo Fisher

Scientific, Waltham, Massachusetts, USA) to measure the pH of a mixture of 3 g of dried sediment in 5 mL of 0.01 mol/L CaCl2, the addition of which lowers sediment pH by ~0.5 pH units compared to water pH but is advantageous for taking measurements (Carter and Gregorich 2008). Twenty percent of pH samples were run in duplicate and were within 5% of each other.

We used a homogenized mixture of equal volumes from all Ponar-grab collected sediment samples from a given sampling event to produce porewater extraction samples for that event. To extract porewater solutes, 2.5 ± 0.25 g of wet sediment and 25 mL of deionized water were added to a falcon tube and were vortexed every 30 minutes for 4 h. The falcon tubes then rested in the fridge overnight and were centrifuged the next day. The supernatant was filtered through Whatman GF/F filters and stored in acid-washed 60 mL HDPE bottles in a freezer at -20°C.

Porewater samples and filtered water chemistry samples were analyzed for anions, dissolved organic carbon (DOC), total dissolved carbon (TDC), total dissolved nitrogen (TDN), ammonium, and orthophosphate. We analyzed samples for bromide (Br−), fluoride (Fl−), nitrite (NO2−), and nitrate (NO3−) concentrations using an ion chromatograph (ICS-2000) with an AS18 anion column and KOH eluent generator (Dionex Corporation, Sunnyvale, California, USA). We analyzed samples for DOC, TDC, and TDN using a TOC analyzer with a TN module (TOC-V CPH; Shimadzu, Kyoto, Japan). We analyzed samples for ammonium (NH4+-N) and orthophosphate (o-P) concentrations using a SEAL AQ2 discrete analyzer (SEAL Analytical, Mequon, Wisconsin, USA) based on USEPA method 350.1 revision 2.0 and USEPA method 365.1 revision 2.0 (US EPA 1993a; b), respectively. We calculated the proportions of ammonia-N and ammonium-N from the aqueous ammonia measured using a calculation that incorporates the influence of temperature and pH (Emerson et al. 1975). We filtered unfiltered surface water samples through pre-weighed Millipore membrane filters which were then dried at 60°C for 48 h to determine total suspended solids (TSS) values.

We used a Marsh McBirney Flo-Mate (Hach, Loveland, Colorado, USA) to measure flow at each studied canal section approximately every two weeks (n = 14-15 per canal section). To increase the frequency of flow estimates in each of the canals, midway through the sampling period (after 4 of the 9 sampling events had occurred), Levelogger 5 Juniors (Solinst Canada Ltd, Georgetown, Ontario, Canada) were deployed at each of the three studied canal sections and a Barologger 5 was deployed within 7 miles of each of the Leveloggers (Solinst Canada Ltd, Georgetown, Ontario, Canada) to allow for 5-minute-interval water level monitoring corrected for barometric pressure. We developed a rating curve for each canal section from Levelogger data and flow rates measured using the Marsh McBirney Flo-Mate (Supplemental Figure 2) which allowed for 5-minute-interval flow rates to be calculated from level data.

We correlated daily flow supervisory control and data acquisition (SCADA) readings from TCID with the Marsh McBirney Flo-Mate derived estimates. Correlation coefficients between SCADA and Flo-Mate discharge estimates were all greater than 0.7. Therefore, we incorporated the SCADA estimates into the final daily flow results that we determined by calculating a daily average for the Levelogger flow data and using our other two sources of daily flow data to develop an average daily flow value for each canal. We then interpolated between these values for where there were gaps in this data. For the downstream L-Line site only, SCADA flow data was adjusted using the average difference between SCADA measurements and Flo-Mate measurements to represent the loss of water in between the head of the L-Line and the downstream location that we monitored before it was incorporated into our final daily estimates.

Approximately every two weeks throughout the sampling period, we used an EXO2 Multiparameter Sonde (YSI Incorporated, Yellow Springs, Ohio, USA) to measure temperature, dissolved oxygen, conductivity, and pH in the water column. We calibrated the pH probe within 24 hours before field measurement. At each sampling event but one (due to equipment unavailability), we used a HOBO Pendant Temperature/Light 64K Data Logger (Onset Computer Corporation, Bourne, Massachusetts, USA) in conjunction with a wading rod to measure light levels at the water surface and at subsequent 10 cm intervals downward. This data was used to calculate light extinction coefficients by fitting a log-linear relationship. Light extinction and TSS values were highly correlated (correlation coefficient = 0.97). Therefore, only TSS was used as a model input as there was TSS data available for all 9 sampling events.

We retrieved water temperature data from MiniDOTs (Precision Measurement Engineering (PME), Vista, California, USA) that were deployed upstream and downstream of each canal section over the sampling period. We downloaded surface light data from NASA's North American Land Data Assimilation System (NLDAS; http://ldas.gsfc.nasa.gov/nldas) and converted shortwave radiation to PAR using a multiplier (Britton and Dodd 1976). We downloaded PM2.5 data from the most central PurpleAir sensor available in Fallon (PurpleAir; Oasis Online; https://www.purpleair.com/sensorlist); this data was used to account for the potential impact that smoke from the nearby Caldor Fire had on the area.

We used miniDOT sensors (PME, Vista, California,USA) to monitor dissolved oxygen and temperature levels at 5 minute intervals at the upstream and downstream end of each canal section. The sensors were deployed near the bank on rebar that was pounded into the stream sediment and were secured with zip ties. For optimal measurement, the sensors faced downstream, away from the bank, at approximately a 45° angle. When deployed, the height of the sensor in the water was recorded – each was placed approximately in the middle of the water column, halfway from the surface to the bottom. We cleaned the sensors of plant matter and debris at least every other week. The sensors we used had been recently calibrated by the manufacturer so although 100% oxygen saturation calibrations were done before and after deployment, no adjustment of values was deemed necessary.

Year 2 (2021) Treatment Evaluation Challenges

The third macrophyte monitoring event of the summer of 2021, was scheduled two weeks after UV-C treatment on August 10th, 2021. Unfortunately, no plants were detected in either the control or treatment reaches at the A-line (Figure 6). In addition, no plant fragments were found in the A-line canal sediment once canals were drained (Figure 7). The exact reason behind this sudden disappearance of plants in both the control and treatment reaches is unclear. There was no evidence of chaining in the canal because no chained plants were deposited by the side of the canal.

Figure 6. **Photo of empty rake with no plants after raking across the canal at the A-line canal during the third and final sampling event (8/10/21).**

Figure 7. **Photo of sediment sampling with no plant fragments found at the A-line canal after canal drainage (8/30/21).**

5. Efficacy of UV-C Treatment on Macrophyte Growth

Determination of the efficacy of using UV treatment in the canals was complicated over the 2 year project by the following factors: 1. delayed implementation of the project in year 1 due to Covid pandemic, 2. unexpected dewatering of the canal after treatment in year 1, 3. rapid loss of plants in the untreated and treated areas during year 2 where there was a heavy amount of wildfire smoke and potential introduction of chemicals or other disturbances by homeowners that cleared the plants. We were not able to determine the efficacy of UV treatment on plants in a field setting at the Truckee Canal. We were able to determine the efficacy of plant treatments in a laboratory setting at the University of Nevada and through some pilot field experiments at Lake Tahoe funded through other sources. Tests suggest 100% mortality of multiple plants species over 2 weeks after one exposure by UV light treatment indicating the promising use of UV light as a noninvasive treatment to water ways.

Objective 4: Quantification of aquatic macrophyte regrowth rates

1. Data Analysis of Macrophyte Regrowth & Relationships with Environmental Controls

We analyzed all available data from the 2021 ultraviolet light treatment and three canal monitoring locations to quantify macrophyte regrowth rates following the annual rewetting of the canals. We quantified variability in macrophyte density within canals and through time by calculating the standard deviation of biomass per area across transects within each canal. We evaluated differences in macrophyte density, macrophyte diversity, and environmental variables among canals and among sampling events with Kruskal-Wallis tests and we used post-hoc Wilcoxon signed-rank tests to identify pairwise differences among canals and events. To account for the cumulative effects of environmental conditions prior to the sampling date, we calculated averages of data from the previous 30 days for variables where daily values were available – surface light, PM2.5, water temperature, and flow.

To assess which environmental conditions predict variation in macrophyte density, we first used bivariate correlations (Kendall's tau) to examine the link between environmental variables and macrophyte biomass per area. Covariates that had correlation coefficients less than 0.15 and p-values greater than 0.05 when analyzed with macrophyte biomass per area were removed from further analyses. We then removed tightly correlated variables (correlation coefficient > 0.7) from this set of variables. To examine the relationships between macrophyte density and the remaining environmental variables, we used generalized linear models (GLMs) with canal and event as fixed effects and a gamma distribution with a log link function. No plants were found at our third sampling event at the A-Line canal so these zero data were removed from our biomass per area GLMs as they disrupted our analyses. We performed GLMs on all possible combinations of one and two environmental variables as two variables was the limit for the interpretability that our data set provided. We performed model selection based on small-sample corrected Akaike Information Criterion (AICc).

