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Research Article

Evaluation of the effects of ultra-violet light treatment on quagga mussel settlement and veliger survival at Davis Dam

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Editor's note:
This study was first presented at the 19th International Conference on Aquatic Invasive Species held in Winnipeg, Canada, April 10–14, 2016 (http://www.icais.org/html/previous19.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

Dreissenid mussels are aggressive biofoulers that threaten water delivery and hydropower reliability. The use of medium pressure UV systems to control dreissenid mussel settlement in industrial cooling water systems is a desirable alternative to chemical treatments. This paper summarizes two experiments, carried out over two years, using a proprietary medium pressure UV system. The first experiment tested veliger settlement after exposure to doses of 50, 40 and 20 mJ/cm². The second experiment tested settlement after exposure to 100 mJ/cm^2, and examined veligers behavior and direct mortality post exposure to UV doses of 100, 50, 40 and 20 mJ/cm^2. All doses tested in the first experiment resulted in settlement reduction between 88 and 99%. The 100 mJ/cm^2 dose reduced settlement by 99%. In the second experiment delayed veliger mortality was observed after every UV level tested. Mortality varied based on UV dose, ambient water temperature, and veliger size.

Key words: dreissenid control, quagga control, ultra-violet light, UV system, control of biofouling, industrial cooling water

Introduction

Dreissenid mussel infestation is a growing concern amongst water management facilities throughout the Western United States. The mussels are aggressive biofoulers that among other impacts threaten water delivery and hydropower reliability (Mackie et al. 1989; MacIsaac 1996; Claudi and Prescott 2007). Conventional treatment methods, such as chemical treatments, are costly, have adverse environmental effects, and require discharge permitting. Consequently, there is a need for innovative treatment methods that will prevent or limit mussel colonization in industrial facilities. Ultra-violet (UV) light irradiation is one such treatment. This treatment does not require discharge permitting in most jurisdictions and has no detrimental effects on the receiving environment. Medium pressure UV light treatments within the UVB and UVC range of the electromagnetic spectrum (<320 nm) are thought to be the most effective at disabling mussels and preventing attachment (Mackie and Claudi 2010). UV radiation treatment is only appropriate for the larval stages of mussels as they have a transparent/translucent shell that may not effectively protect their vital organs (Lewis and Whitby 1996). UV will kill settled, adult mussels given long exposure times (Chalker-Scott et al. 1993; Thaw et al. 2014), however this strategy lacks practical application in the field.

Figure 1. Bioboxes 1 and 2 with settlement plates for settlement monitoring.
Photograph by Sherri Pucherelli (USBR).

The effectiveness of UV treatment is dependent on site specific water characteristics such as water UV transmittance, presence of suspended solids, and flow conditions. Effectiveness also depends on achieving the correct UV dose (= intensity × exposure time). Previous studies have indicated that UV systems are able to prevent attachment of dreissenid veligers (Chalker-Scott et al. 1993; Chalker-Scott et al. 1994; Lewis and Whitby 1996; Wright et al. 1997; Chalker-Scott and Scott 1998; Stewart-Malone et al. 2015). More recently, Claudi and Prescott (2013) tested a medium pressure UV unit at Hoover Dam, NV, USA that completely prevented downstream settlement at an approximate dose of 100 mJ/cm². Although the exact effects of UV exposure on veligers are unknown, previous studies have indicated that UV exposure causes both immediate and latent mortality (Lewis and Whitby 1996; Wright et al. 1997).

Dense quagga mussel (*Dreissena rostriformis bugensis* Andrusov, 1897) populations in the lower Colorado River System have become problematic for hydropower facilities. This study was designed to determine the effectiveness of several levels of UV treatments for prevention of quagga mussel settlement in hydropower generator cooling lines using a full sized UV system which had been installed on the cooling water supply line of an operating unit of a hydraulic power plant.

Methods

A full sized medium pressure ultra-violet (UV) hydro-optic disinfection system from Atlantium Technologies Ltd. was installed on the Unit 3 cooling water line (25.4 cm) at Davis Dam AZ, USA. The unit treated approximately 13,250 L/min (3,500 GPM) and contained six medium pressure UV lamps with a maximum power of 4.2 kW each. The UV dose was controlled by automatic modulation of lamp output, and in-line sensors measured the water flow rate, ultraviolet transmittance (UVT), and incoming water temperature in order to achieve the selected UV dose. Real-time readings of the set dose, actual dose, UVT, flow rate, water temperature, lamp power, and lamp age were monitored and recorded during both experiments using the integrated control panel on the UV unit. To evaluate the power usage of the UV unit, an EKM omnimeter power use data logger was installed on the UV power supply. The power usage was recorded during each treatment cycle in 2013.

