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Research Article

Control of biofouling in hydropower cooling systems using HOD ultraviolet light

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This study was contributed in relation to the 20th International Conference on Aquatic Invasive Species held in Fort Lauderdale, Florida, USA, October 22–26, 2017 (http://www.icais.org/html/previous20.html). This conference has provided a venue for the exchange of information on various aspects of aquatic invasive species since its inception in 1990. The conference continues to provide an opportunity for dialog between academia, industry and environmental regulators.

Abstract

Reservoirs along the lower Colorado River are infested with *Dreissena rostriformis bugensis* (Andrusov, 1897) (quagga mussel) and *Cordylophora caspia* (Pallas, 1771) (colonial hydroid). These invasive species, along with native freshwater sponges and bacteria, pose significant biofouling issues for hydropower facilities in the area. Biofouling in the generator cooler systems at Parker Dam, on Lake Havasu, AZ has resulted in increased annual maintenance costs of approximately $80,000/year. Medium pressure, hydro-optic ultraviolet (HOD UV) light systems with a 100 mJ/cm^2 target dose were installed on four main turbine cooling water lines and a raw water supply for the onsite water treatment facility at Parker Dam to mitigate biofouling. This study was designed to monitor the impact of HOD UV on biofouling over a two-year period. Comparison of biofouling dry weight from settlement plates exposed to HOD UV-treated and untreated water indicate a significant reduction in total biofouling after HOD UV exposure. Mussel settlement and bacterial sludge formation were consistently reduced in test chambers (bioboxes) despite lower than expected average HOD UV dose and contamination with untreated water. Hydroid larvae were not found in any plankton samples collected from the forebay at Parker Dam during the study, indicating asexual reproduction was the main source of downstream colony formation. Hydroid settlement reduction data after HOD UV treatment were inconclusive. The Parker Dam facility manager confirmed that biofouling-related maintenance of the coolers was reduced by 75 percent after the first year of HOD UV operation and eliminated in the second and third years after implementation.

Key words: invasive mussels, colonial hydroid, HOD UV treatment, settlement reduction, quagga mussel, dreissenid mussel control, biofouling control

Introduction

Substantial populations of invasive *Dreissena rostriformis bugensis* (Andrusov, 1897) (quagga mussel) are present in lower Colorado River reservoirs, presenting a significant threat to hydropower infrastructure function in the region. Hydro-optic ultraviolet (HOD UV) light treatment was found to significantly reduce quagga mussel settlement at Davis Dam, located on Lake Mohave, AZ (Pucherelli and Claudi 2016). HOD UV systems were subsequently installed at Parker Dam, located on Lake Havasu, AZ, in 2015 to control quagga mussel settlement in generator cooling systems. Although quagga mussel settlement is the primary biofouling concern, native freshwater sponge, colonial hydroids, and bacteria-based microfouling issues also exist at Parker Dam. In 2017, operators at Parker Dam noticed increased sponge settlement on penstock gates during inspection. Additionally, the presence of the invasive colonial hydroid, *Cordylophora*

caspia (Pallas, 1771) in Lower Colorado River Reservoirs (Pucherelli et al. 2016) is of specific concern as it is known to have serious negative economic impacts associated with biofouling at hydropower facilities (Folino 2000). *Cordylophora caspia* has been found colonizing and clogging intake tunnels, filters, condenser tube sheets, power plant pipes, and drinking water treatment plants in Europe and the United States (Lipsey and Chimney 1978; Jenner and Janssen-Mommen 1993; Moreteau and Khalanski 1994; Folino-Rorem and Indelicato 2005).

Cordylophora caspia originates from the Black and Caspian Seas, commonly co-existing with and possibly benefiting from the range expansion of dreissenid mussels, which originate from the same native range. *Cordylophora caspia* feeds on dreissenid mussel larva, as well as other prey, and uses mussel shells as a substrate (Olenin and Leppakoski 1999; Folino-Rorem et al. 2006). *Cordylophora caspia* propagation occurs by both sexual and asexual reproduction. Colonies can be initiated by free swimming, ciliated planula (larvae), asexual budding (hydrorhiza fragments), and temperature- and drought-resistant dormant stage (menonts). An increase in hydroid biofouling was observed at Parker and Davis Dams in 2015 (Pucherelli, *personal observation*). Hydroid biofouling also became a significant issue at the Central Arizona Project Mark Wilmer Pumping Plant, located on Lake Havasu just east of Parker Dam. Severe hydroid biofouling of the surface-air coolers overheated pump units, resulting in one unplanned outage in 2014 and three unplanned outages in 2015 (Bryan 2017).

The following study was conducted over a two-year period and was designed to evaluate the effectiveness of the HOD UV systems at Parker Dam for settlement reduction of multiple biofouling species. The impact of HOD UV on biofouling was monitored by measuring the combined dry weight of dreissenid mussel, freshwater sponge, colonial hydroid, and bacterial settlement on plates in bioboxes downstream of the HOD UV units and comparing the results with data collected from an identical biobox upstream of the HOD UV. The overall performance of the HOD UV units and the impact on the maintenance of the generator cooling systems was also observed.

