Results from an assessment of the Asian clam (Corbicula fluminea) treatment project in Emerald Bay, Lake Tahoe, California

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Principal Investigators: Allison Gamble, Sudeep Chandra, John Reuter, and Geoffrey Schladow

Report Prepared By: Zachary P. Hymanson and Katie J. Webb

University of California Davis, Tahoe Environmental Research Center
291 Country Club Drive, Suite 320
Incline Village, NV 89451

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I. Introduction

The Asian clam (*Corbicula fluminea*) is identified as an aquatic invasive species that is well established in Lake Tahoe (TRPA 2014, Wittmann 2015). First recorded in Lake Tahoe in 2002, Asian clam densities of up to 5,000 individuals-m^{-2} have since been reported, and its range has expanded substantially throughout much of the Lake's southeastern area (Wittmann et al. 2012; Wittmann et al. 2015). The Asian clam often dominates the benthos where it occurs in Lake Tahoe (Wittmann et al. 2015). It is associated, but not necessarily the cause of, filamentous algal blooms (Forest et al. 2012), and deposition of clam shells in the nearshore is considered a degradation of aesthetic conditions in Lake Tahoe (TRPA 2014).

Emerald Bay is a special management area, and there is strong interest from resource and regulatory agencies in preserving its natural character. The clam population discovered in 2009 was considered localized in extent, and of low density; thus, it was thought to have the potential for treatment in its entirety (Zabaglo 2015). However, the special designations of Lake Tahoe and Emerald Bay limit the methods available to control clam populations to mechanical treatments (Wittmann et al. 2015). In 2010, Agency personnel decided to pursue a large-scale clam control project in Emerald Bay using benthic barriers supplemented with organic material. Implementation of this project occurred between 2012 and 2014 (Zabaglo 2015).

Benthic barrier and organic material deployment (and in-progress redeployment) to treat the Asian clam population in Emerald Bay occurred under the direction of agency personnel (Zabaglo 2015). Science investigations associated with benthic barrier deployment occurred under the direction of University of California, Davis (UCD), and University of Nevada, Reno (UNR) personnel, and focused on:

(1) Assessing the effects of a large-scale benthic barrier deployment on the Asian clam population in Emerald Bay. Results of this assessment are reported in Appendix A.
(2) Investigating how dissolved oxygen, nutrients, and food supply may influence the survival, and reproduction of the Emerald Bay clam population under the barrier treatments. Results from dissolved oxygen and nutrient investigations are reported in Appendix B. Results from food supply investigations are reported in Appendix A.
(3) Determining whether augmenting benthic barriers with organic material can further influence the survival or reproduction of the Emerald Bay Asian clam population. Results of this assessment are reported in Appendix B.

This document presents key findings from the investigations described in Appendixes A and B, with the aim of answering the question of how to optimize the effectiveness of benthic barriers to treat the Asian clam population in Emerald Bay.

I. Study Site

Emerald Bay is a small natural embayment in the southwest corner of Lake Tahoe (Figure 1). From a physical perspective it is essentially a small, shallow (less than 50 m) lake connected to Lake Tahoe by a 70-m wide and 3-m deep channel over the remnants of a glacial moraine or sill (Gardner et al. 2000) that eventually filled with water to form Emerald Bay.