We also investigated the composition of the different macrophyte species in each of the monitored canal reaches. To assess which environmental conditions predict variation in macrophyte diversity, we first used bivariate correlations (Kendall's tau) to examine the link between environmental variables and Shannon's Diversity Index (SDI). Covariates that had correlation coefficients less than 0.15 and p-values greater than 0.05 when analyzed with SDI were removed from further analyses. We then removed tightly correlated variables (correlation coefficient > 0.7) from this set of variables. To examine the relationships between SDI and the remaining environmental variables, we used GLMs with canal and event as fixed effects and a gamma distribution with a log link function. We performed GLMs with only one environmental variable at a time as this was the limit for the interpretability that our data set provided. We performed model selection based on small-sample corrected Akaike Information Criterion (AICc). We performed all analyses using R version 4.1.2 (R Core Team 2020).

2. Results: Year 2 (2021) Macrophyte Biomass Regrowth & Composition

Macrophyte biomass & composition changes over time & among canals

Biomass per area measurements varied considerably among transects within canals but each canal showed the general trend of mean biomass per area peaking in July. Mean biomass per area was greatest in the second sampling event (late June to early July) and lowest in the third sampling event (August) for all sites except the upstream L-Line site wherein average biomass per area increased in each subsequent event (Figure 8A). A Kruskal-Wallis test showed that sampling event (timing) significantly affected biomass per area across canals ($H(2)=32.9$, $p<0.01$). Pairwise comparisons using a Wilcoxon rank sum test with continuity correction revealed that the difference in biomass per area between the second sampling event and the other two events was significant ($p<0.01$) while the difference in biomass per area between first sampling event and the third sampling event was not significant ($p=0.13$). There was variation among sites across sampling events when grouped ($H(2)=9.0$, $p<0.05$). For individual events, variation among sites was present for the first ($H(2)=11.8$, $p<0.01$) and third ($H(2)=23.8$, $p<0.01$) sampling events but not for the second event in the middle of the summer when macrophyte density was high in every canal ($H(2)=4.1$, $p=0.13$).

Macrophyte biomass was similar in the control and treatment reaches in the A-line canal during the first ($H(1)=0.74$, $p=0.39$) and second sampling events ($H(1)=0.21$, $p=0.64$). As stated before, in the third sampling event, post-UV-C treatment, no plants were detected in either the control or treatment reaches at the A-line (Figure 6). In addition, no plant fragments were found in the A-line canal sediment once canals were drained (Figure 7).

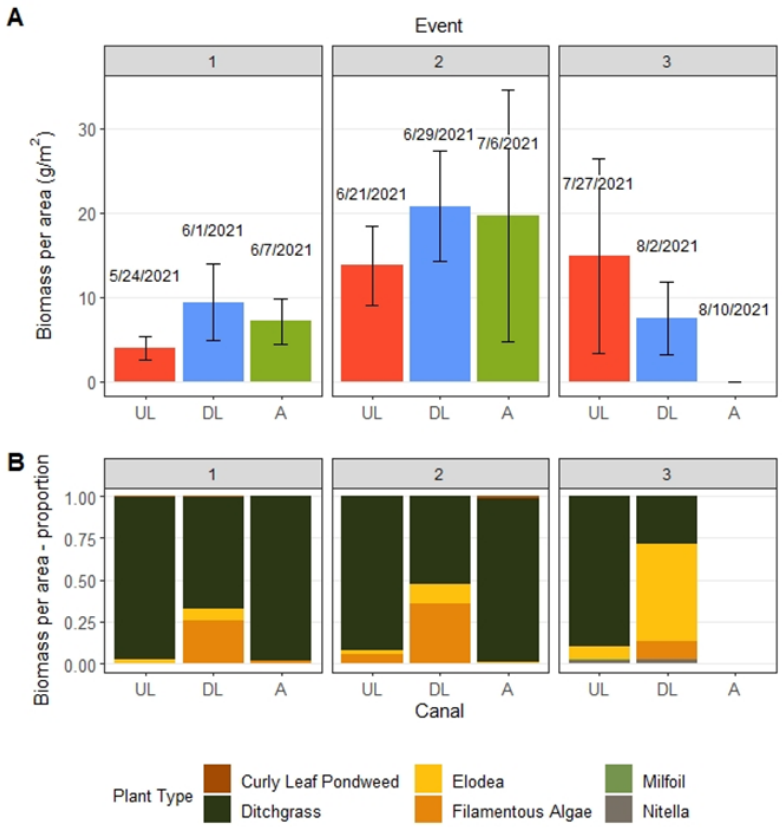

Figure 8. **(A) Plot of biomass per area for each sampling event with labels for sampling dates. Error bars show standard deviation. (B) Proportions of plant types for each sampling event.**

Ditchgrass heavily dominated measurements of macrophyte biomass until the final sampling event (> 50% of macrophyte biomass in all canals; Figure 8B). The composition of macrophyte biomass was consistently dominated (> 80%) by ditchgrass in the upstream L-line canal and in the A-line canal (apart from the missing plants in August) while the downstream L-Line canal showed more genus variation than the others, with a quarter of the total biomass in each of the sampling events being made up of Elodea and filamentous algae. The composition of macrophyte biomass overall, as represented by the Shannon Diversity Index, changed over the summer in both the downstream L-line ($H(2)=7.9$, $p<0.05$) and upstream L-Line ($H(2)=7.0$, $p<0.05$) but not in the A-Line canal ($H(2)=3.0$, $p=0.23$) or for all sites when grouped ($H(2)=5.2$, $p=0.07$). For both L-Line sites where seasonal variation was present, the proportion of macrophyte biomass not consisting of ditchgrass increased in each subsequent event. Across sampling events, the diversity of the macrophyte community as represented by the Shannon Diversity Index varied among sites ($H(2)=24.7$, $p<0.01$) with each site differing from each other site in a Wilcoxon pairwise comparison ($p<0.01$).

The abundance of each plant type varied uniquely through time and among canals. Curly leaf pondweed was present in small amounts in the first and second sampling events in all canals but was not present in the third sampling event. There was no seasonal or among site statistical variation in curly leaf pondweed abundance. Elodea abundance varied seasonally ($H(2)=10.3$, $p<0.01$) with average biomass per area values for Elodea

increasing throughout the summer. Elodea abundance also varied among sites ($H(2)=21.7$, $p<0.01$) with the downstream L-Line consistently having the most, followed by the upstream L-Line and then the A-Line. There was no seasonal variation in filamentous algae abundance at the canals, however there was among site variation ($H(2)=19.9$, $p<0.01$) with the downstream L-Line site consistently showing the most abundance. The abundance of Nitella changed over time in the canals ($H(2)=21.4$, $p<0.01$). No Nitella was present at any of the canals in the first sampling event. In the second sampling event only the A-Line site showed Nitella presence while during the third sampling event only the L-Line sites showed Nitella presence. There was seasonal variation in milfoil abundance at the canals ($H(2)=23.2$, $p<0.01$). Milfoil was not present in the first or second sampling events but was found in both L-Line sites in the third sampling event.

Canal environmental conditions

Macrophyte biomass and diversity are associated with both physical and chemical characteristics of the aquatic environment.

Light

The incoming and within-canal light availability varied among canals and across the growing season. For each site, TSS (representative of within-canal light attenuation) was lowest in the second sampling event (late June early July; 0.004 - 0.008 mg/mL) and peaked in the third sampling event (late July, early August; 0.058 – 0.104 mg/mL). There was both seasonal ($H(2)=79.7$, $p<0.01$) and among site variation in TSS values ($H(2)=8.7$, $p<0.05$). When averaged over the 30 days prior to each sampling event, surface light values were similar for the first (late May, early June; 623 - 667 PAR) and third (late July, early August; 630 - 659 PAR) sampling events but higher for the second sampling event (late June, early July; 705 - 708 PAR). There was both seasonal ($H(2)=69.0$, $p<0.01$) and among site variation in surface light values ($H(2)=7.6$, $p<0.05$).