Methods

HOD UV treatment

Atlantium Technologies Ltd., medium pressure, HOD UV light systems were installed on four main turbine cooling water lines and a raw water supply for the onsite water treatment facility at Parker Dam in 2015. The units were installed downstream of a 0.32-cm self-cleaning strainer which filter mussel shells and other debris. The units were designed to deliver 100 mJ/cm^2 based on average flow and UVT readings collected prior to installation. Actual HOD UV dosages varied depending on water flow rate, ultra-violet transmittance (UVT, a factor of water clarity), and lamp intensity. Hourly values of dose and UVT were measured and logged by the HOD UV system and downloaded monthly for analysis during the study.

Biofouling analysis

The impact of HOD UV on biofouling was analyzed by monitoring bioboxes (settlement chambers designed to simulate cooling system conditions) installed at Parker Dam on the generator cooling lines of Units 3 and 4 in 2016, and cooling lines of Units 4 and 5 in 2017. Cooling lines of Units with the fewest scheduled maintenance activities each year were selected to prevent interference with the study. Bioboxes were plumbed into the cooling line and were outfitted with flowmeters and baffling to maintain consistent flow and to replicate water residency time comparable to a cooling water system. Bioboxes were approximately 43 cm tall, 91 cm long and 40 cm wide (156.5 L) and constructed as described in Mackie and Claudi (2010). Control bioboxes were installed upstream of the HOD UV system and test bioboxes were installed downstream of the HOD UV system. Six plates, made of polyvinyl chloride (PVC), were placed in each biobox. Two of the six plates were 35.56 cm × 28.575 cm, and the other three plates were 6 cm × 6 cm. Three plates (1 large and 2 small) were examined monthly, and three (1 large and 2 small) were examined after six months. All plates were surveyed visually for *C. caspia* colonies and photographed at each examination.

The settlement on each plate was collected by scraping both sides of the plate into a tray using a razor blade. The collected material was transferred into a bottle and preserved with 75% isopropanol. The dry and ash free weights of the collected material were determined in accordance with Standard Methods for the Examination of Water and Wastewater (10300C; Rodger and Eaton 2017). Evidence of settlement inhibition was determined by comparing the dry weight collected from the control and HOD UV treated bioboxes. Statistix analytical software was used to conduct a paired t-test for differences in the mean biofouling dry weight between HOD UV treated and control bioboxes. A Shapiro-Wilk Test was conducted to examine the assumption of normality.

Hydroid planula samples

Plankton tow samples were collected monthly for 12 months from the forebay at Parker Dam, to detect the presence of hydroid larvae (planula). Two water samples were collected for independent analysis, with each sample consisting of two 15 m plankton tows collected with a 20-µm plankton tow net. Samples were preserved by adding 75% isopropanol (70% final sample concentration) per volume of sample. One sample was sent to the Reclamation Detection Laboratory for Exotic Species (RDLES) and the other was analyzed by KASF Consulting. Additional samples were collected from the outflow of bioboxes with dense hydroid settlement to increase the likelihood of detection. In all samples collected, the entire sample was microscopically analyzed for the presence of planula larvae. Any suspected organisms were genetically analyzed by polymerase chain reaction (PCR) for species confirmation.

Bacterial analysis

Bacterial deposits in the control and HOD UV treated bioboxes were compared to determine differences in density and community composition. Additional control and HOD UV treated bioboxes were installed on the cooling line of Unit 3 to observe bacterial microfouling. A 100-µm cartridge filter was installed upstream of each of these small bioboxes to filter out macrofouling species (mussels, hydroids, and sponges). Six settlement plates were placed in each biobox to monitor monthly bacterial growth. Total living microorganism biomass was measured by adenosine triphosphate (ATP) analysis, using a LuminUltra® test kit. A surface swab was used to collect microbial particles from a, randomly selected, 1 cm^2 measured area on three plates per month for three months. The sample was extracted, diluted, and assayed with the addition of luminase and read on a luminometer. The luminometer provided an RLU_{tATP} reading which could be converted to total ATP (tATP) concentrations and microbial equivalents (ME, based on standard conversion 1 *E. coli*- sized bacteria contains 0.001 pg of ATP) using the following calculations (LuminUltra®).

$$tATP/\ cm^2 = RLU_{tATP} / RLU_{ATP1}(\text{calibration}) \times 50{,}000/\text{surface area } (cm^2)$$

$$ME/\ cm^2 = tATP \times 1\ ME / 0.001\ pg\ ATP$$

Bacteria samples were also analyzed by biological activity reaction tests (BART™) to determine differences in community composition between treated and untreated water. Samples were collected from the plates in the microfouling bioboxes and from the bottom of the macrofouling bioboxes. Aseptic sampling techniques were used to insure samples were not contaminated, including the use of sterilized equipment, rinse water, and gloves. The samples were shipped to the RDLES lab on ice and were cultured less than 24 hours later using iron-related bacteria (IRB), sulfate-reducing bacteria (SRB), slime-forming bacteria (SLYM), and heterotrophic aerobic bacteria (HAB) BART™ kits (Hach™). Bacteria presence and approximate abundance could be determined at the end of the eight-day reaction period.

