

The Impact of Diquat on Macrophytes and Water Quality in Battle Ground Lake, Washington

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ABSTRACT

A nearly monotypic population of egeria (*Egeria densa* Planch.) was interfering with recreation in a popular lake in southwest Washington. In June 2003 the littoral zone was treated with the contact herbicide diquat (6,7-dihydrodipyrido [1,2-a²,1'-c] pyrazinediium dibromide). Aquatic plant frequency and biomass data were collected on all submersed species before treatment, and eight weeks, one year and two years after treatment. Water quality and herbicide dissipation data were also collected before and for one season after the treatment. Results from the aquatic plant data showed a significant reduction in egeria frequency and biomass after the herbicide treatment, although the species did not disappear entirely. Two native submersed species, water moss (*Fontinalis antipyretica* Hedw.) and stonewort (*Nitella* sp.), increased after treatment. However their increase was not enough to offset the egeria population reduction, as total plant abundance was significantly reduced after treatment. The herbicide dissipation data illustrated the dispersal of diquat throughout the lake and persistence at low concentrations (up to 10.4 ppb) in the water column for at least two weeks after treatment. Water quality data demonstrated a slight decrease in dissolved oxygen and water transparency following the herbicide treatment, potentially due to plant die-off and subsequent plant decomposition.

Key words: *Egeria densa*, Reward®, Brazilian elodea, native macrophytes, herbicide residue.

INTRODUCTION

Egeria (also known by the common names Brazilian elodea and anacharis) is a robust submersed plant native to southeastern Brazil, Uruguay and northeastern Argentina. It has spread around the world because it is both a popular aquarium plant, admired because it is easy to grow and rumored to be a good 'oxygenator' (Cook and Urmi-König 1984), and it has been widely used in classroom physiology experiments (Catling and Wojtas 1986, Haramoto and Ikusima 1988). Although it is dioecious, with only male plants reported outside of South America, egeria is effective at vegetative reproduction and spread. When introduced to lakes and rivers, egeria can grow densely throughout the wa-

ter column impacting native plant diversity, fish and wildlife habitat, aesthetics and recreational uses of the waterbody (Wells and Clayton 1991, Getsinger 1991). Thus, egeria is an undesired invasive species in the western U.S. as well as many other parts of the world (Cook and Urmi-König 1984).

Egeria was first identified in Washington State lakes sometime prior to the mid-1970s, likely an introduction from a discarded aquarium. Naturalized populations are currently known from more than 20 lakes and rivers in the western part of the state (Parsons 2006). In 1992 egeria was added to Washington's Noxious Weed Quarantine list, meaning it was no longer legal to sell or possess. However, egeria continues to be found in new locations, and it has proven to be a difficult invasive weed to control.

Diquat is effective for Egeria control in many situations (Berry and Schreck 1975, Tanner et al. 1990). However, for many years diquat use was not allowed in Washington due to significant information gaps on its fate and environmental impacts. In 2002 the Washington Department of Ecology (WA-DOE) updated its Supplemental Environmental Impact Statement for Diquat Bromide (Emmett 2003) allowing the use of diquat in Washington waterbodies. At that time WA-DOE wanted to evaluate the persistence of diquat in a lake environment, its impact on aquatic plants, and determine its effectiveness for managing egeria populations in Washington.

MATERIALS AND METHODS

Site Description

The study was conducted at Battle Ground Lake, located about 21 miles northeast of Vancouver, Washington (Figure 1). The lake is contained in a small crater formed by a steam explosion, known as a maar volcano. The surface area is about 11 ha with a maximum depth of 18 m and mean depth of 9 m (Bortleson et al. 1976). An examination of lake sediments has shown Battle Ground Lake to be at least 20,000 years old (Barnosky 1985). It has no permanent tributaries or outflows, and the watershed only consists of the exposed portion of the small crater, a total of about 0.2 km². The lake level is likely maintained through rainwater and ground water. During this study the water level did not fluctuate markedly.

Water quality data collected between May and October 2003 indicate that Battle Ground Lake is strongly stratified. Well-defined thermal boundaries were established by May, and the hypolimnion was essentially anoxic through October. The lake experiences occasional algae blooms, but generally has good water clarity. Based on algal biovolume and chlorophyll-a concentration the lake can be classified as meso-eutrophic (Wierenga 2004).