Two bioboxes, used to monitor mussel settlement, were installed on the cooling system (Figure 1). Water continuously flowed through each biobox at two gallons per minute. One biobox received water from upstream of the UV unit and the other received water that had passed through the UV unit. Flow totalizers were installed on the inflow of each biobox in order to balance and monitor the flow rate and the total amount of water entering each biobox. Each biobox was equipped with three large (approximately 35.56 × 28.58 cm) settling plates placed perpendicular to the flow that baffled flow by allowing water to either pass above or below. Additionally, four small (approximately 15.24 × 15.24 cm) settling plates were placed parallel to the flow (Figure 1).

Table 1. Start and end dates of each settlement test cycle and dose delivered.

Experiment	Start Date	End Date	UV Dose mJ/cm^2	Time (# of days)
1	6 June 2013	10 July 2013	50	35
2	11 July 2013	12 August 2013	40	33
3	13 August 2013	17 September 2013	20	36
4	18 September 2013	28 October 2013	40	41
5	29 October 2013	19 November 2013	40	21
6	28 July 2014	27 August 2014	100	31

Table 2. Dates on which veliger mortality was tested at each UV dose.

Dose Tested (mJ/cm^2)	Date Sample Collected
20	3 June 2014
40	28 July 2014
50	28 July 2014
100	24 May 2014
20	4 August 2014
40	11 August 2014
50	11 August 2014
100	4 August 2014
100	25 August 2014

Both bioboxes were covered with black plastic to eliminate ambient light during the experiments. Mussel larvae (veliger) samples were collected from hoses connected to the inflow of each biobox.

The water quality of the cooling system was monitored in order to track shifts in environmental variables. During each sampling event, a YSI Inc., water quality multi-probe, was used to monitor the temperature, dissolved oxygen, pH, and conductivity in each biobox to detect water quality changes that might influence mussel survival. UVT readings were taken with a Real Tech Inc. handheld UVT meter for comparison to the UVT reading from the control panel. Monthly water quality readings were also collected from the Davis Dam forebay.

UV effect on veliger settlement

In 2013 the effectiveness of three low UV doses was tested for quagga mussel settlement prevention. Settlement was analyzed after exposure to UV dose of 50, 40, and 20 mJ/cm^2. The 40 mJ/cm² dose was tested during three different months to examine seasonal differences in settlement prevention. Settlement prevention at 100 mJ/cm² was tested in 2014 (Table 1). The incoming cooling water was treated with the selected UV dose for approximately 30 days. At the end of each treatment period the settlement in both the control and treated bioboxes was visually evaluated. The settlement plates were removed and any individual mussel with shell length greater than 500 microns was counted. The edges of the settling plates were not counted. Note was made of any individuals larger than 6 mm. These individuals were considered translocators from upstream locations. This assumption was based on maximum potential growth rate of the individual mussels, conservatively estimated at 1 mm/week, which is above that reported by Wong et al. (2012) for Lake Mead, NV. Given this growth rate, 6 mm and greater individuals could not have reached their size by settling as pediveligers in the biobox during any of the experimental treatments which lasted less than 5 weeks. The total settlement surface monitored per biobox was 0.80 m^2 (four 15.24 × 15.24 cm plates counted on both sides = 0.19 m^2 plus three 35.56 × 28.57 cm plates counted on both sides = 0.61 m^2).

UV effect on veliger mortality

In 2014, the same UV system installation was used to determine how UV exposure affects veligers and prevents settlement. The effect of each previously tested dose (50, 40, and 20 mJ/cm²) and a higher dose of 100 mJ/cm² were evaluated to determine if the doses produced immediate or latent mortality. The effects of UV exposure were determined for each veliger life stage (straight-hinged, umbonal, and pediveliger) to determine if one life stage was more impacted by exposure to UV over another.

Each UV dose was tested twice during the summer months, once in the early summer and once later in the season to determine seasonal variability of veliger mortality rates (Table 2).The early summer tests at doses 50 and 40 mJ/cm^2 were tested later than originally planned because the UV unit was down for maintenance from June 26–July 17. An additional test was conducted at the 100 mJ/cm^2 dose in late August. On dates where samples from two separate dose treatments were collected, the water lines were allowed to run for 30 minutes between each sample collection to ensure veligers treated by the previous dose were cleared out of the line.