The sludge deposits found at the bottom of the bioboxes were also examined for petrographic and organic content. Samples were sent to Reclamation's Materials Engineering and Research Laboratory, where the inorganic portion of each sample was examined megascopically, microscopically, and by X-ray diffraction for petrographic characterization. The percent organic content was determined by loss on ignition (LOI) testing following 10300C; Rodger and Eaton 2017. Prior to LOI testing, the samples were microscopically examined (40^x magnification) to confirm bacterial presence.

Results

HOD UV treatment

The monthly average UV dose and UVT readings from each cooling line is presented in Figures 1 and 2. The average UV dose fell below the 100 mJ/cm^2 target during the study. The dose on Unit 5, plumbed in to the raw water supply line to the onsite water treatment facility was expected to be higher than other units because the water flow rate was 200–650 gpm lower (Figure 2). Average UVT readings across all units were between 84% and 92% during the two-year study.

Monthly HOD UV dose and flow monitoring indicated periods of time when untreated water was flowing into the treated bioboxes during the first year of testing. The HOD UV units were designed to automatically shut off when cooling water flow was stopped. During the study, flow to the cooling water lines was stopped for operational or maintenance activities on several occasions, and the HOD UV units performed as designed and automatically shut off. However, untreated water continued to back-flow into treated bioboxes due to head pressure in the pipes. The amount of untreated back-flow entering each biobox was variable. Untreated water entered the Unit 4 biobox for approximately 192 hours and the Unit 3 biobox for five hours out of the approximately 5,136 hours during which testing occurred in 2016. Additionally, there were periods of

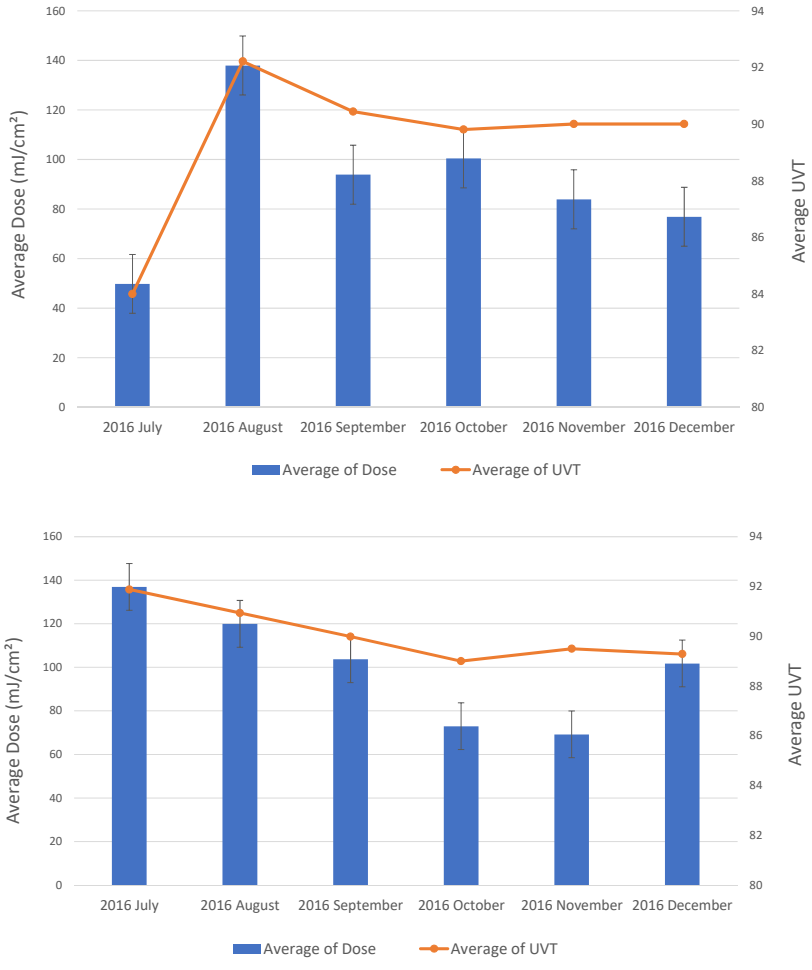

Figure 1. Average monthly HOD UV dose with standard error, and UVT on Parker Dam generator cooling lines 3 (top) and 4 (bottom) during 2016 testing.

time when the lamps malfunctioned, and the dose dropped to zero. During this time, untreated water entered the Unit 4 biobox for seven hours and the Unit 3 box for nine hours. These results prompted installation of automated shut-off valves in 2017 that automatically closed and prevented flow into each biobox in the case of lamp or cooling water shut-down.

Biofouling analysis

Despite contamination of bioboxes with untreated water in 2016, visual observation of the HOD UV treated bioboxes indicated a reduction of overall biofouling compared to the untreated control bioboxes (Figure 3). Dense quagga mussel, hydroid, and sponge settlement were found on control settlement plates (Figure 4, top) and reduced settlement was observed on plates in the HOD UV treated bioboxes (Figure 4, bottom). The greatest density of hydroid colonies was observed around the inflow pipe and on the walls and bottom of the first chamber in the biobox. Decreased mussel settlement was consistently observed in the HOD UV treated bioboxes during the study.