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Herbicide Application and Water Quality Analysis

Battle Ground Lake was treated with diquat (Reward®) on the morning of June 16, 2003. Weighted trailing hoses were used to achieve a subsurface injection at about 1 m deep; therefore placing the herbicide above the thermocline depth, which was between 3-4 m deep on the day of treatment (T. McNabb, Aquatechnex, 2006 pers. comm.). The herbicide was applied at the rate of 2 gallons per surface acre through the littoral zone. This would achieve the maximum label rate of 370 ppb active ingredient in water 1.2 m deep. However, in Battle Ground Lake the treatment area averaged about 2.9 m deep, so a lower resultant herbicide concentration was expected. Because the vegetated littoral zone makes up less than one half of the lake's volume, we determined that all of the vegetated area (about 3 ha) could be treated at once without adversely affecting the dissolved oxygen content from rapid plant decomposition.

Water quality samples were collected prior to treatment and 4-hours, 1, 2, 3, 7 and 14 days after treatment (DAT) for diquat concentration analysis. In addition, a calibrated Hydrolab DS4 multiprobe was used to collect water temperature, pH, dissolved oxygen concentration and percent saturation, and conductivity data. Turbidity was measured in the field with a calibrated Hach 2100P field turbidimeter. Secchi depth was measured using a 20 cm Secchi disk and a marked rope. Total suspended solid analyses were performed on water samples collected pretreatment and 4-hours, 1 and 2 DAT.

The water quality samples were collected from four sites at mid-depth except where the water column was thermally stratified. In such cases samples were collected from the middle of each layer above and below the thermocline (Figure 1). Station 1 (S1) was in a dense egeria bed close to the public swimming area; the water was about 4.6 m deep. Station 2 (S2) was at the edge of the egeria bed at a depth of about 6.1 m. Station 3 (S3) was mid-way between the edge of the egeria bed and the middle of the lake, the depth was about 11.6 m. Station 4 (S4) was in the lake center, the depth was about 15 m. Stations 1 and 2 were in the area treated with diquat; stations 3 and 4 were untreated.

The water quality samples were collected starting from the untreated area at S4 to the treated area at S1 during each sampling event. Samples for diquat and total suspended solids analysis were collected with a Van Dorn sampling bottle pre-cleaned at the start of each day with a commercial cleaning agent (Alconox®). The sample bottles were amber, high-density plastic with sulfuric acid as a preservative. Each bottle was individually enclosed in a sealed plastic bag to prevent cross-contamination. The samples were stored on ice until analysis. Samples were analyzed for diquat following method EPA 549.2. The Practical Quantitation Limit (PQL) for diquat in water was 2 µg/L with a method detection limit (MDL) of 0.14 µg/L. Samples were analyzed for total suspended solids following SM2540 D. The MDL was 1 mg/L and the PQL was 4 mg/L.

Sediment samples were collected using a petite ponar dredge from S1 for diquat analysis prior to treatment and 1 DAT. The dredge was deployed three times, and the top layer (approximately 2 cm) of sediment that was not touching the

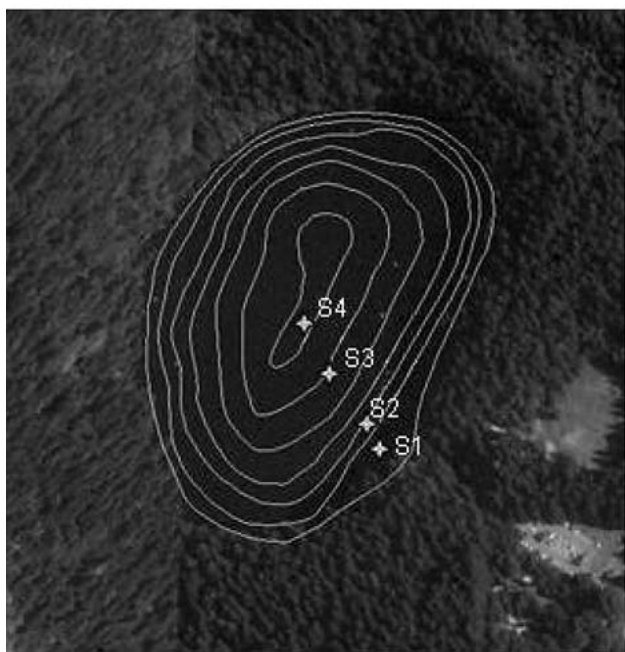


Figure 1. Battle Ground Lake, Washington. Depth contour intervals are in 3 m increments. Water sample stations indicated as S1, S2, S3, and S4.