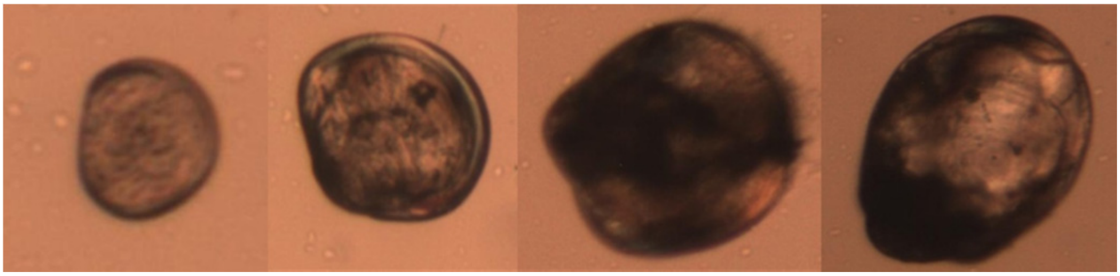

Figure 2. Microscopic images of quagga mussel veliger life stages, from left to right, straight-hinge, small umbonal, large umbonal, and pediveliger. Photomicrographs by Jamie Carmon (USBR).

The effect of each UV dose on the mortality of three veliger life stages (straight-hinged, umbonal, and pediveligers) was determined by observing a sample of quagga mussel veligers immediately after exposure, and every 24 hours thereafter for a total of 120 hours post exposure. Veligers were collected by allowing untreated (control) and UV treated water to flow into 64-µm plankton tow nets for 30 minutes. The consolidated samples were transferred into Petri dishes and observed under a dissecting microscope. Twenty live veligers, per life stage, (60 total veligers) were randomly selected from the sample and transferred into another Petri dish. Five replicates (petri dishes) of 20 veligers per life stage (a total of 100 veligers per life stage) were analyzed for each UV treatment and associated control. Veliger life stage was determined based on morphology as opposed to size since the size ranges of the different life stages tends to overlap (Figure 2).

After initial observation, the samples were placed in a water bath that was maintained at 16 °C by a water chiller (Teco Seachill® Chiller, Aquatic Ecosystems, Inc.). Larval mussels were kept at what is considered an optimum temperature so they would survive for multiple days in order to observe any delayed effects of UV exposure. Fresh water, filtered through 64-µm mesh (to exclude veligers), was collected from the Davis cooling system (Unit 3) and added to each Petri dish every few days to provide the mussels with additional nutrients. Veligers were examined at 24-hour intervals and categorized as alive or dead. Veligers were considered alive if movement of the velum or foot was seen. If a veliger's shell was closed and internal movement could not be seen, but the organs appeared to be intact (not degraded) the veliger was also considered alive. A veliger was only considered dead if its shell was open and the organs were exposed, without movement, and/or if the tissue was beginning to noticeably disintegrate. If the status of a veliger was questionable, the veliger was considered alive.

Statistix Analytical Software was used to conduct Kaplan-Meier survival analysis to compare mortality response times to each UV treatment. The data set contains censored observations because mortality observations did not continue after 120 hours, and many of the veligers were still alive. Kaplan-Meier procedures are suitable for data sets with censored data. Kaplan-Meier product limit estimates of survival function were computed for each dose in order to compare survivorship between months. Lethal time estimates for 50% sample mortality (LT50) were calculated for each dose during each month tested when possible. Many of the data sets contained too many censored data points to calculate LT50 values. Proportional hazards regression was used to compute statistical relationships between survival time and month tested. Proportional hazards regression was also used to compute the effect of life stage on survival time.

Results

Environmental variables

During each experiment only slight variations in water quality readings were observed between control and test bioboxes and all values recorded were within the mussel's acceptable habitat range. As expected, the water temperature in Lake Mohave (upstream of Davis Dam) increased throughout the summer (Figure 3). The water entering the cooling system is mixed in the forebay and the temperature recorded is usually cooler than what the mussels are experiencing in open water upstream of the dam. All water quality readings in Table 3, except for UVT, were collected from the Davis Dam forebay (Lake Mohave) to provide a better representation of the habitat the veligers experienced before entering the dam.