Sponge settlement was also reduced by HOD UV exposure. After a 3-month (August–October) test in 2017, 112 sponges were found in the control biobox (Unit 3) and only three were found in the HOD UV treated biobox. The sponge was identified by polymerase chain reaction (PCR) and was found to be in the order Spongillida of Heteroscleromorph sponges, and in the genus *Ephydatia*.

Hydroid settlement was visibly reduced after HOD UV exposure in 2016, but in 2017 settlement was generally greater in the treated bioboxes, especially in the final months of the study. Hydroid colony counts were greater in treated bioboxes on cooling line 3 during June–August 2017 (Figure 5) and treated biobox 5 in July–August (Figure 6) despite

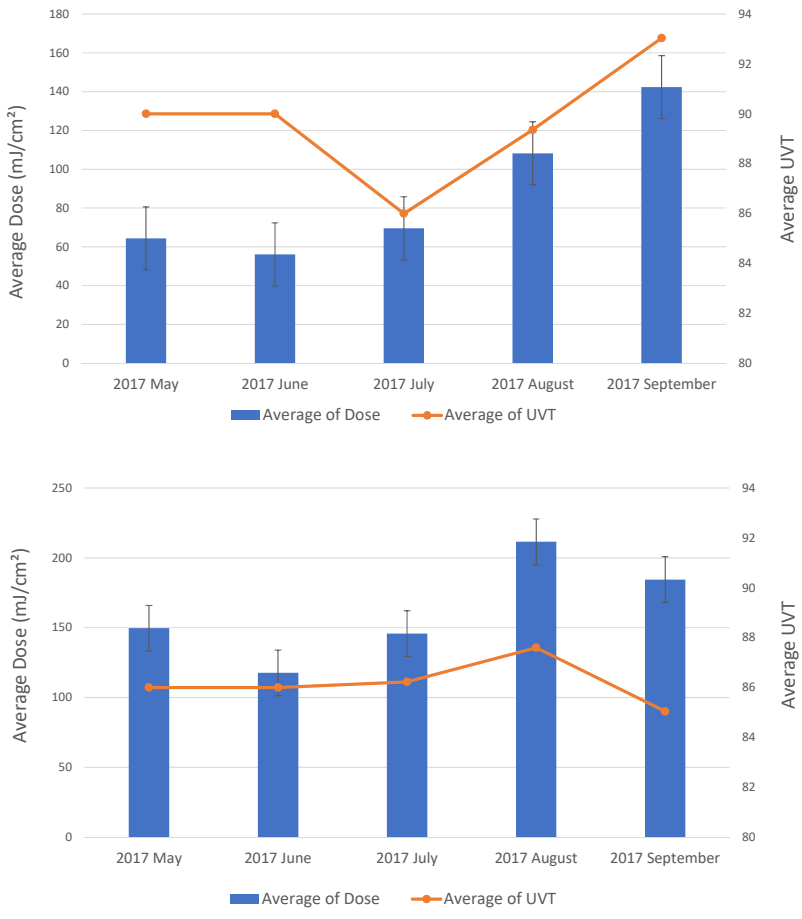

Figure 2. Average monthly HOD UV dose with standard error, and UVT on Parker Dam generator cooling lines 3 (top) and 5 (bottom) during 2017 testing.

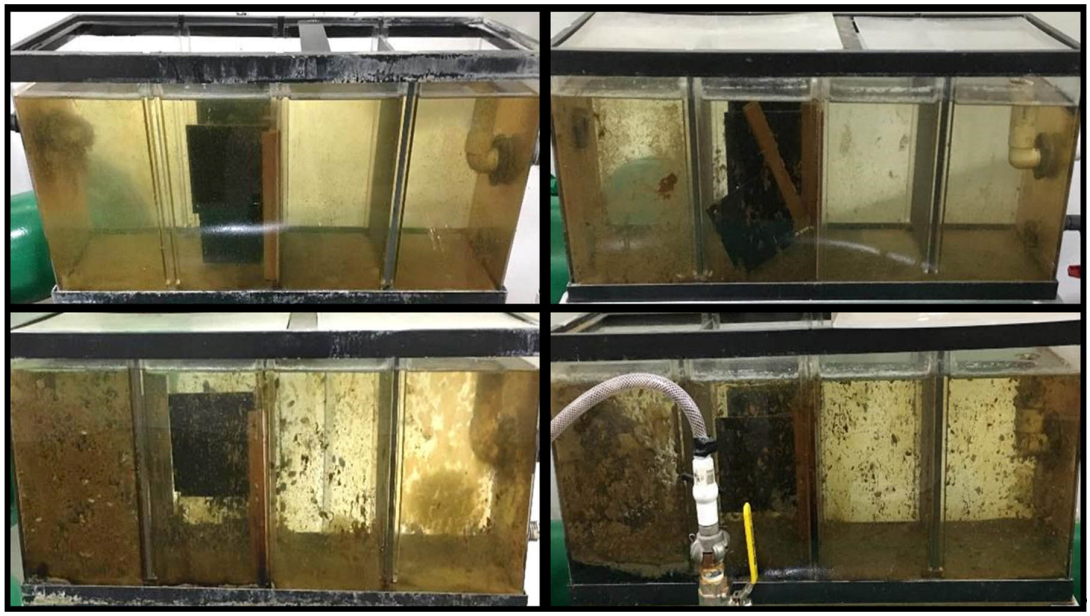

Figure 3. Settlement after six months during 2016 in bioboxes receiving HOD UV treated water (top left and right) and control bioboxes receiving untreated water (bottom left and right) on cooling lines 3 (left) and 4 (right). Photographs by Sherri Pucherelli.