The lake and watershed are contained in Battle Ground State Park, a popular recreational area that provides camping, fishing, swimming, non-motorized boating, hiking and horse riding opportunities. The lake is surrounded by forest, but the land outside the State Park has largely been converted to small-scale agriculture and suburban development. Battle Ground Lake is routinely stocked with rainbow trout (*Oncorhynchus mykiss* Walbaum) and also supports sea-run cutthroat trout (*Salmo clarki* Rich), largemouth bass (*Micropterus salmoides* Lac.) and sculpin (*Cottus* sp.). It was previously stocked with eastern brook trout (*Salvelinus fontinalis* Mitchell), and a few may still be present in the lake (S. Kelsey, WD-FW Inland Fish Program 2006, pers. comm.).

Egeria was introduced to Battle Ground Lake prior to 1994. At the study's inception it dominated the submersed plant community to a depth of about 5.5 m., and few other submersed species were found in the lake. The lake managers were becoming increasingly concerned about the egeria growth as a danger to swimmers and a nuisance to anglers.

dredge was removed and composited in a stainless steel bowl. The composited material was placed in a 250 ml amber glass sample jar, and stored on ice until analysis. Samples were analyzed following EPA method 549.2; the PQL was 2 µg/l and the MDL was 0.02 µg/l.

Aquatic Plants

The aquatic plant community was assessed four times following methods recommended by Madsen (1993, 1999): before the herbicide treatment in May 2003, 8 weeks after treatment (WAT) in August 2003, and 1 and 2 years after treatment (YAT) (May 2004 and June 2005). In June 2005 the Washington Parks and Recreation Commission stocked triploid grass carp to control the remaining egeria, so this study was discontinued at that time.

Aquatic plant frequency data were collected at points on a 15-meter sample grid covering the lake margin to approximately the 6 m contour. The points were located in the field with a Global Positioning System unit aided by aerial photographs and maps overlaid with the sample grid. All points were sampled if possible, for a total of 563 points on the four sample dates: 140 in May 2003, 142 in August 2003, 141 in May 2004 and 140 in June 2005. Samples were gathered at each point using a sampling rake consisting of two metal leaf rakes bolted back to back and weighted with a metal plate. The handles were removed and replaced with a 30 m marked rope. The rake was thrown two times from the side of a boat and the collected plant species names and the sample depth were recorded. The data were analyzed using Chi square two-by-two analysis for the common species. The probability was adjusted using a Bonferroni correction to account for multiple comparisons.

Biomass data were collected each sampling date from 30 points randomly selected from the same sample grid used for the frequency data collection. Plants were sampled by a SCUBA diver. The diver collected all above sediment plant growth within a 0.1 m² frame, placed the plants in a goody bag and brought them to attendants on the boat. The plants were sorted by species and placed in pre-weighed paper bags. The samples were dried to a constant weight at 70°C and weighed to 0.01 g accuracy. The data were analyzed using

one-way Analysis of Variance after performing a log₁₀ + 1 transformation to approximate a normal distribution. The resultant p-values were adjusted using a Bonferroni correction to account for multiple comparisons. Post-hoc analysis determined which of the comparisons were significant.

RESULTS AND DISCUSSION

Herbicide Analysis

Diquat was consistently below the maximum label concentration of 370 ppb throughout the lake (Table 1). This was expected due to the dilution caused by the large treatment area depth. Also diquat is rapidly bound by clays and other inorganic and organic particulates and is also absorbed by submersed vegetation (Simsiman and Chester 1975, Simsiman et al. 1976, Murphy and Barrett 1993, Ahrens 1994, Ritter et al. 2000). Inorganic turbidity and high conductivity can have a negative impact on diquat efficacy (Murphy and Barrett 1993, Hofstra et al. 2001, Poovey and Getsinger 2002). However in Battle Ground Lake turbidity was less than 1 NTU (Table 2) and total suspended solids were below detection limits during and just after the time of treatment. The specific conductance was also low (about 16 µS/cm) and Secchi depth was between 4 to 5 m on the day of treatment and for three days after treatment. These data indicate that particles or ions suspended in the water column probably had little impact on the amount of herbicide available for uptake by the macrophytes. Using computer simulations, Ritter et al. (2000) predicted the highest concentration of diquat would occur one hour after treatment and decline rapidly afterwards. We did not collect samples for diquat analysis until four hours after treatment, and some of the herbicide may have already been absorbed by plants, broken down by sunlight, or adsorbed to sediments.