Power consumption

Energy consumption was recorded during the 20 mJ/cm^2 and the three 40 mJ/cm^2 tests (Table 4).

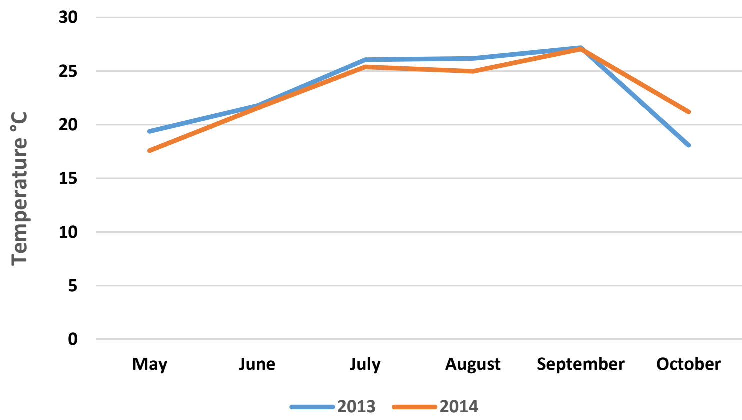

Figure 3. Surface temperature in the Davis Dam forebay during 2013 and 2014 UV testing.

Table 3. Surface water quality readings from the Davis Dam forebay (Lake Mohave) during the 2013 and 2014 testing periods. UVT readings were recorded at the UV unit.

Month	Temperature °C	Dissolved Oxygen (LDO) mg/L	LDO %	pH	Specific Conductivity mS/cm	Average UVT
2013						
May	19.38	9.95	111.4	8.54	0.87	NA
June	21.76	9.67	113.1	8.26	NA	89.79
July	26.04	8.86	121.6	8.40	0.90	89.50
August	26.17	7.73	116.4	8.27	0.89	90.83
September	27.16	8.20	125.6	8.28	0.89	89.89
October	18.08	7.16	92.3	8.22	0.88	86.15
2014						
May	17.57	8.52	101.3	8.23	0.92	89.55
June[a]	21.56	9.42	NA	8.20	0.95	88.33
July	25.37	8.85	118.2	8.13	0.95	89.99
August	24.98	8.67	115.1	8.10	0.96	91.11
September	27.04	9.34	120.4	8.41	0.97	NA
October	21.20	8.37	96.7	8.23	0.96	NA

[a] June 2014 water quality data retrieved from Southern Nevada Water Authority (SNWA) database, except for UVT
NA: water quality not available

Power consumption data was not collected during the 50 mJ/cm^2 test because the power recording meter was not yet installed. At the 20 mJ/cm^2 dose level the energy use translates to 1.11 kWh/100 m^3 (4.21 kWh/100,000 gallons). Conservatively, a unit UV system at Davis would need to run for a maximum of 11 months of the year allowing for a one month annual outage. The UV unit may run for a shorter period if there are very few veligers present in the raw water; possibly January and February. Based on the electrical consumption value the total projected electricity use for eleven months would be approximately 65,000 kWh. Using a generating cost for electricity of 3 cents per kWh, the annual operating cost for power for a UV system protecting the cooling water of one Davis Dam unit would be approximately $1,950.

At the 40 mW-s/cm^2 dose level, energy readings were taken during three separate tests. It was observed that the energy use readings varied and this appeared to be related to the on board UVT instrument reading water transmissibility low as compared to the independent instrument grab samples. The effect of this was that the UV unit was dosing higher than necessary during some periods of its operation thereby using more energy. More frequent cleaning of the onboard UVT sensor would alleviate the sensor drift that results in overdosing.

The energy use at 40 mW-s/cm^2 is reported as a maximum and minimum, where the minimum coincides with the UVT sensor recording transmissibility readings that match the independent grab sample measurements. The energy use translates to a range of 1.82 to 2.49 kWh/100 m^3 (6.90 to 9.43 kWh/

Table 4. UV unit power consumption during various dose levels during 2013 tests.