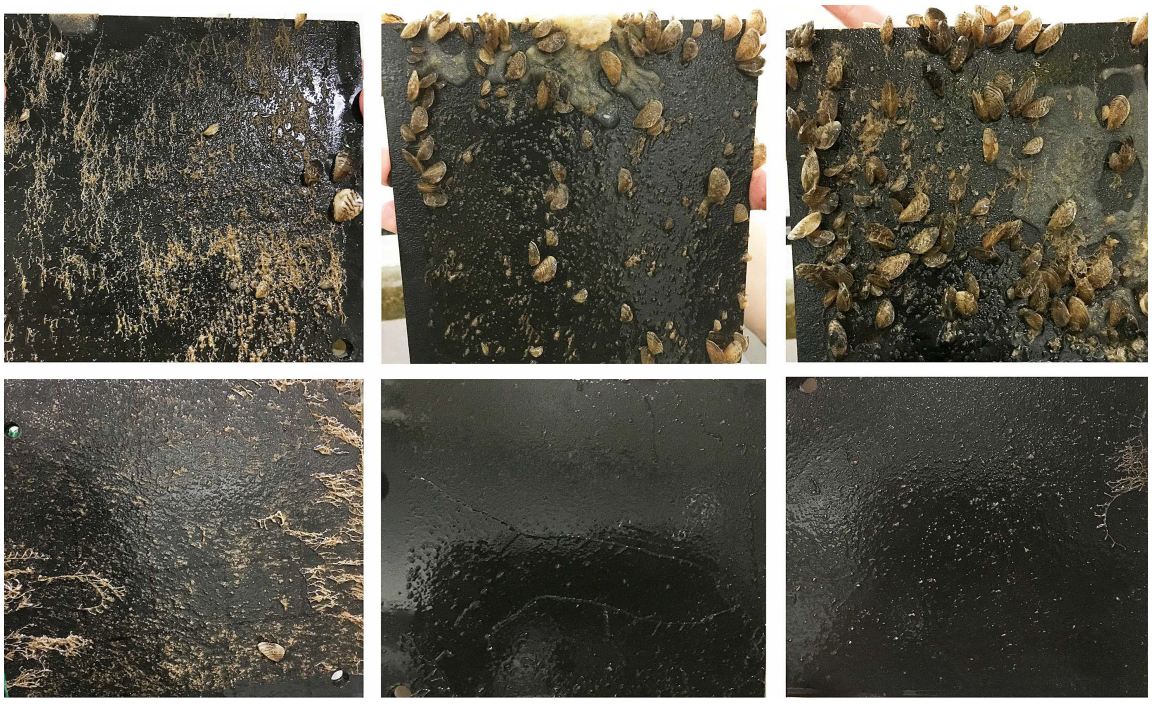

Figure 4. Mussel, hydroid, and sponge settlement, after 6-months, on plates from the control biobox receiving untreated water (top). Hydroid and mussel settlement after 6-months on plates from the biobox receiving HOD UV treated water (bottom). Photographs by Sherri Pucherelli.

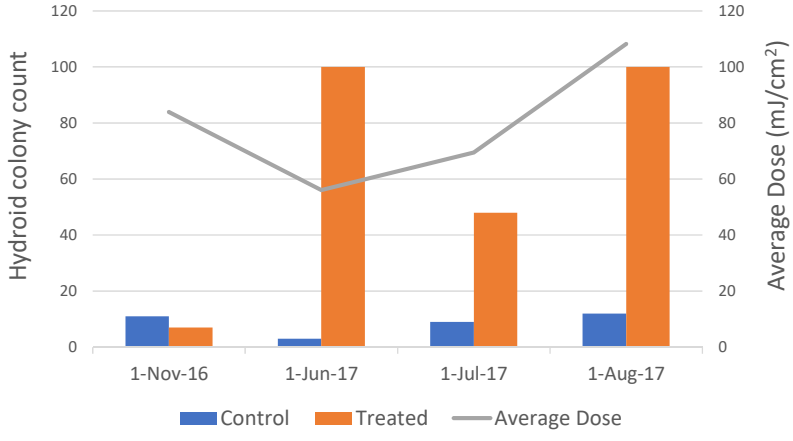

Figure 5. Total monthly hydroid colony settlement on three plates in control and treated bioboxes on cooling line 3. Colony counts were set at 100 when settlement was too dense to distinguish individual colonies.

the highest average HOD UV doses recorded during this period.