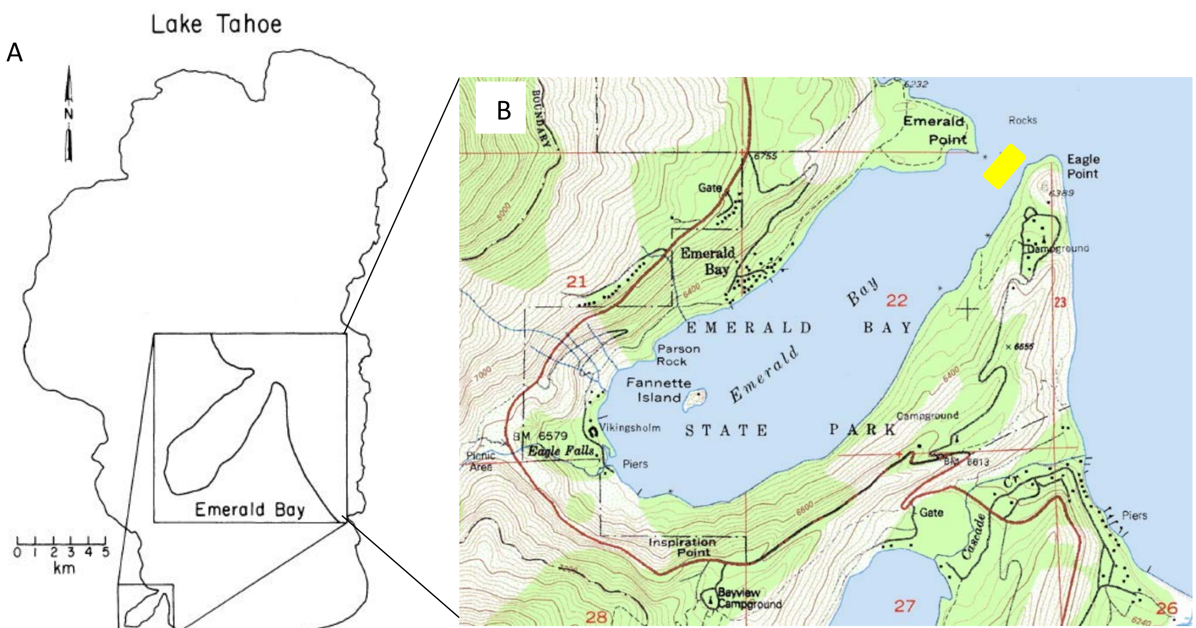

Figure 1. Location of (A) Emerald Bay in Lake Tahoe and (B) a topographic image of Emerald Bay showing the approximate location of the Asian clam control project (yellow rectangle).

Emerald Bay is part of the California State Park system and is a hallmark attraction for those visiting the Lake Tahoe basin. Emerald Bay was designated a National Natural Landmark by the National Park Service in 1968; a designation that recognizes unique biological and geological resources selected for their outstanding condition, illustrative value, rarity, diversity, and value to science and education (NPS 2014). The California portion of Lake Tahoe (including Emerald Bay) is designated an Outstanding National Resource Water under the Federal Clean Water Act, which affords special protection to areas of exceptional water quality, recreational, and ecological significance. These special designations underscore the unique character of Emerald Bay, and heighten the concern over impacts associated with the relatively recent establishment of several aquatic invasive species.

A satellite population of Asian clam was first detected in Emerald Bay in 2009, and continued to increase in extent through 2011 (D. Shaw, pers. comm.; Figure 2), although densities were low (1-100 individuals-m^2) compared to other locations in Lake Tahoe (A. Gamble, unpubl. data) .

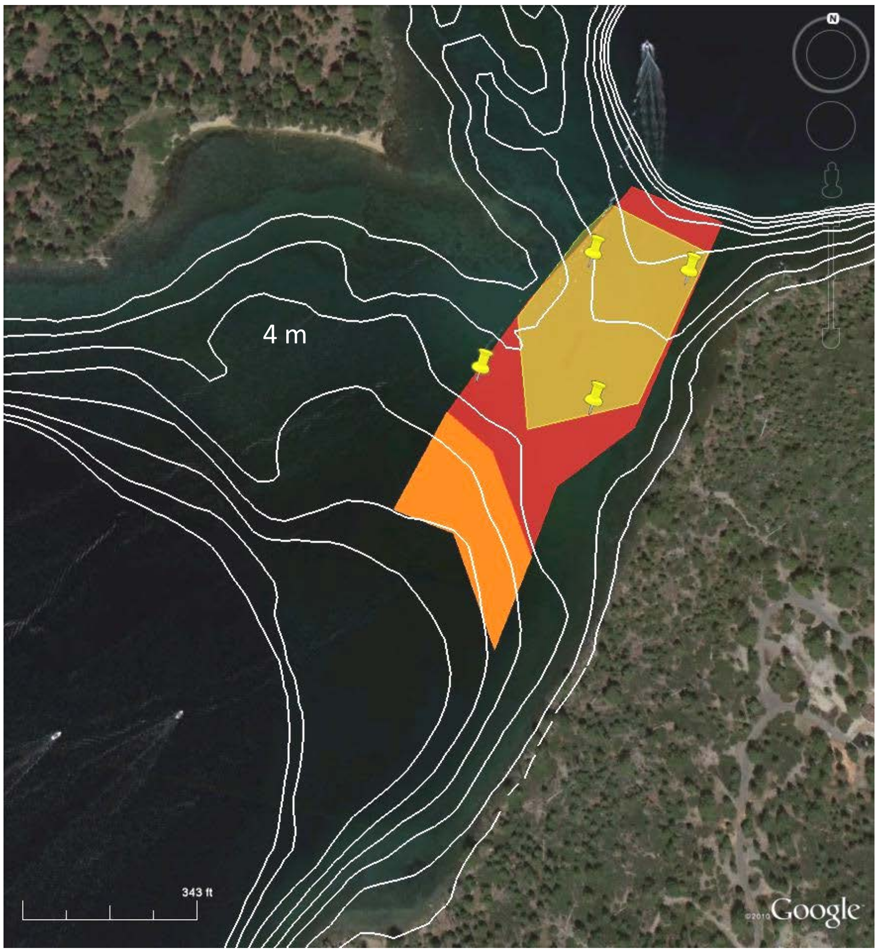

Figure 2. Asian clam infestation area at the entrance channel of Emerald Bay. The ochre polygon represents the extent of live clams in 2009 (~3.5 acres). The red polygon represents the increased extent of live clams in 2011 (combined area of ~5.5 acres). The orange polygon represents where dead clams only were found in 2011 (~1.5 acres). The yellow tacks represent the approximate locations of the channel navigation buoys. White lines represent bathymetric contours (1 m intervals) of the entrance channel and surrounding area, collectively referred to as the sill.