Experiment	Start Date	End Date	UV Dose	Total Days	Total Flow[c] (100 m³)	Cumulative Energy Use (kWh)	Energy used in interval (kWh)	Energy used per 100 m³ (kWh)	Energy used per 1000,000 gallons (kWh)
1	6/6/2013	7/10/2013	50	35	6678				
2[a]	7/11/2013	8/12/2013	40	14.75	2814	5127	5127	1.82	6.90
3	8/13/2013	9/17/2013	20	36	6869	12770	7643	1.11	4.21
4	9/18/2014	10/28/2013	40	43.5	8300	33454	20684	2.49	9.43
5[b]	10/29/2013	11/6/2013	40	7.2	1374	36063	2609	1.90	7.19
5	11/7/2013	11/12/2013	40	5.8	1107	38405	2342	2.12	8.01

[a] Power meter was turned on July 30th, recorded Aug 14th
[b] Unit continued to run until November 19th
[c] Based on a flow rate of 13250 L/min

Table 5. Total settlement of mussels per square foot, including percent reductions, at each dose and corresponding average surface temperature recorded in the Davis Dam forebay.

Experiment	Dose (mJ/cm²) Test Months	Average Temp °C	Control (Box 1)	UV (Box 2)	Box 1 to 2
3	20 (Aug-Sept)	26.67	223	26	88%
2	40 (July-Aug)	26.11	386	8	98%
4	40 (Sept-Oct)	22.62	1445	18	99%
5	40 (Oct- Nov)	18.08	810	76	91%
1	50 (June-July)	23.90	160	8	95%
6	100 (July-Aug)	23.47	1314	10	99%

Table 6. Total percent mortality of each veliger life stage at 120 hours post UV exposure. The percentage in parentheses is the total mortality observed in the associated control samples.

Test (Dose mJ/cm², sample date)	Straight-hinge	Umbonal	Pediveliger
100, May 24th	36% (1%)	63% (1%)	18% (0%)
100, August 4th	100% (0%)	100% (3%)	98% (5%)
100, August 25th	100% (3%)	100% (10%)	99% (3%)
50, July 28th	45% (3%)	48% (3%)	4% (1%)
50, August 11th	100% (2%)	99% (3%)	91% (0%)
40, July 28th	46% (1%)	49% (0%)	9% (1%)
40, August 11th	83% (4%)	69% (6%)	37% (4%)
20, June 3rd	43% (2%)	80% (3%)	26% (3%)
20, August 4th	21% (1%)	17% (4%)	13% 0%)

100,000 gallons). Using the same annual operating base as for the 20 mW-s/cm² dose, the total projected electricity use for eleven months of UV operation at 40 mW-s/cm² would be in the range of approximately 106,000 to 145,000 kWh. This electricity use to protect the cooling water of one Davis Dam unit would have an annual cost of $3,150 to $4,350.

UV effect on veliger settlement

New mussel settlement was observed during each experiment. Mussel settlement numbers in the control biobox were significantly greater than those in the treated biobox in each case. There did not appear to be a profound difference in settlement reduction at the different UV dose levels (Table 5). Seasonally, the same dose level of 40 mJ/cm² appeared to be less effective in October (exp. 5) than in July (exp. 2) and September (exp. 4). Less settlement was observed at the 40 mJ/cm² dose during the September (exp. 4) and July (exp. 2) tests when average forebay temperatures ranged between 25–27 °C (Figure 3). Temperatures during the October test (exp. 5) were approximately 10° cooler and therefore not as close to the mussel's upper thermal limit. Mackie and Claudi (2010) give temperature between 26 and 32 °C as the range which has little potential for larval development. It is therefore possible that the incoming pediveligers were negatively affected by the high ambient water temperature prior to entering the dam and therefore more susceptible to the UV treatment.

UV effect on veliger mortality

All of the doses tested in this study produced delayed veliger mortality. At each dose tested, veligers were

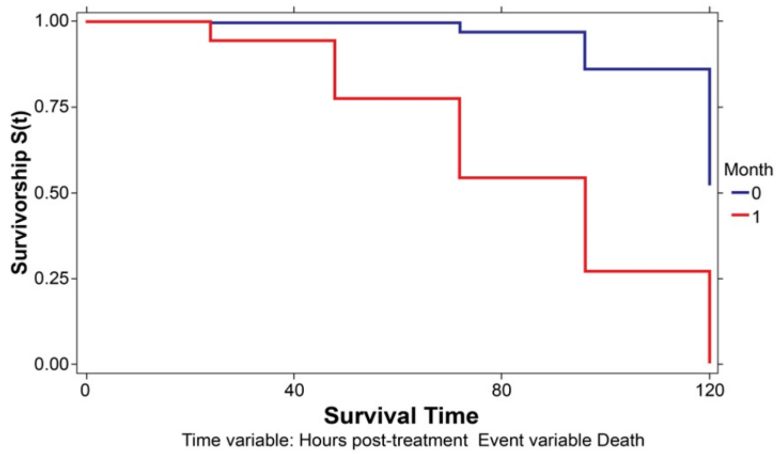

Figure 4. Kaplan-Meier product limit estimates of veliger survival functions at the 100 mJ/cm^2 dose in May (0, blue line) and August (1, red line).