A paired-samples t-test was conducted to compare the biofouling dry weight collected from settlement plates in the HOD UV treated bioboxes to those in the control bioboxes during the 2016 study. The dry weights collected from settlement plates in HOD UV treated bioboxes (M = 2.67 g/m^2, SD = 1.64) were found to be significantly less than those collected from the control bioboxes (M = 4.57 g/m^2, SD = 2.04); $t(38) = 6.33$, $p < 0.0001$. On average, the dry weight was 1.9 g/m^2 less on plates in the treated bioboxes compared to the controls (Figure 7). The dry weight includes both organic (tissue) and inorganic (mussel shells, hydroid chitin, and sponge spicules) components of biofouling.

Less biofouling was observed on plates in the HOD UV treated bioboxes over the course of 126 days (July–November 2016) than in the control bioboxes. The total dry weight of settlement from three plates

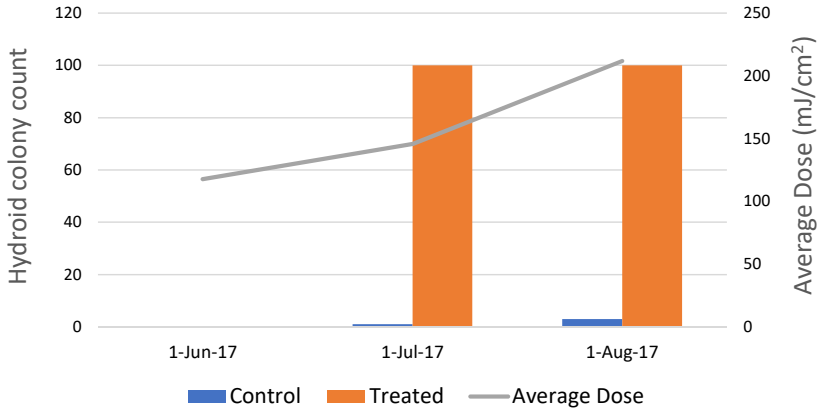

Figure 6. Total monthly hydroid colony settlement on three plates in control and treated bioboxes on cooling line 5. Colony counts were set at 100 when settlement was too dense to distinguish individual colonies.

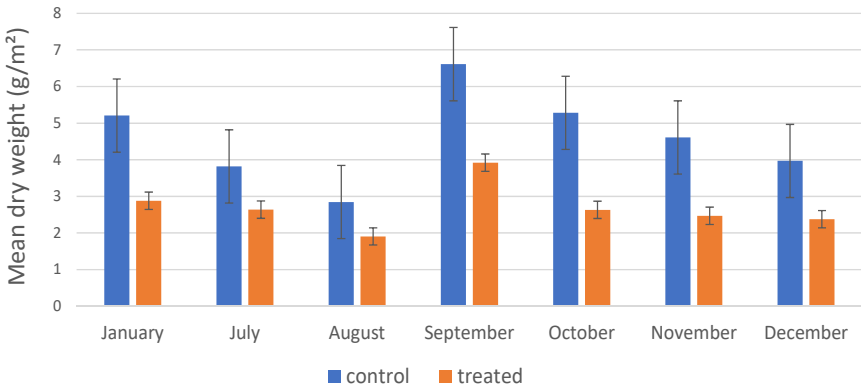

Figure 7. Mean dry weight (g/m^2) (of mussels, hydroid, sponge, and bacteria) with SE from six settlement plates from control and treated bioboxes on cooling lines 3 and 4 in 2016.

in the Unit 3 control biobox was 69.8 g/m^2 compared to 1.3 g/m^2 total dry weight observed from three plates in the HOD UV treated biobox. Dry weight totals from the Unit 4 control and treated bioboxes were 502.6 g/m^2 and 8.3 g/m^2, respectively.

Hydroid planula samples

Hydroid planulae are difficult to detect as they have a nondescript morphology. Therefore, all planula-like organisms were genetically analyzed by PCR for identification confirmation. Hydroid planulae were not discovered in any of the plankton tow samples collected from the Parker Dam forebay (Lake Havasu) or from the biobox outflow. Although hydroid larvae were not found, hydroid colonies with ovoid reproductive polyps were noted, indicating sexual reproduction was likely occurring.

Bacterial analysis

A 5.08–7.62-cm layer of black sludge-like biofilm was observed at the bottom of the untreated control bioboxes but not in the HOD UV treated bioboxes (Figure 3, bottom left and right). Microscopic examination showed the sludge collected from the control bioboxes consisted primarily of cocci and rod bacterial cells, with a lower density of cocci and many whole veliger shells (without tissue) in the treated bioboxes. A loss on ignition test was performed on the material deposited at the bottom of the control biobox. The test confirms that 95.92% of the sample was organic. The remaining 4.08% of the sample was clay sediment. There was not enough material in the bottom of the treated biobox to conduct a loss on ignition test.