Water chemistry

Specific conductivity varied seasonally ($H(2)=87.3$, $p<0.01$) with values increasing through the summer from the first sampling event (240.7 – 270.4 μS/cm) to the third sampling event (380.4 – 387.0 μS/cm). Specific conductivity at the three sites were similar ($H(2)=3.5$, $p>0.1$). All porewater and surface water solutes used as model inputs showed seasonal variation. Porewater TDC values showed seasonal variation ($H(2)=20.0$, $p<0.01$) with values increasing through time at two out of three sites and among site variation ($H(2)=76.8$, $p<0.01$) with TDC values highest at the downstream L-Line site, followed by the upstream L-Line site, and then lowest at the A-Line site. Porewater TDN values also showed seasonal variation ($H(2)=55.4$, $p<0.01$) with values increasing through time at all sites and among site variation ($H(2)=40.9$, $p<0.01$) with TDN values highest at the downstream L-Line site at two out of three sites and lowest at the A-Line site at two out of three sites. Surface water ammonium showed seasonal variation ($H(2)=35.0$, $p<0.01$) with values generally increasing through time and among site variation ($H(2)=55.9$, $p<0.01$) with ammonium values highest at the A-Line site, followed by the upstream L-Line site, and then lowest at the downstream L-Line site. Surface water bromide showed seasonal variation ($H(2)=62.8$, $p<0.01$) with values increasing through time but not among site variation ($H(2)=2.0$, $p>0.1$). Surface water nitrate showed seasonal variation ($H(2)=70.3$, $p<0.01$) with values increasing from the first event to the second event and then decreasing in the third event. Surface water nitrate showed among site variation ($H(2)=21.0$, $p<0.01$). Surface water DOC showed seasonal variation ($H(2)=68.9$, $p<0.01$) with values increasing through time and among site variation ($H(2)=24.0$, $p<0.01$) with values consistently higher at the A-Line site, followed by the upstream L-Line site, and then lowest at the downstream

L-Line site. Surface water TDN showed seasonal variation ($H(2)=67.7$, $p<0.01$) with values increasing through time at two out of three sites. TDN concentrations were highest at the A-Line site and consistently lowest at the upstream L-Line site.

Flow

There was seasonal variation in flow among sampling events ($H(2)=72.5$, $p<0.01$). For all three sites, flow was highest in the third sampling event (late July, early August; 4.3 - 6.4 cms) and similar in the first (late May, early June; 1.4 - 4.0 cms) and second (late June, early July; 2.7 - 4.1 cms) sampling events. There was variation in flow between sites; for all three sampling events, the upstream L-Line canal had the highest flow averaged over the 30 days prior to sampling events, followed by the A-Line canal, and then the downstream L-Line canal (Table 1).

Sediment

Sediment percent organic matter showed no seasonal variation ($H(2)=0.4$, $p>0.1$) but did show among site variation ($H(2)=7.5$, $p<0.05$) with the A-Line site having lower sediment percent organic matter on average than the L-Line sites.

Table 1. **Summary of model input environmental variables for each site (three time points and one observation per time point). Asterisks indicate variables with statistically-significant among site variation ($p < 0.05$).**

Predictor Variable	Site	Average	Standard Deviation	Range
TSS (μg/mL)*	A	26.3	27.5	6.9 - 57.8
	UL	34.2	33.9	8.1 - 72.6
	DL	38.6	57.1	4.3 - 104.5
Previous 30 day average of surface light (PAR)*	A	668	38	630 - 706
	UL	662	41	623 - 705
	DL	671	35	638 - 708
Specific conductivity (μS/cm)	A	336	61	266 - 380
	UL	312	71	241 - 382
	DL	328	58	270 - 387
Previous 30 day average of flow (cms)*	A	3.55	1.02	2.47 - 4.49
	UL	4.83	1.34	3.99 - 6.38
	DL	2.81	1.45	1.39 - 4.29

Surface water ammonium (µg N/L)*	A	27.3	18.7	8.2 - 45.5
	UL	10.5	10.5	2.3 - 22.4
	DL	40.3	66.8	0 - 117.4
Surface water bromide (µg/L)	A	40.7	3.8	37.2 - 44.8
	UL	40.3	1.5	39.3 - 42.0
	DL	40.8	0.8	40.2 - 41.4
Surface water nitrate (µg/L)*	A	120	83	63 - 215
	UL	74	36	33 - 100
	DL	140	10	133 - 147
Surface water non-purgeable organic carbon (mg/L)*	A	15.0	1.5	13.5 - 16.4
	UL	13.9	1.9	12.6 - 16.0
	DL	13.1	2.5	10.7 - 15.7
Surface water total dissolved nitrogen (µg/L)*	A	404	120	279 - 518
	UL	297	52	246 - 350
	DL	469	193	262 - 644
Sediment % organic matter*	A	0.95	0.62	0.45 - 2.91
	UL	1.62	1.33	0.48 - 6.01
	DL	2.01	1.90	0.41 - 7.55
Porewater total dissolved carbon (mg/L)*	A	3.07	0.65	2.61 - 3.53
	UL	5.52	1.45	4.57 - 7.19
	DL	8.63	1.63	7.40 - 10.48
Porewater total dissolved nitrogen (µg/L)*	A	245	74	193 - 298
	UL	410	101	322 - 521
	DL	787	562	267 - 1384

3. Results: Environmental controls on macrophyte biomass regrowth

TSS, surface light, porewater ammonium, porewater fluoride, porewater DOC, porewater TDN, surface water nitrate, surface water DOC, surface water TDN, and flow all produced correlation coefficients greater than 0.15 ($p < 0.05$) when analyzed with biomass per area. Among these variables, porewater TDN showed a strong correlation with porewater ammonium, porewater fluoride, and porewater DOC (correlation coefficient > 0.7). These variables were removed from further analysis as porewater ammonium is contained within porewater TDN and we hypothesize that porewater TDN is more important to the growth of macrophyte biomass than porewater fluoride or porewater DOC. Surface water nitrate was also removed from analyses as nitrate is a component of TDN and had missing values that yielded poorer models.

The model that resulted in the lowest AICc value explained 19% of the biomass per area variation based on significant main effects of canal, event, and the environmental variable TSS (Table 2). Biomass per area was negatively related to TSS indicating that higher TSS inhibits biomass density. The impact of TSS on biomass density was similar across sites (Figure 7).

Although the model with TSS had the best fit, all environmental variables that were included in the analyses were found to influence biomass per area except flow (as indicated by confidence interval overlapping zero; Figure 4). Surface light was the only variable included that had a positive effect on biomass density. Porewater and surface water nitrogen and carbon concentrations were negatively related with biomass density.

Table 2. (A) Fitted model comparisons for biomass per area in order of best fit based on small-sample-corrected Akaike Information Criterion (AICc). Models with AICc values less than 546 are displayed. (All models are in Supplemental Table 4.) (B) Summary of the best-fit model – includes mean-centered standardized slope, standard error, and t-value. The model was statistically significant ($p < 0.001$).

A. Model comparisons	
Model form	AICc
~f (Canal + Event + TSS)	543.4
~f (Canal + Event + TDN.PW)	544.6
~f (Canal + Event + TSS^2)	545.7
~f (Canal + Event + TSS + DOC.SW)	545.7
~f (Canal + Event + TSS + TDN.PW)	545.8
~f (Canal + Event + TSS + Flow)	545.8
~f (Canal + Event + TSS + TDN.SW)	545.8

~f (Canal + Event + TSS + Surface Light)			545.8
~f (Canal + Event + Flow^2)			546.0
B. Best Fit Model Summary			
Main effect	Standardized slope	Standard error	t-value
Canal A	1.5	0.15	10.5
Canal UL	1.2	0.16	7.4
Canal DL	1.5	0.15	10.5
Event 2	0.8	0.14	5.5
Event 3	3.0	0.53	5.6
TSS	-1.1	0.23	-4.8

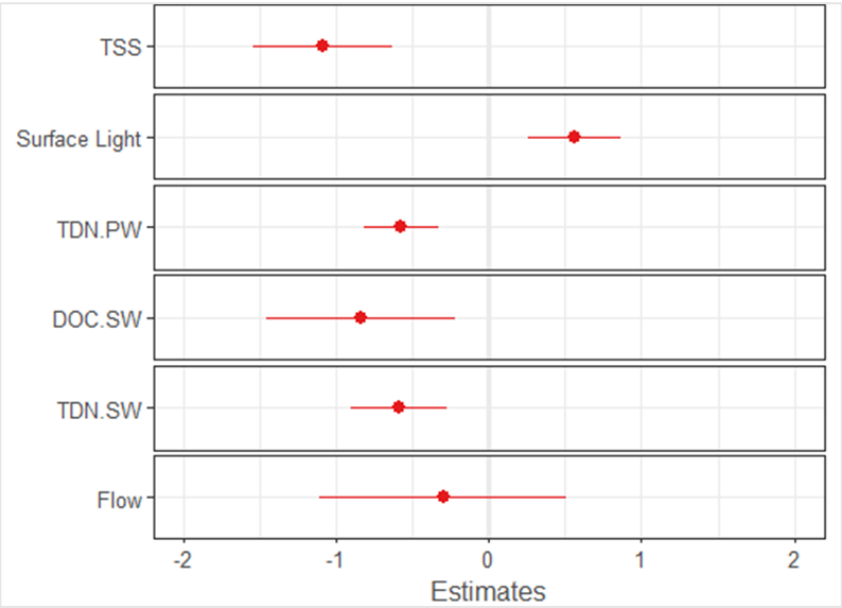

Figure 10. Comparison of estimates for centered data from models with a single environmental variable. Flow is the only variable that overlaps with zero, indicating no significant effect on biomass per area.