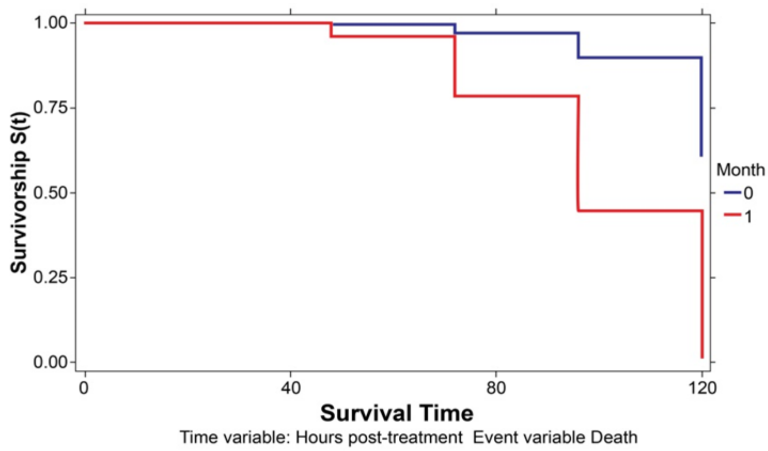

Figure 5. Kaplan-Meier product limit estimates of veliger survival functions at the 50 mJ/cm^2 dose in July (0, blue line) and August (1, red line).

found to be alive immediately and within two hours after exposure. Mortality rates appeared to be based on the UV dose received, date of treatment, and veliger life stage (Table 6). The relative risk of veliger mortality was significantly greater during the "late summer" tests compared to the "early summer" tests at the 100 (p=0.0000), 50 (p=0.0000), and 40 mJ/cm^2 (p=0.0000) doses (Figures 4–6). The estimated risk of dying for veligers exposed to the 100 mJ/cm^2 dose in August is 5.44 times higher than that for veligers exposed to the same dose in May. Similarly, risk of veliger death is 4.45 and 2.67 times higher in August compared to July at the 50 and 40 mJ/cm^2 doses respectively. Unlike the higher doses, veliger risk of death was 0.38 times higher in June compared to August at the 20 mJ/cm^2 dose (p=0.0000; Figure 7). The LT50 for mussels exposed to 100, 50, and 40 mJ/cm^2 doses in August were 96, 96, and 120 hours respectively. The LT50 for mussels exposed to the 20 mJ/cm^2 dose in June was 120 hours. It was not possible to calculate LT50 values for the other tests because of the insufficient number of uncensored observations.

Low levels of mortality were seen in control samples at each dose, there was a slight increase in control mortality in August samples compared with samples collected earlier in the summer (Table 6). The "early summer" 50 and 40 mJ/cm^2 tests were conducted on July 28th (a month later than originally planned, due to UV unit maintenance) and the "late summer" samples were only collected two weeks later on August 11th. Even in this short period of time, mortality rates were greater in August.

Veliger survival time was found to be influenced by life stage. Pediveliger risk for death was found to be less than straight-hinged and umbonal mussels at all doses tested (Table 6). The estimated risk of dying for pediveligers exposed to the 100 mJ/cm^2 dose in May and August was 0.27 and 0.80 times less than for straight-hinged and umbonal veligers (p=0.0000). The estimated risk of dying for pediveligers exposed to the 50 mJ/cm^2 dose in July

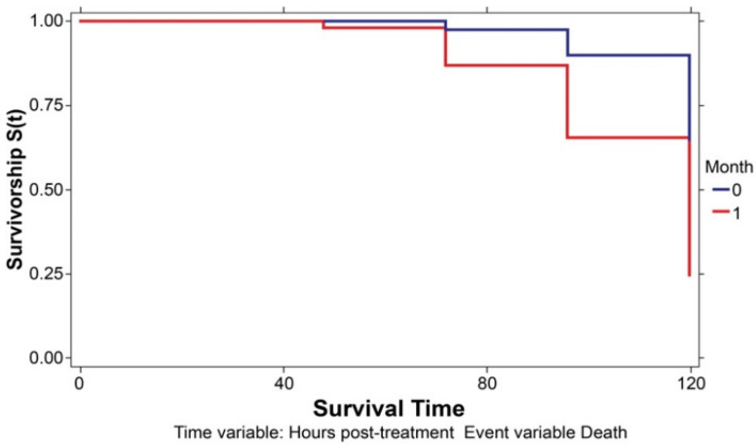

Figure 6. Kaplan-Meier product limit estimates of veliger survival functions at the 40 mJ/cm^2 dose in July (0, blue line) and August (1, red line).