ATP and microbial equivalent (ME) concentrations were not considerably different between the treated and untreated bioboxes, despite higher bacterial accumulation in the control biobox. Microbial abundance (log [ME/cm^2]) values were similar between control and treated samples after each one-month exposure (Figure 8). Bacterial reaction tests from the control and treated bioboxes on Unit 4 and 3 were conducted to ascertain differences in bacteria communities and concentrations that may be resulting in sludge formation. Similar bacterial groups

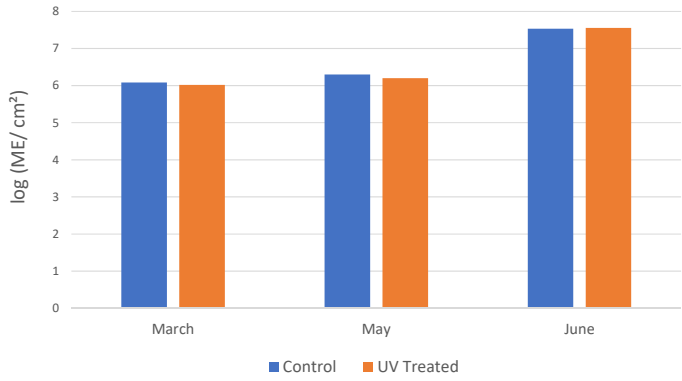

Figure 8. Average monthly microbial abundance, presented as log (ME/ cm^2), observed in control and HOD UV treated bioboxes after one-month periods.

Table 1. Type of bacteria detected in the BART™ culture and the approximate population in colony forming units per mL (cfu/mL) in large control and HOD UV treated bioboxes installed on Parker Dam Unit 4, and small, filtered bioboxes on Unit 3.

Cooling Unit	Sample	Iron-Related Bacteria	Sulfate- Reducing Bacteria	Slime-Forming Bacteria	Heterotrophic Aerobic Bacteria
Unit 4	Control Biobox	[a]BR (35,000) [b]FO (500) [b]RC (25)	[a]CL (500,000) [a]BT (115,000) [a]BB (115,000)	[a]CL (1,750,000) [b]PB (13,000)	[a]UP (5,400,000)
Unit 4	HOD UV Treated Biobox	[a]BR (9,000)	[a]CL (500,000) [a]BT (27,000) [a]BB (27,000)	[b]CL (13,000) [b]PB (13,000)	[a]UP (575,000)
Unit 4	Control Sample	No reaction	No reaction	No reaction	No reaction
Unit 3	Control Biobox	[a]BR (35,000) [b]CL (2,200) [b]RC (25)	[a]CL (115,000) [a]BT (27,000)	[a]CL (1,750,000) [a]SR (440,000) [a]PB (67,000)	[a]UP (5,400,000)
Unit 3	HOD UV Treated Biobox	[b]CL (500) [b]BR (500)	[a]CL (27,000) [b]BT (1,400)	[a]CL (1,750,000) [b]PB (13,000)	[a]UP (5,400,000)
Unit 3	Control Sample	No reaction	No reaction	No reaction	No reaction

[a] Aggressive populations with abundant bacteria that have the potential to cause biofouling issues.
[b] Moderate populations with less abundant bacteria.

Key to Bacterial Types

Iron-Related Bacteria (IRB)
BR = Iron-related bacteria
FO = Anaerobic bacteria
RC = Enteric bacteria
CL = Heterotrophic bacteria

Sulfate-Reducing Bacteria (SRB)
BB = Dense slime bacteria and SRB consortium
BT = Aerobic slime bacteria and SRB consortium
CL = Anaerobic bacteria present

Slime-Forming Bacteria (SLYM)
SR = Dense slime bacteria
CL = Slime-forming bacteria
PB = Fluorescing Pseudomonads

Heterotrophic Aerobic Bacteria (HAB)
UP = Aerobic bacteria

were found in the control and treated bioboxes, but several groups were present at greater concentrations in the control biobox (Table 1). Water samples were collected from the bottom of the macrofouling bioboxes on Unit 4 in 2016. Only anaerobic sulfate-reducing bacteria and fluorescing pseudomonad population levels were the same before and after HOD UV treatment. All other population levels were reduced after HOD UV treatment. Iron-related anaerobic and enteric bacteria populations were detected in the untreated biobox but were absent in the HOD UV treated biobox (Table 1).

In 2017, samples were collected (biofilm scraped from the plate with a razorblade) from the plates in the filtered, microfouling bioboxes on Unit 3. Only slime-forming and heterotrophic aerobic bacteria populations were found to be similar before and after HOD UV treatment. All other population levels were

reduced after HOD UV treatment (Table 1). Moderate enteric bacteria populations and aggressive dense slime-forming bacteria were detected in the untreated biobox, while none were found in the HOD UV treated biobox.

Discussion

Despite lower than expected HOD UV dose, the HOD UV units performed relatively consistently with few malfunctions during the two-year study. Reductions of biofouling were observed in treated bioboxes during the first year despite periods of contamination of the bioboxes with untreated water. Mussel settlement was also reduced as a result of HOD UV treatment, even during months with average doses near 50 mJ/cm^2 (50% of target dose), consistent with previous findings at Davis Dam (Pucherelli and Claudi 2016).