In Battle Ground Lake the highest diquat concentrations were measured in the untreated areas (S3 and S4) 1 and 2 DAT (Table 1). In a study on two western Washington lakes using the same diquat formulation and application technique, Serdar (1997) also found that diquat drifted off the application site within 1 DAT and concentrations were highest 1 to 2 DAT. This is counter to the computer simulations

TABLE 1. DIQUAT CONCENTRATIONS IN WATER SAMPLES (PPB) PRETREATMENT (PRE) AND 4 HOURS AFTER TREATMENT (HAT) AND 1, 2, 3, 7 AND 14 DAYS AFTER TREATMENT (DAT).

Station	Depth (m)	Diquat concentration (ppb)						
		Pre	4 HAT	1 DAT	2 DAT	3 DAT	7 DAT	14 DAT
S1	1	ND	89.7 (1.5 m)	19.9	21.7	43.8	14.9	ND
	3	ND	0.8*	2.9	0.6*	6.2	11.1	4.1
S2	2	ND	80.2	26.0	11.1	42.1	9.0	2.6
	5	ND	0.7*	0.7*	ND	0.9*	ND	ND
S3	2	ND	ND	115.9	32.6	35.9	1.6*	10.4
	9	ND	ND	1.1*	0.7*	0.5*	ND	ND
S4	2	ND	ND	126.9	157.9	38.0	ND	5.0
	9	ND	ND	1.2*	1.7*	0.5*	ND	ND

ND—Not detected above the Method Detection Limit (MDL) of 0.14 ppb.

*Estimated concentration that is below the instrument calibration range but above the MDL.

TABLE 2. SUMMARY OF SELECTED WATER QUALITY DATA FROM THE EPILIMNION OF BATTLE GROUND LAKE (HERBICIDE TREATMENT TOOK PLACE JUNE 16, 2003).

Date	Mean oxygen concentration (mg/l)	Mean oxygen saturation (%)	Mean water temperature °C	Secchi depth (m)	Turbidity (NTU)	Mean specific conductance (µS/cm)
5/27/2003	8.6	90.0	16.8	5.0	0.8	15.8
6/16/2003	8.3	92.1	19.5	4.6	0.7	16.1
6/23/2003	7.9	85.3	18.6	3.8	0.9	16.7
6/30/2003	7.0	80.7	21.9	3.8	1.6	17.8
7/28/2003	7.4	90.8	24.8	2.1	1.7	16.8
8/25/2003	7.5	87.2	22.1	5.2	0.5	17.5
9/29/2003	7.2	83.6	19.3	6.2	0.2	17.4
10/27/2003	6.5	68.9	15.2	7.0	0.5	16.7

of Ritter (2000), which predicted very low diquat concentrations outside the treatment area. High diquat concentrations 1 to 2 DAT may have been due to the low turbidity and conductivity providing few opportunities for herbicide adsorption. It is noteworthy that diquat persisted in the water at levels above the EPA drinking water standard of 20 ppb for at least 3 DAT. This suggests that the current 3-day drinking water restriction is not sufficient under all application scenarios. Diquat was not detected in either the before treatment or 1 DAT sediment sample.

Data from this study, combined with additional water quality data collected through the summer by Clark County, show evidence of impacts caused by the plant die-off. The dissolved oxygen percent saturation in the epilimnion declined by about 10% 1 to 2 WAT (Table 2), then returned to pre-treatment saturation in mid-summer before declining in the fall. Also Secchi depth was reduced in July compared with other months, potentially due to algae taking advantage of nutrients released by the decaying macrophytes.

Aquatic Plants

Submersed and floating species found in Battle Ground Lake are listed in Table 3. Compared with other lakes in southwest Washington, Battle Ground Lake had a very limited number of submersed species, both before and after the treatment (Parsons 2006). One species, water purslane (*Ludwigia palustris* (L.) Ell.) was present (though uncommon) in the lake prior to treatment and was not observed again until after the study's conclusion in 2006.