4. Results: Environmental controls on macrophyte biomass composition

Specific conductivity, porewater ammonium, porewater fluoride, porewater TDC, porewater DOC, porewater TDN, surface water ammonium, surface water bromide, surface water nitrate, and sediment percent organic matter all produced correlation coefficients greater than 0.15 ($p < 0.05$) when analyzed with biomass per area. Among these variables, porewater TDN showed a strong correlation with porewater ammonium, porewater fluoride, and porewater DOC (correlation coefficient > 0.7). In addition, porewater ammonium was correlated with surface water bromide (correlation coefficient = 0.72) and porewater DOC was correlated with porewater TDC (correlation coefficient = 0.92). Porewater ammonium, porewater fluoride, and porewater DOC were removed from further analysis as porewater ammonium is contained within porewater TDN and we hypothesize that porewater TDN is more important to the growth of macrophytes than porewater fluoride or porewater DOC.

The model that resulted in the lowest AICc value explained 68% of the SDI variation based on significant main effects of canal, event, and the quadratic term ammonium (Table 2). All of the best fit models (AICc < -10) for macrophyte diversity contain surface water nutrient terms indicating the importance of ammonium, nitrate, and bromide as controls. Models containing surface water specific conductivity and porewater nutrient terms resulted in better fit models than those with sediment percent organic matter terms indicating that sediment percent organic matter was the least important driver of macrophyte diversity. Comparison among models indicates that different model forms yielded the lowest AICc for biomass per area and SDI meaning that the drivers of macrophyte biomass density and the drivers of macrophyte diversity are different.

Table 3. (A) Fitted model comparisons for Shannon's Diversity Index in order of best fit based on small-sample-corrected Akaike Information Criterion (AICc). Models with AICc values less than -10 are displayed. (All models are in Supplemental Table 7.) (B) Summary of the best-fit model – includes mean-centered standardized slope, standard error, and t-value. The model was statistically significant (p < 0.001).

A. Model comparisons	
Model form	AICc
~f (Canal + Event + $NH_4.SW^2$)	-23.5
~f (Canal + Event + $NO_3.SW^2$)	-22.0
~f (Canal + Event + Br.SW)	-14.1
~f (Canal + Event + NO_3.SW)	-12.2

~f (Canal + Event + NH_4.SW)			-12.2
~f (Canal + Event + Br.SW^2)			-10.8
B. Best Fit Model Summary			
Main effect	Standardized slope	Standard error	t-value
Canal A	2.5	0.64	3.9
Canal UL	12.7	1.55	8.2
Canal DL	18.9	2.14	8.8
Event 2	-6.6	0.82	-8.0
Event 3	-22.3	2.36	-9.5
NH_4.SW	17.5	1.93	9.1
$NH_4.SW^2$	-7.2	0.80	-9.0

5. Discussion: Macrophyte Density & Composition in Canals

To address objective 4 to quantify macrophyte density in irrigation canals, we found that the canals exhibited similar temporal variation in macrophyte density with average macrophyte biomass per area peaking in July while macrophyte diversity generally increased through the irrigation season. Among transect variation in macrophyte density within canals (coefficient of variation (CV) range: 0.31 – 0.78) was similar to among canal variation (CV range: 0.21 – 0.99) across events. Across events, among transect variation in diversity within canals (CV range: 0.05 – 1.17) was less than among canal variation (CV range: 0.93 – 1.07) for all sampling events but one. Different temporal and spatial trends in macrophyte density and diversity indicate that macrophyte density and diversity are not necessarily correlated. This is confirmed by our models which show that macrophyte density and diversity have different primary controls. Our modeling approach revealed that benthic light availability (as represented by TSS) explained the most variation in macrophyte biomass among canals and surface water ammonium explained the most variation in macrophyte diversity among canals.

Although each canal was chained in between the first and second sampling events, biomass per area increased significantly from the first event to the second event highlighting how ineffective chaining is in decreasing macrophyte biomass and justifying leaving the negligible effects of chaining out of our analyses. There were no macrophytes or algae growing in the A-line canal during the third sampling event; this observation was

unexpected and the reason for it is unclear because there was no chaining by TCID management in the A-line between the second and third sampling event.

Benthic light availability (as represented by TSS in the water column) was the strongest predictor of macrophyte density (Table 2), which is consistent with previous studies on environmental drivers of macrophyte abundance in regulated waterways (Zefferman and Harris 2016). Although our model containing both TSS and surface light terms was ranked relatively high through our model selection (Table 2), surface light on its own was not a strong control on macrophyte density relative to nutrients and TSS. This suggests that the effects of the light attenuation within the water column outweigh the effects of incident light outside the water column. This may be especially true at our studied canals since surface light is relatively consistent throughout time due to a lack of canopy cover and little cloud cover. Although there were fires nearby at the end of the summer, they did not appear to have a significant impact on macrophyte density through reducing light availability (Supplemental Figure 3).

Other variables included in our models had unexpected relationships with biomass density as compared to what was anticipated based on plant growth mechanisms and previous studies. Our models indicate that both surface water and porewater nitrogen have a negative impact on biomass density despite nitrogen being an important resource for plant growth. This is a surprising finding but may indicate that biomass density in these canals is not driven by nitrogen availability. The macrophytes at our study sites could be controlled by other limiting resources such as carbon dioxide (Hammer et al. 2019) or, more likely based on our modeling results, light.

Throughout the summer, irrigation demand is high leading to relatively consistent flows in the canals, especially in our study sites which are located on main line canals for the Newlands Project. Similar to surface light, there was little variability in flow as a resource and therefore it was not found to have a large impact on biomass per area. This lack of variability in flow is particular to the managed canal system we studied; flow is often an important driver of macrophyte presence in natural streams that experience disturbances (Riis and Biggs 2003; Franklin et al. 2008).

Throughout most of the summer the community composition of macrophytes in the canals was dominated by ditchgrass, which is overwhelmingly the nuisance macrophyte causing the most management issues. However, the downstream L-line macrophyte communities shifted over the summer from ditchgrass dominance to *Elodea* dominance. This difference among canals with similar flows, substrates, and canopy cover may have been driven by variability in the concentration of chemical constituents across canals as we found those to be the strongest controls on macrophyte diversity in our models. Different types of macrophytes have different tolerances for UV exposure (Fernanda Pessoa 2012) and the increased turbidity in the late summer, particularly in the downstream L-Line canal, may have allowed Elodea to outcompete ditchgrass in conditions of suppressed light.

Surface water nutrients (ammonium, nitrate, and bromide), porewater TDN and TDC, and surface water specific conductivity drove the most variability in macrophyte composition in our studied canals. Chemical variables have often been found to be a major control on macrophyte diversity (Hrivnák et al. 2014; Baláži and Hrivnák 2016), a phenomenon explained by each macrophyte type having a different relationship with "ambient water variables" than each other (Haroon 2020). However, there is also evidence that hydrology and substrate type are important drivers of macrophyte diversity and, in some cases, have a stronger relationship with macrophyte diversity than chemical variables (Dorotovičová 2013; Hrivnák et al. 2014; Weekes et al. 2014; Baláži and Hrivnák 2016). There exists a large range of variables with the potential to impact macrophyte

diversity and our results were limited by the scope of our data set and limited to explaining trends in the small subset of canals we studied.

Study Conclusions

Canals are faced with nuisance macrophyte growth which reduces their ability to operate as water allocation systems. In some cases, these macrophyte growths raise the water surface to potentially unsafe levels for the surrounding communities. Although we were not able to fully evaluate the efficacy of UV treatment on aquatic macrophytes in the canals due to canal dewatering and unexplained disappearance of plants from both the control and treatment reaches, the monitoring data from Year 2 provides insights into when and where we might expect macrophyte interference with canal operation to be greatest. The knowledge that macrophyte biomass in these irrigation canals peaks in July suggests that the best timing for intervention to reduce nuisance macrophytes is at the initial growth of the plants earlier in the season (June). The importance of total suspended solids (an indicator of light availability) in driving macrophyte density indicates that creating shading structures (potentially made of solar panels) over the canals to reduce surface light availability may be a solution to limiting macrophyte growth. To figure out the best path forward to manage the risk of excessive macrophyte growth, we must understand the macrophyte community composition which is understudied in canals. We found that ditchgrass, an assemblage of aquatic grasses, was the most abundant macrophyte type. Treatments should be targeted at this plant type when possible. Laboratory and field tests in other ecosystems using UV light suggests a 100% decline and mortality of macrophytes. A refocused project during non-COVID pandemic periods coupled with examination of plant mortality from canals that are least likely to be dewatered or controlled by the local management authority as opposed to homeowners would assist in testing the efficacy of UV light in canals managed by BOR.