Visual observation and dry settlement weight indicated that hydroid and sponge settlement was reduced during the first year of study. Hydroid growth was more prevalent in the HOD UV treated bioboxes during the second year despite contamination prevention. Hydroid planulae are considered to be particularly susceptible to HOD UV treatment because they are soft bodied. However, planula settle quickly after release and may not spend much time freely floating in the water column, making detection of plankton difficult. Hydroid planulae were not found in any of the monitoring samples collected during the two-year study, suggesting the primary means of colony formation is by hydroid fragments. Mature hydroid stalks are composed of a thick, pigmented chitin that would provide more protection from HOD UV exposure. It is possible the doses tested in this study were not high enough to inactivate all hydroid fragments entering the system, or that the source of the hydroid fragments was, at least in part, the delivery line between the HOD UV system and the biobox.

Additionally, the biobox study design for monitoring growth may not be the most appropriate method for monitoring asexually reproducing species like sponges and hydroids. Successful hydroid settlement in both the treated bioboxes and their supply-line piping during periods of contamination or inadequate HOD UV dosages likely resulted in additional colony formation by localized sexual and asexual reproduction. Although a significant effort was made to completely clean out bioboxes after contamination events and between tests, it was unlikely all settlement was completely removed, particularly in the biobox water delivery piping. Therefore, the greater hydroid colony counts observed during the end of the study may be attributed to reproduction by survivors in the biobox system, and low-flow conditions favourable to establishment. *Cordylophora caspia* and dreissenid mussels are thought to compete for suitable substrate for colonization (Folino 2000). Since there were very few mussels settled in the treated bioboxes, localized hydroid settlement in the treated bioboxes may have been more successful than in the control bioboxes because of the reduced substrate competition with mussels. The counterintuitive hydroid settlement results indicate the need for additional research and methods to determine the effects of HOD UV on hydroids.

Aggressive populations of iron-related bacteria, sulfate-reducing bacteria, slime-forming bacteria, and heterotrophic bacteria were found in the untreated biobox. Aggressive populations indicate that there are abundant bacteria present and that there is a greater potential for reactions that could lead to biofouling problems in the facility. The thick bacterial growth observed in the untreated control biobox was likely produced by aggressive sulfate-reducing bacteria populations. Sulfate-reducing bacteria react with dissolved metals, such as iron and magnesium, to produce black slimes that can be corrosive and are capable of clogging certain structures at facilities (Cullimore 2000). The HOD UV treatment reduced bacterial populations in each of these major groups including the sulfate-reducing bacteria, likely accounting for the reduced sludge formation in the treated bioboxes. The greatest impact of HOD UV treatment on bacteria was observed in iron-related species and and enteric bacteria. Despite visual observations indicating lower levels of bacterial growth post-HOD UV exposure, ATP analysis indicated total bacterial populations were similar regardless of treatment. BART tests found populations were reduced by HOD-UV, but the majority of the surviving populations were considered to have aggressive biofouling potential. It is possible that ATP results did not show a reduction due to high levels of bacterial reproduction in the biobox or on the upstream filter in the absence of competition from other species. Additionally, ATP from bacteria recently inactivated by the HOD UV treatment may have also been detected.

Filtration of the microfouling bioboxes was intended to eliminate all macrofouling, but a few hydroid colonies and mussels were found downstream of the 100-µm filter in the untreated biobox. Interestingly, no settlement was observed in the filtered, HOD UV-treated biobox. This finding could mean that a faulty filter was installed on the control line or that the HOD UV treatment successfully deactivated mussel larvae and hydroid larvae and fragments smaller than 100 µm.

Figure 9. Parker Dam heat exchanger (left) with significant biofouling prior to implementation of HOD UV treatment, and heat exchanger (right) with no visible biofouling after same exposure time with HOD UV treatment. Photographs by Parker Dam Staff.

Prior to HOD UV installation, all sixteen coolers required yearly cleaning and maintenance due to biofouling induced overheating. This maintenance required around 640 staff hours, equating to approximately $80,000 in additional labor costs per year (personal communication with Parker Dam management). In the first year after the HOD UV installation, only four coolers required maintenance, some of which unrelated to biofouling. In 2017 and 2018, none of the coolers required maintenance, resulting in an estimated savings of $80,000 per year. Figure 9 shows two heat exchangers, the unit on the left was pulled for maintenance due to biofouling prior to HOD UV treatment implementation, the unit on the right was examined after a similar exposure time but with HOD UV treatment.

Lake Havasu contains the greatest populations of quagga mussel and *C. caspia* on the lower Colorado River and associated biofouling in Parker Dam cooling systems has resulted in significant annual maintenance costs. This facility has operational and regulatory barriers to installation of chemical addition systems, and mechanical self-cleaning filters or UV treatment were the only options available to maintain cooling system functionality once dreissenid mussels invaded the Lower Colorado River. Self-cleaning mechanical filters were piloted at this facility but were deemed too labor intensive to maintain. This study indicates HOD UV treatment at Parker Dam reduced maintenance due to biofouling despite lower than expected HOD UV doses.

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