The diquat significantly reduced both the frequency and biomass of egeria in Battle Ground Lake for at least 2 YAT (Tables 4 and 5). This reduction was in spite of an apparently short exposure time since four hours after treatment the her-

bicide concentration in the treatment area was approximately 23% of maximum label rate. In a recent study, greater than 90% control of egeria was attained with diquat at 185 ppb at a 4.5-hr half-life in mesocosms (Skogerboe et al. 2006). Lower effective rates are also suggested by Glomski et al. (2005), who achieved 96 to 100% control of American elodea (*Elodea canadensis* Rich.) at 90 ppb of diquat for a 4-hour exposure time; and other studies have found egeria to be more susceptible to diquat than American elodea (Berry and Schreck 1975, Tanner et al. 1990).

The egeria was beginning to recover throughout the littoral zone 2 YAT, in spite of one day of diver hand pulling in the summer 2004 to try to reduce the population. This is consistent with other studies that have found that egeria recovers unless additional control methods are used (Blackburn et al. 1976, Martins et al. 2005). In June 2005, the Parks and Recreation Commission added 100 triploid grass carp to Battle Ground Lake to control the recovering egeria.

The biomass of all plants combined decreased significantly (Table 5) and the frequency of samples where no plants were collected increased significantly post-treatment (Table 4). This is due to Battle Ground Lake having had a very limited native submersed plant community prior to treatment. Those species that were present have been slow to move into habitat opened up by the reduction of egeria. The frequency and biomass of the macroalgae stonewort was significantly higher 2 YAT compared to before treatment (Tables 4 and 5). An increase of macroalgae was noted in another study following diquat treatment (Tanner et al. 1990), suggesting it is tolerant of this herbicide. Although diquat has been shown to control water moss (PMIS 2003), in this study the biomass did not change significantly after treatment and the frequency increased significantly 1 and 2 YAT, indicating no detrimental impact from the herbicide at the concentrations used.

TABLE 3. AQUATIC PLANT SPECIES IN BATTLE GROUND LAKE AND DATES THEY WERE OBSERVED.

Scientific name	Common name	May 2003	Aug 2003	May 2004	June 2005
<i>Chara</i> sp. Valliant	Muskwort			✓	
<i>Egeria densa</i> Planch.	Egeria	✓	✓	✓	✓
<i>Fontinalis antipyretica</i> L.	Water Moss	✓	✓	✓	✓
<i>Ludwigia palustris</i> (L.) Ell.	Water Purslane	✓			
<i>Nitella</i> sp.	Stonewort	✓	✓	✓	✓
<i>Nymphaea odorata</i> Ait.	Fragrant waterlily	✓	✓	✓	✓
<i>Polygonum persicaria</i> L.	Spotted ladythumb	✓	✓	✓	✓
<i>Sparganium</i> sp.	Bur-reed	✓			✓

TABLE 4. FREQUENCY DATA CHI SQUARE ANALYSIS RESULTS, NUMBERS ARE THE PERCENT OF POINTS WHERE THE PLANT WAS FOUND.

Plant	% of samples with species present			
	May 2003	Aug 2003	May 2004	June 2005
Egeria	57	13*	1*	9*
Water moss	14	23	26*	34*
No plants	29	65*	67*	48*
Stonewort	4	1	8	19*

*Significantly different from pretreatment frequency (May 2003). Significance level corrected for multiple comparisons is $p < 0.017$.

TABLE 5. MEAN BIOMASS WITH STANDARD DEVIATION IN PARENTHESES AND ANOVA RESULTS FROM COMMON SUBMERSED SPECIES.

Plant name	Biomass (g/m ²)			
	May 2003	Aug 2003	May 2004	Jun 2005
Egeria	82.15 (109.52)	0.93 (2.26)*	0.003 (0.02)*	4.67 (14.49)*
Water moss	3.79 (15.16)	2.62 (10.01)	8.91 (24.90)	8.00 (37.41)
Stonewort	0	0	0.01 (0.06)	0.26 (0.59)*
Total of all plants	87.12 (107.09)	3.55 (10.11)*	8.92 (24.94)*	12.95 (39.20)*

*Significantly different from pretreatment biomass (May 2003) at $p \leq 0.05$.

In conclusion, the herbicide diquat provided control of egeria for 2 YAT at low herbicide concentration and exposure times. This illustrates the sensitivity of this species to diquat. Native plant species in Battle Ground Lake were not adversely affected by the treatment, and increased in areas where egeria had been eliminated. The herbicide persisted in the lake at levels higher than the drinking water standard for at least 3 days, perhaps a result from the low conductivity and turbidity of Battle Ground Lake. Thus the 3-day drinking water restriction set by the herbicide label may not be sufficient in all lake situations.

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