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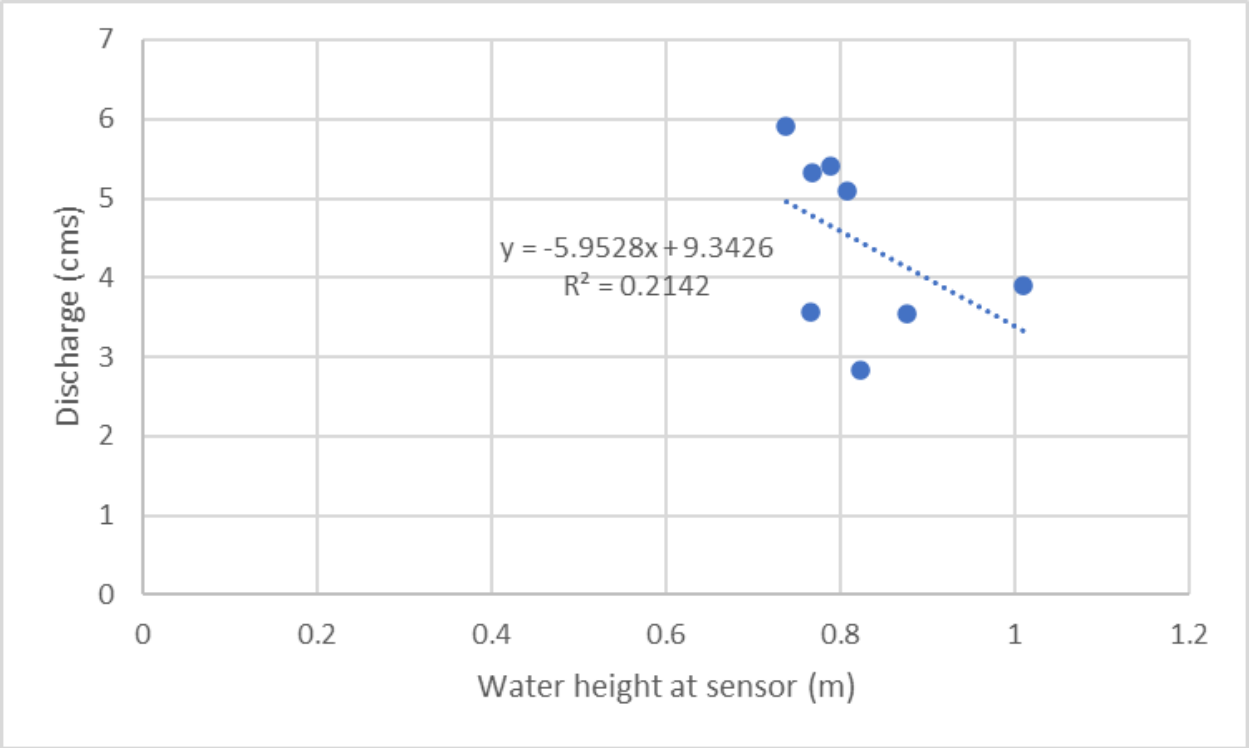
Metric Conversions

Provide metric equivalents for non-metric units used in the text:

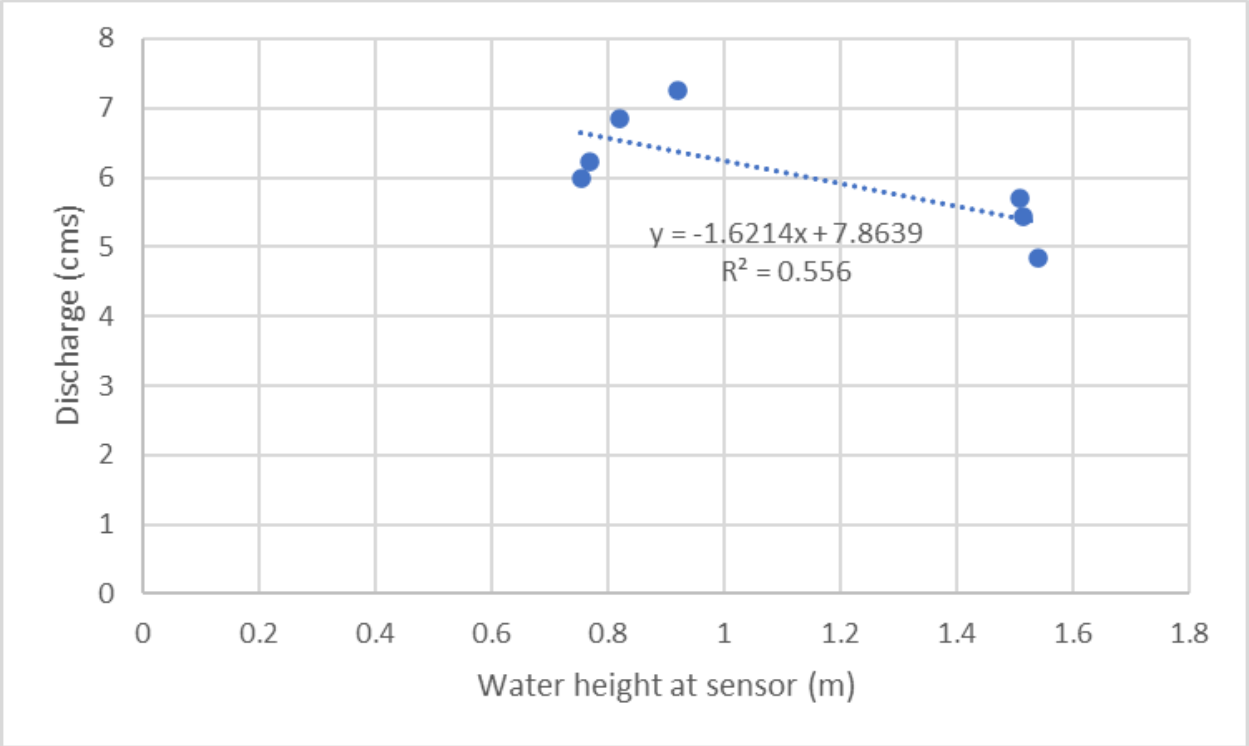
Unit	Metric Equivalent
1 gallon	3.785 liters
1 gallon per minute	3.785 liters per minute
1 gallon per square foot of membrane area per day	40.74 liters per square meter per day
1 inch	2.54 centimeters
1 million gallons per day	3,785 cubic meters per day
1 pound per square inch	6.895 kilopascals
1 square foot	0.093 square meters
°F (temperature measurement)	(°F–32) × 0.556 = °C
1 °F (temperature change or difference)	0.556 °C

Appendix A - Supplemental figures

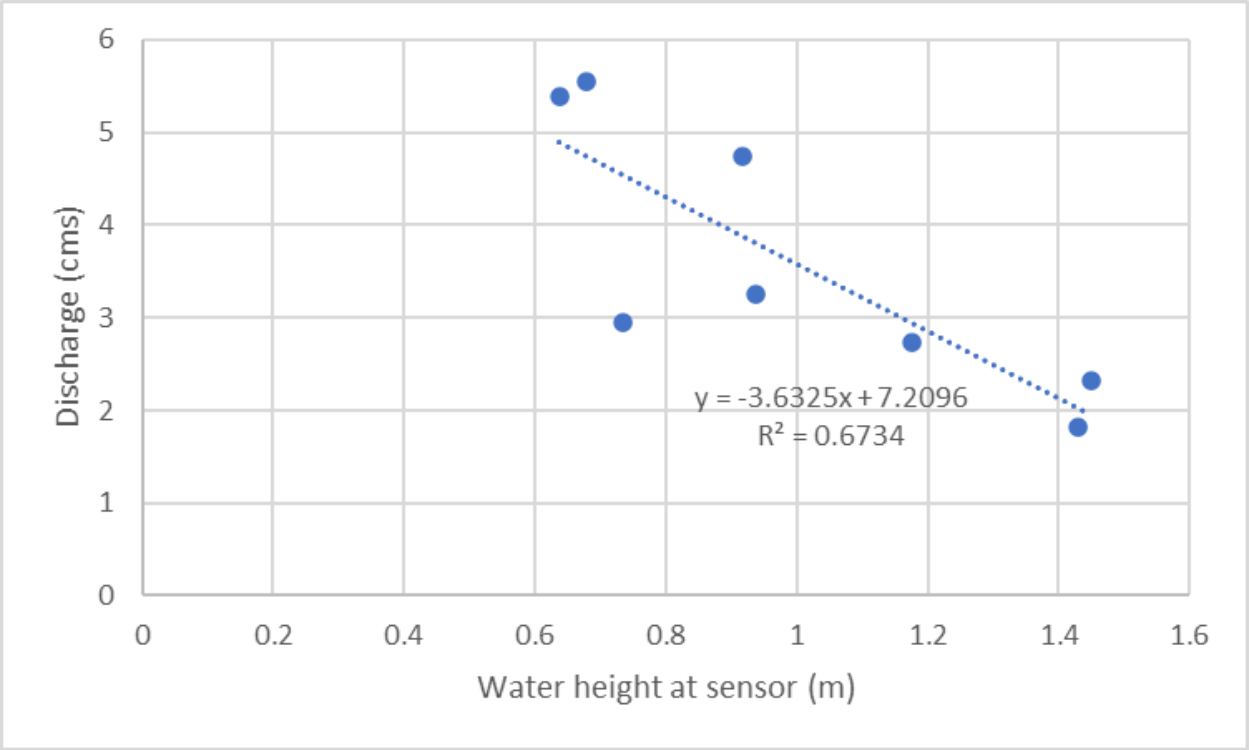
Supplemental Figure 1. Layout of sampling transects at the A-Line canal. Transects designed to include areas treated with varying amounts of UV radiation as specified in Figure 3 in the main text.