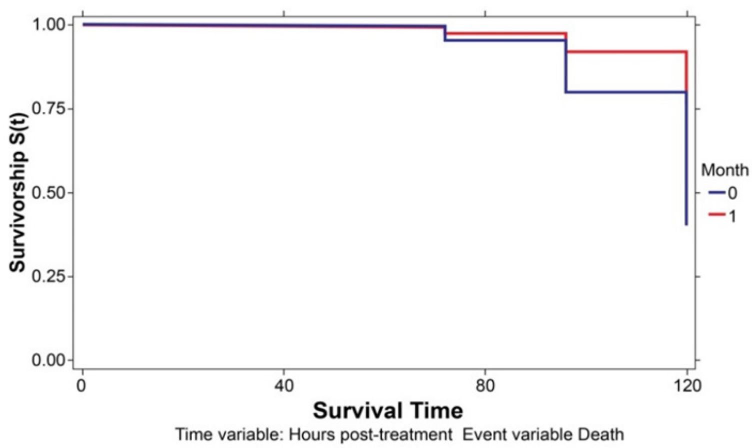

Figure 7. Kaplan-Meier product limit estimates of veliger survival functions at the 20 mJ/cm^2 dose in June (0, blue line) and August (1, red line).

and August was 0.09 and 0.69 times less than for straight-hinged and umbonal veligers (p=0.0000). Similarly, pediveligers exposed to the 40 mJ/cm^2 dose in July and August experienced 0.18 and 0.45 times less risk of death compared to smaller mussels (p=0.0000). Mussel mortality was low overall in the August 20 mJ/cm^2 test and pediveliger mortality risk was not found to be significantly different than the other mussel life stages (p=0.6412). The risk for pediveliger mortality was 0.45 times less than smaller mussels in the June 20 mJ/cm^2 test (p=0.0000).

Veligers observed immediately after UV exposure were moving around the petri dish in a manner similar to veligers that were not exposed and did not appear to be physically damaged, stunned or inactivated. Two hours post UV exposure; treated veligers were notably more active compared to control veligers. In general, most of the UV treated veligers were quickly swimming around the petri dish, while control veligers were closed or moving more slowly. Over time, treated veligers, that appeared to be dying, would begin to shake from side-to-side with their shell open and cilia exposed. Most dead veligers were easy to detect as they had gaping shells with quickly deteriorating tissue.

Discussion and Conclusions

The UV system installed at Davis Dam effectively reduced quagga mussel settlement at all doses tested. The results of this study indicate that the settlement reduction, at least in part, is likely a result of latent veliger mortality. Wright et al. (1997) and Chalker-Scott et al. (1993) also found UV exposure caused a delayed mortality effect. Veliger mortality and settlement reduction was varied somewhat throughout the year at the same UV dose. Other than the 20 mJ/cm^2 dose, all other UV doses produced less veliger mortality in the early summer months when compared to later in the summer. The variability seen in the 20 mJ/cm^2 dose tests is an anomaly for which we have no hypothesis. Settlement prevention at the 40 mJ/cm^2 dose was slightly less effective in October (exp. 5) than when tested in July (exp. 2) and September (exp. 4). This variation may be due to environmental variables such as temperature, which has been found to impact mussel robustness (McMahon 1996). Veligers may become less robust as they are exposed to increasing water temperatures in Lake Mohave for longer periods of time. It is possible that less robust veligers are more susceptible to UV exposure.

Significant settlement reduction was observed even during seasonal periods when latent mortality was low. It is possible that mussels exposed to UV in environmental conditions that are more favorable to mussel survival may experience an even greater delay in mortality compared to larval mussels which experienced unfavorable conditions. In this study veligers were only observed for 120 hours after collection. It is likely that post exposure mortality continues past this arbitrary time point and that this study's time-frame did not allow for observation of the majority of the mortality of larval mussels in the early summer.