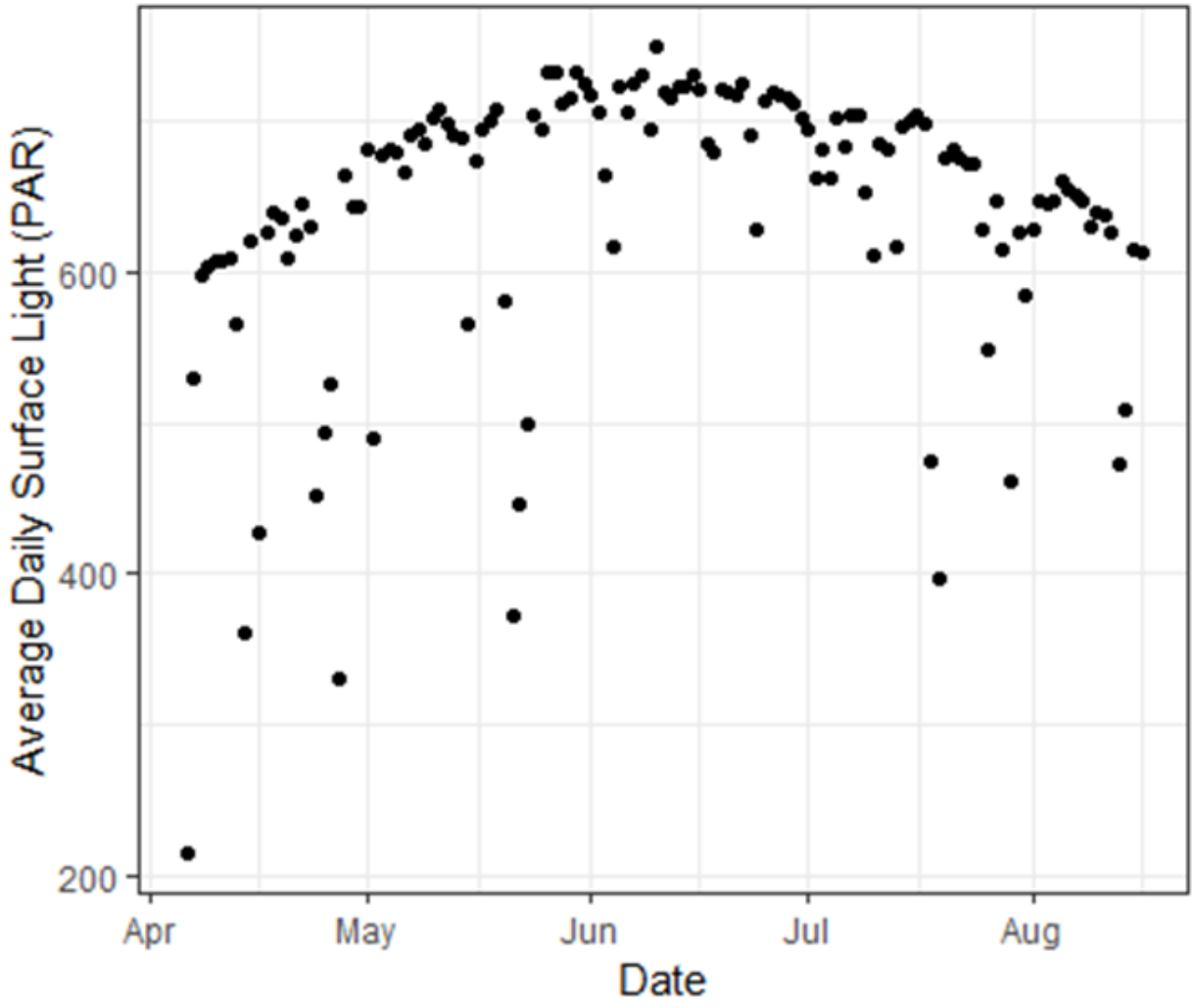
Supplemental Figure 2A. A-Line rating curve comparing water height (m) and discharge (cms).



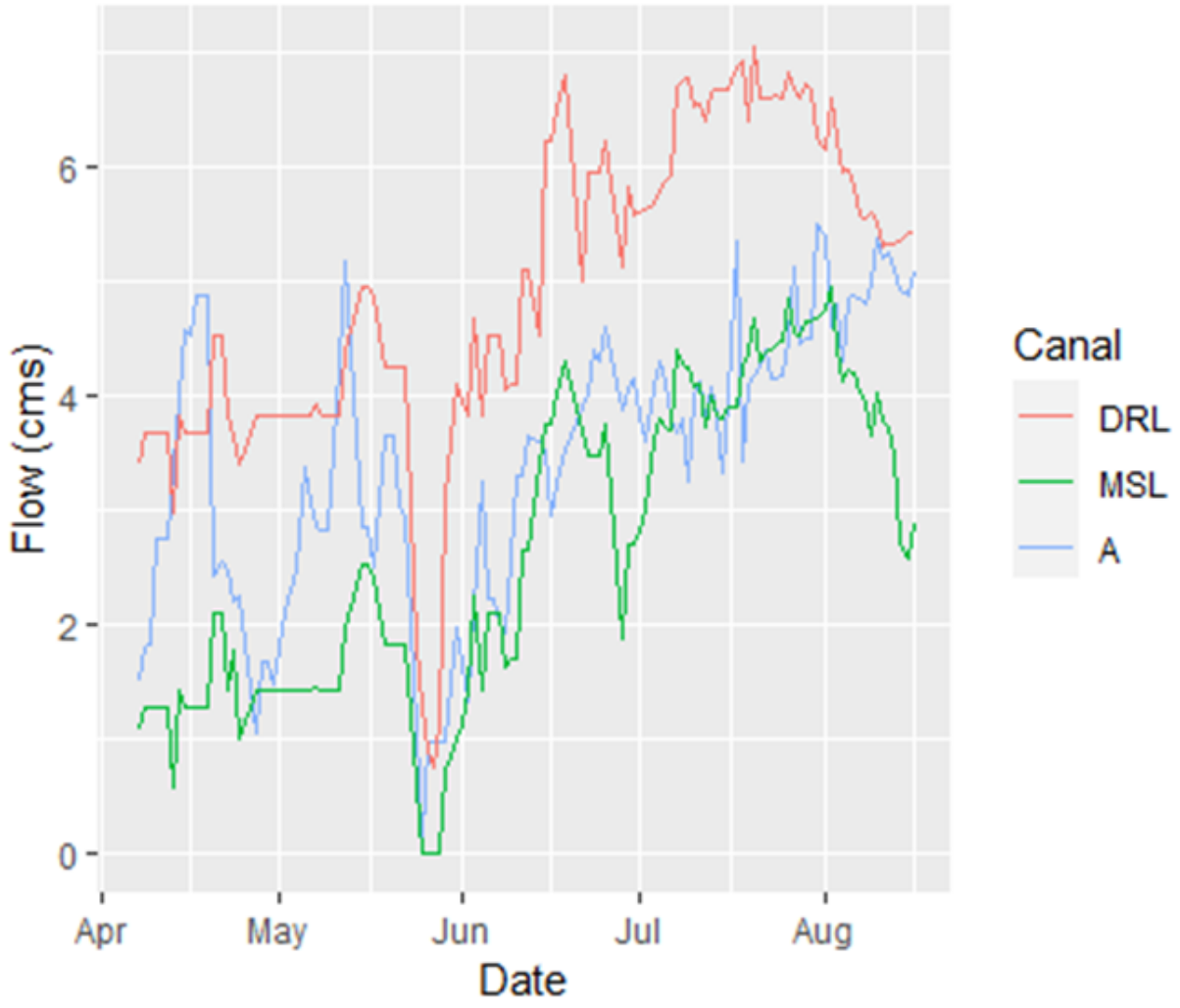
Supplemental Figure 2B. Upstream L-Line rating curve comparing water height (m) and discharge (cms).



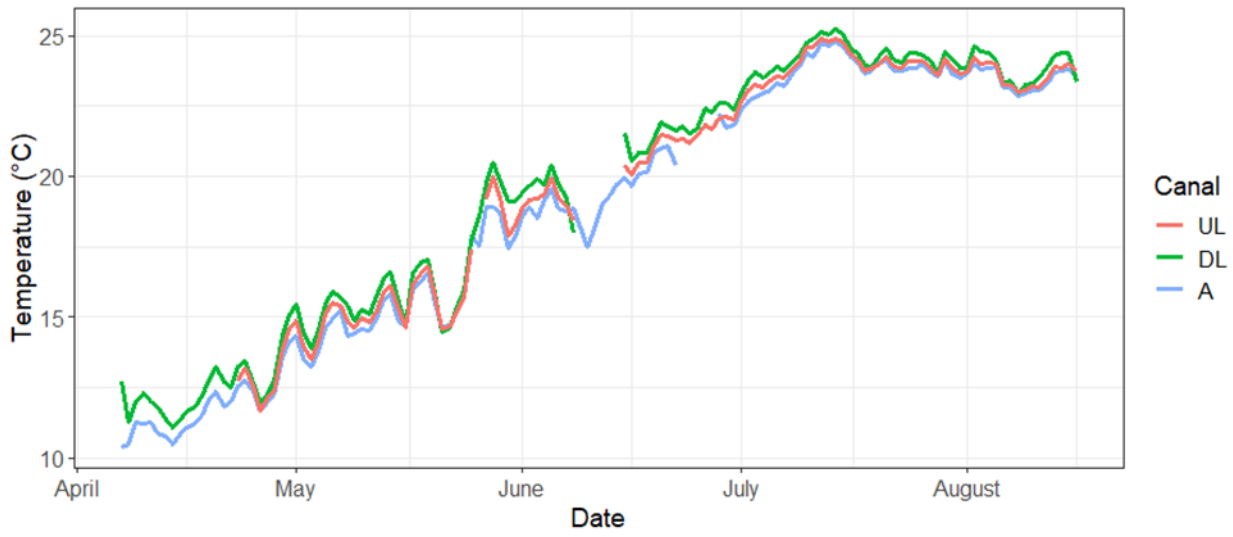
Supplemental Figure 2C. Downstream L-Line rating curve comparing water height (m) and discharge (cms).



Supplemental Figure 3. Daily surface light values for each day throughout the study period.



Supplemental Figure 4. Daily flow (cms) values for each day throughout the study period.



Supplemental Figure 5. Daily temperature (°C) values for each day throughout the study period.

Appendix B - Supplemental tables

Supplemental Table 1. Summary of all collected environmental data for each site (three time points per site).

Predictor Variable	Site	Average	Standard Deviation	Range
TSS (µg/mL)	A	26.3	27.5	6.9 - 57.8
	UL	34.2	33.9	8.1 - 72.6
	DL	38.6	57.1	4.3 - 104.5
Light extinction coefficient	A	0.036	0.009	0.028 - 0.046
	UL	0.039	0.017	0.023 - 0.056
	DL	0.046	0.025	0.028 - 0.064
Previous 30 day average of surface light (PAR)	A	668	38	630 - 706
	UL	662	41	623 - 705
	DL	671	35	638 - 708
Previous 30 day average of AQI	A	58.2	16.9	47.7 - 77.6
	UL	55.7	11.6	48.4 - 69.1
	DL	55.7	14.0	47.0 - 71.9
Previous 30 day average of PM2.5	A	17.7	25.1	2.4 - 46.7
	UL	12.3	16.7	2.3 - 31.6
	DL	13.2	18.4	2.2 - 34.4
Specific conductivity (µS/cm)	A	336	61	266 - 380
	UL	312	71	241 - 382
	DL	328	58	270 - 387
Surface water pH	A	8.14	0.17	8.03 - 8.34

	UL	8.35	0.44	8.07 - 8.86
	DL	8.34	0.50	7.93 - 8.89
Previous 30 day average of temp (°C)	A	20.5	3.5	16.8 - 23.8
	UL	19.2	4.5	14.7 - 23.8
	DL	20.5	3.9	16.5 - 24.3
Previous 30 day average of flow (cms)	A	3.55	1.02	2.47 - 4.49
	UL	4.83	1.34	3.99 - 6.38
	DL	2.81	1.45	1.39 - 4.29
Surface water ammonium (µg N/L)	A	27.3	18.7	8.2 - 45.5
	UL	10.5	10.5	2.3 - 22.4
	DL	40.3	66.8	0 - 117.4
Surface water orthophosphate (µg/L)	A	24.4	18.4	7.2 - 43.7
	UL	10.5	4.8	5.5 - 15.1
	DL	12.2	8.1	3.7 - 19.7
Surface water fluoride (µg/L)	A	287.4	69.7	224 - 362
	UL	253.9	65.4	198 - 326
	DL	248.1	78.5	168 - 325
Surface water bromide (µg/L)	A	40.7	3.8	37.2 - 44.8
	UL	40.3	1.5	39.3 - 42.0
	DL	40.8	0.8	40.2 - 41.4
Surface water nitrite (µg/L)	A	19.6	25.3	5.0 - 48.8
	UL	17.2	12.2	5.0 - 29.3
	DL	13.2	7.1	5.0 - 17.7
Surface water nitrate (µg/L)	A	120	83	63 - 215

	UL	74	36	33 - 100
	DL	140	10	133 - 147
Surface water total dissolved carbon (mg/L)	A	25.1	2.3	22.7 - 27.2
	UL	23.5	3.4	20.3 - 27.0
	DL	22.5	4.8	17.2 - 26.6
Surface water non-purgeable organic carbon (mg/L)	A	15.0	1.5	13.5 - 16.4
	UL	13.9	1.9	12.6 - 16.0
	DL	13.1	2.5	10.7 - 15.7
Surface water total dissolved nitrogen (µg/L)	A	404	120	279 - 518
	UL	297	52	246 - 350
	DL	469	193	262 - 644
Sediment bulk density (g/mL)	A	1.87	0.12	1.54 - 2.05
	UL	1.77	0.20	1.29 - 2.04
	DL	1.70	0.18	1.28 - 1.92
Sediment % organic matter	A	0.95	0.62	0.45 - 2.91
	UL	1.62	1.33	0.48 - 6.01
	DL	2.01	1.90	0.41 - 7.55
Sediment pH	A	7.18	0.41	6.14 - 7.74
	UL	7.17	0.29	6.63 - 7.63
	DL	7.35	0.36	6.83 - 7.96
Porewater ammonium (µg N/L)	A	43.4	33.5	6.9 - 72.8
	UL	131.0	150.0	30.8 - 303.5
	DL	359.5	343.8	21.3 - 708.7
Porewater orthophosphate (µg/L)	A	44.2	20.7	31.2 - 68.1

	UL	11.9	2.2	9.5 - 13.9
	DL	13.6	8.3	7.6 - 23.1
Porewater fluoride (µg/L)	A	105	6	98 - 110
	UL	123	15	113 - 140
	DL	130	22	106 - 148
Porewater nitrate (µg/L)	A	229	14	219 - 238
	UL	108	NA	108
	DL	295	97	184 - 357
Porewater total dissolved carbon (mg/L)	A	3.07	0.65	2.61 - 3.53
	UL	5.52	1.45	4.57 - 7.19
	DL	8.63	1.63	7.40 - 10.48
Porewater non-purgeable organic carbon (mg/L)	A	2.16	0.49	1.81 - 2.50
	UL	3.71	0.81	3.06 - 4.62
	DL	5.60	1.28	4.50 - 7.00
Porewater total dissolved nitrogen (µg/L)	A	245	74	193 - 298
	UL	410	101	322 - 521
	DL	787	562	267 - 1384

Supplemental Table 2. Kendall rank correlation coefficients and p-values for correlations between environmental variables and macrophyte density.

Variable	Bivariate correlation coefficients	Bivariate correlation p-values	Remove?