Generator cooling water has a relatively short residence time within the dam, and it appears that the delayed effects of the UV treatment are still effective at reducing settlement within the system. It is possible that ready-to-settle veligers (pediveligers) are able to settle within the system immediately after UV exposure. However, over the course of a few days they may die before they can grow to adulthood and cause blockages. Additional research into this subject is required as mortality of newly settled mussels was not examined in this study. It is also important to consider that UV may impact the mussels in a way that we were not able to visibly detect, such as attachment inhibition.

UV exposure appears to be most effective at killing smaller veligers (straight-hinged and umbonal) that are not a direct threat to the cooling water system. These less developed veligers are not capable of settling within the cooling system because they do not have enough residency time to develop into the settling stage. Although pediveligers experienced lower mortality rates over time it is possible that mortality continues past the observed 120-hour mark resulting in the significant settlement reduction which we have observed.

By tracking the power consumption at the different UV dose levels we can estimate that at 40 mW-s/cm^2 UV dose electricity use to protect the cooling water of one Davis Dam unit would have an annual cost of \$3,150 to \$4,350. At a dose of 20 mW-s/cm^2 the annual operating cost for power for a UV system protecting the cooling water of one Davis Dam unit would be approximately \$1,950. At either dose level the cost of power for preventative treatment of unit cooling water is very modest for the high degree of settlement control achieved.

The results of this research indicate that treatment with the Atlantium medium pressure UV is effective in preventing quagga mussel settlement in hydropower generator cooling systems. The results observed are only applicable to Atlantium UV systems and may be in part the result of the innovative way UV energy is distributed within the reaction vessel. Studies similar to this one have not been done with a traditional medium pressure UV system. Several previous research studies have examined the effect of UV on dreissenid mussels, but it is difficult to compare the results to this study due to the variability in study design. Most previous studies tested unique wavelengths and doses under static conditions using collimated beam apparatus and utilized variable methods to analyze mortality and settlement. Recently, Stewart-Malone et al. (2015) exposed quagga mussel veligers to UV-C wavelength doses of 13.1, 26.2, and 79.6 mJ/cm^2 in a static table-top design and found 80% mortality 96 hours post-UV exposure at the highest dose. Our study tested a flow-through system with UV-B wavelength and despite these differences, the observed dose response results are similar to those reported by Stewart-Malone et al. (2015). Other studies tested significantly higher doses of UV with individuals mussels exposed till mortality was achieved. Thaw (2013) tested a static, table-top UV unit that produced UV-B wavelengths at doses ranging from 360- 3×10^5 mJ/cm^2 for adult, juvenile, and veliger quagga mussels and found LD_{50} values to be 44,255 mJ/cm^2, 10,537 mJ/cm^2, and 857 mJ/cm^2 respectively. Wright et al. (1997) found 100% veliger mortality, 168 hours post-exposure to 702, 1404, and 2808 mJ/cm^2 doses. Chalker-Scott et al. (1994) found veliger mortality to occur sooner, at 24 hours post-exposure to doses ranging from 348 to 3067 mJ/cm^2.

While few studies have tested the effect of UV exposure on settlement reduction, the results of this study were similar to settlement reduction discovered previously by Claudi and Prescott (2013) and Pickles (2000). Claudi and Prescott achieved 100% settlement reduction with a 100 mJ/cm^2 dose at Hoover Dam, AZ, and Pickles (2000) achieved 80% settlement reduction with a dose range of 70 to 100 mJ/cm^2, at a Lake Huron power plant, despite several issues with the UV unit.

Site specific water quality is a critical consideration when applying UV treatment for mussel settlement prevention. Increased levels of turbidity (decreased UVT readings) may limit UV penetration and greatly impact the effectiveness of this control strategy against veligers. Therefore a more powerful UV system able to deliver higher doses may be required based on site specific conditions.

Although the effectiveness of each dose tested was variable throughout the year, the high settlement reduction, although not 100%, can significantly reduce impacts to treated cooling water systems. The mortality and settlement results between the 50 and 100 mJ/cm^2 doses were similar, suggesting that the lower dose could be used as effectively while reducing electrical and equipment costs. Further study is warranted to understand how UV treatment can be integrated with other control methods to increase effectiveness. In situations where complete veliger mortality is the main objective, a higher dose regime would need to be evaluated.

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