TSS	-0.394	0.000	
Extinction Coefficient	-0.348	0.000	Yes, strongly correlated with TSS
Surface Light (PAR)	0.497	0.000	
AQI	-0.169	0.021	Yes, strongly correlated with PM2.5
PM2.5	-0.064	0.378	Yes
Specific Conductivity	0.090	0.212	Yes
pH	-0.140	0.052	Yes
Temperature	0.023	0.750	Yes
PW Phosphate	-0.129	0.105	Yes
PW Ammonium	0.211	0.004	
PW Fluoride	0.316	0.000	
PW Bromide	NA	NA	Yes
PW Nitrate	0.058	0.537	Yes
PW TDC	0.134	0.084	Yes
PW DOC	0.163	0.035	
PW TDN	0.156	0.044	
SW Phosphate	-0.085	0.276	Yes
SW Ammonium	-0.077	0.313	Yes
SW Fluoride	-0.046	0.526	Yes
SW Bromide	-0.008	0.922	Yes
SW Nitrate	0.397	0.000	
SW TDC	-0.046	0.526	Yes
SW DOC	-0.195	0.007	
SW TDN	0.174	0.016	

Flow (cms)	-0.158	0.029	
Bulk Density	-0.068	0.494	Yes
% Organic Matter	0.118	0.237	Yes
Sediment pH	-0.001	0.993	Yes

Supplemental Table 3. Kendall rank correlation coefficients for correlations among environmental variables for macrophyte density models.

	TSS_mgmL	PAR_30da	Ammonium.mg.L.PW	Fluoride.ppb.PW	DOC.mg.L.PW	TDN.ug.L.PW	Nitrate.SW	DOC.mg.L.SW	TDN.ug.L.SW	cms_30da	Remove?
TSS_mgmL	1.00	-0.63	0.06	0.10	0.04	0.15	-0.23	0.39	0.02	0.53	
PAR_30da	-0.63	1.00	0.17	0.16	0.05	-0.06	0.55	-0.23	0.24	-0.26	
Ammonium.mg.L.PW	0.06	0.17	1.00	0.57	0.59	0.85	0.59	0.24	0.59	0.35	Yes
Fluoride.ppb.PW	0.10	0.16	0.57	1.00	0.58	0.84	0.21	0.04	0.30	0.38	Yes
DOC.mg.L.PW	0.04	0.05	0.59	0.58	1.00	0.74	0.33	-0.04	0.32	0.33	Yes
TDN.ug.L.PW	0.15	-0.06	0.85	0.84	0.74	1.00	0.25	0.22	0.45	0.59	
Nitrate.S	-0.23	0.55	0.59	0.21	0.33	0.25	1.00	0.04	0.68	0.0	

W										0
DOC.mg.L.SW	0.39	-0.23	0.24	0.04	-0.04	0.22	0.04	1.00	0.44	0.57
TDN.ug.L.SW	0.02	0.24	0.59	0.30	0.32	0.45	0.68	0.44	1.00	0.30
cms_30da	0.53	-0.26	0.35	0.38	0.33	0.59	0.00	0.57	0.30	1.00

Supplemental Table 4. Model comparisons for all macrophyte density models run.

Model form	AICc
~f (Canal + Event + TSS)	543.4
~f (Canal + Event + TSS^2)	545.7
~f (Canal + Event + Surface Light)	549.1
~f (Canal + Event + $Surface\ Light^2$)	550.4
~f (Canal + Event + TDN.PW)	544.6
~f (Canal + Event + $TDN.PW^2$)	546.2
~f (Canal + Event + DOC.SW)	554.5
~f (Canal + Event + $DOC.SW^2$)	556.1
~f (Canal + Event + TDN.SW)	549.1
~f (Canal + Event + $TDN.SW^2$)	547.1
~f (Canal + Event + Flow)	561.0
~f (Canal + Event + $Flow^2$)	546.0
~f (Canal + Event + TSS + Surface Light)	545.8

~f (Canal + Event + TSS + TDN.PW)	545.8
~f (Canal + Event + TSS + DOC.SW)	545.7
~f (Canal + Event + TSS + TDN.SW)	545.8
~f (Canal + Event + TSS + Flow)	545.8
~f (Canal + Event + Surface Light + TDN.PW)	546.5
~f (Canal + Event + Surface Light + DOC.SW)	551.4
~f (Canal + Event + Surface Light + TDN.SW)	551.5
~f (Canal + Event + Surface Light + Flow)	547.6
~f (Canal + Event + TDN.PW + DOC.SW)	546.9
~f (Canal + Event + TDN.PW + TDN.SW)	546.7
~f (Canal + Event + TDN.PW + Flow)	547.0
~f (Canal + Event + DOC.SW + TDN.SW)	551.1
~f (Canal + Event + DOC.SW + Flow)	550.1
~f (Canal + Event + TDN.SW + Flow)	546.8

Supplemental Table 5. Kendall rank correlation coefficients and p-values for correlations between environmental variables and macrophyte diversity (SDI).

Variable	Bivariate correlation coefficients	Bivariate correlation p-values	Remove?
TSS	-0.081	0.508	Yes
Extinction Coefficient	0.094	0.479	Yes

Surface Light (PAR)	-0.007	0.956	Yes
AQI	0.131	0.286	Yes
PM2.5	0.114	0.349	Yes
Specific Conductivity	0.354	0.004	
pH	-0.027	0.825	Yes
Temperature	0.209	0.087	Yes
PW Phosphate	-0.224	0.110	Yes
PW Ammonium	0.404	0.001	
PW Fluoride	0.377	0.002	
PW Nitrite	-0.211	0.131	Yes
PW Bromide	NA	NA	Yes
PW Nitrate	0.152	0.390	Yes
PW TDC	0.736	0.000	
PW DOC	0.672	0.000	
PW TDN	0.515	0.000	
SW Phosphate	0.207	0.114	Yes
SW Ammonium	-0.326	0.011	
SW Fluoride	0.084	0.491	Yes
SW Nitrite	0.141	0.272	Yes
SW Bromide	0.320	0.016	
SW Nitrate	0.306	0.022	
SW TDC	0.084	0.491	Yes
SW DOC	-0.125	0.308	Yes
SW TDN	0.222	0.069	Yes

Flow (cms)	0.111	0.363	Yes
Bulk Density	-0.274	0.092	Yes
% Organic Matter	0.400	0.014	
Sediment pH	0.080	0.626	Yes

Supplemental Table 6. Kendall rank correlation coefficients for correlations among environmental variables for macrophyte diversity (SDI) models.

	Sp.C	Ammonium.mg.L.PW	Fluoride.ppb.PW	TDC.mg.L.PW	DOC.mg.L.PW	TDN.ug.L.PW	Ammonium.mg.L.SW	Bromide.SW	Nitrate.SW	%OM	Remove?
Sp.C	1.00	0.65	0.35	0.38	0.45	0.54	0.34	0.57	0.68	0.14	
Ammonium.mg.L.PW	0.65	1.00	0.63	0.38	0.59	0.86	0.17	0.72	0.52	0.21	Yes
Fluoride.ppb.PW	0.35	0.63	1.00	0.46	0.54	0.81	0.15	0.53	0.24	0.16	Yes
TDC.mg.L.PW	0.38	0.38	0.46	1.00	0.92	0.65	-0.44	0.54	0.36	0.40	
DOC.mg.L.PW	0.45	0.59	0.54	0.92	1.00	0.73	-0.34	0.54	0.36	0.36	Yes
TDN.ug.L.PW	0.54	0.86	0.81	0.65	0.73	1.00	-0.01	0.60	0.29	0.23	
Ammonium.mg.L.SW	0.34	0.17	0.15	-0.44	-0.34	-0.01	1.00	0.16	0.39	-0.36	
Bromide.SW	0.57	0.72	0.53	0.54	0.54	0.60	0.16	1.00	0.45	0.	

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Nitrate.SW	0.68	0.52	0.24	0.36	0.36	0.29	0.39	0.45	1.00	-0.04
%OM	0.14	0.21	0.16	0.40	0.36	0.23	-0.36	0.26	-0.04	1.00

Supplemental Table 7. Model comparisons for all macrophyte diversity (SDI) models run.

Model form	AICc
~f (Canal + Event + Specific Conductivity)	-6.6
~f (Canal + Event + Specific Conductivity^2)	-4.7
~f (Canal + Event + TDC.PW)	-3.9
~f (Canal + Event + TDC.PW^2)	-0.9
~f (Canal + Event + TDN.PW)	-4.6
~f (Canal + Event + TDN.PW^2)	-1.2
~f (Canal + Event + NH_4.SW)	-12.2
~f (Canal + Event + NH_4.SW^2)	-23.5
~f (Canal + Event + Br.SW)	-14.1
~f (Canal + Event + Br.SW^2)	-10.8
~f (Canal + Event + NO_3.SW)	-12.2
~f (Canal + Event + NO_3.SW^2)	-22.0
~f (Canal + Event + Sed%OM)	10.1
~f (Canal + Event + Sed%OM^2)	15.8