II. Benthic Barrier Deployment

Agency personnel oversaw benthic barrier deployment in Emerald Bay throughout the duration of the project. Here we present a summary of the deployment, and its relationship to the contemporaneous science investigations. See Zabalgo 2015 for more details about the benthic barrier deployment.

In 2012, approximately 5 acres (20,234 m^2) of Curlex™ NetFree (biodegradable organic aspen material[1]; and EPDM benthic barriers (ethylene propylene diene monomer rubber pond liner sheets) were installed over the sill of Emerald Bay at water depths of 3 m – 10 m (Figure 3). Preliminary experiments using small (10 ft x 10 ft trial barriers and laboratory investigations indicated elevated rates of biological oxygen demand in the presence of biomass.

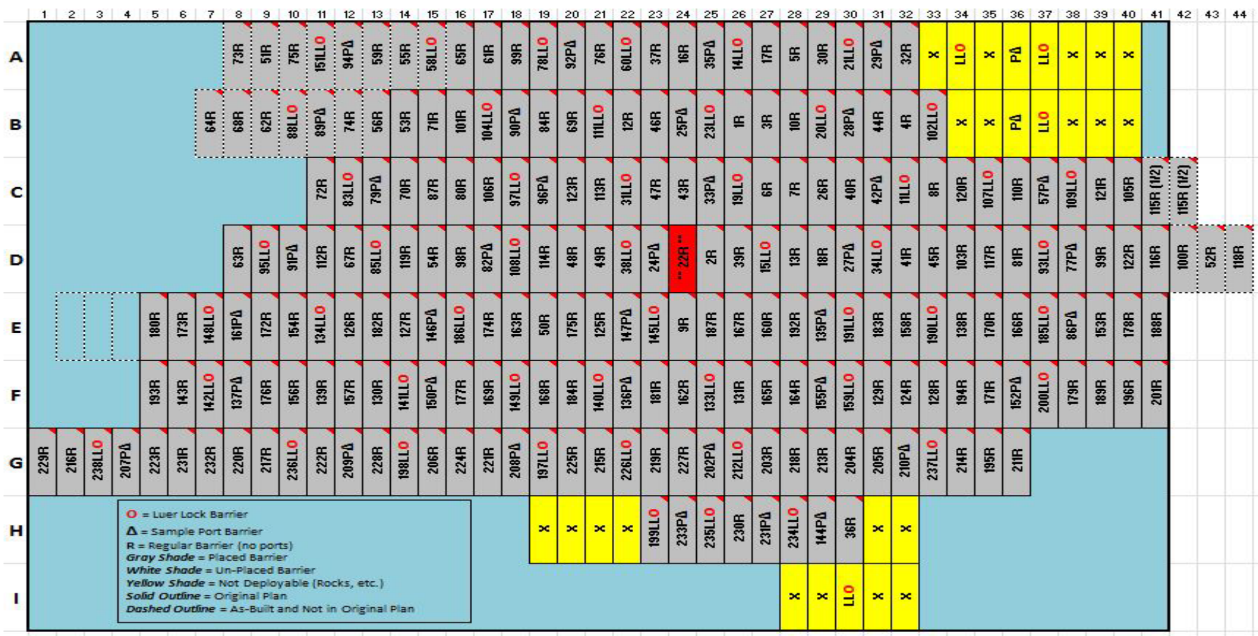

Figure 3. Diagram of benthic barrier deployment within the sill area of Emerald Bay, and the location of various sampling points. Yellow rectangles denote locations where barriers were not deployed due to the presence of boulders or other obstacles. Figure from Zabaglo 2015.

Benthic Barrier installation involved lowering rolls of individual EPDM barrier sheets (3 m x 30 m), and rolls of Curlex™ (2.4 m x 27.4 m) from a barge to the bottom of Emerald Bay. These materials were unrolled underwater and secured *in-situ* by a SCUBA diving contractor. Divers unrolled the Curlex™ material over the sediment first, and then applied a sheet of EPDM over the top (Figure 4). Rebar rods (~1.6 cm diameter) were placed along the benthic barrier seams (~15 cm overlap), and around the periphery of the deployment area. The rebar was intended to prevent barrier movement, and to preclude water exchange around the edges. Full benthic barrier deployment covered areas in the Emerald Bay sill identified to have live clams in the 2011 surveys (Figure 2).

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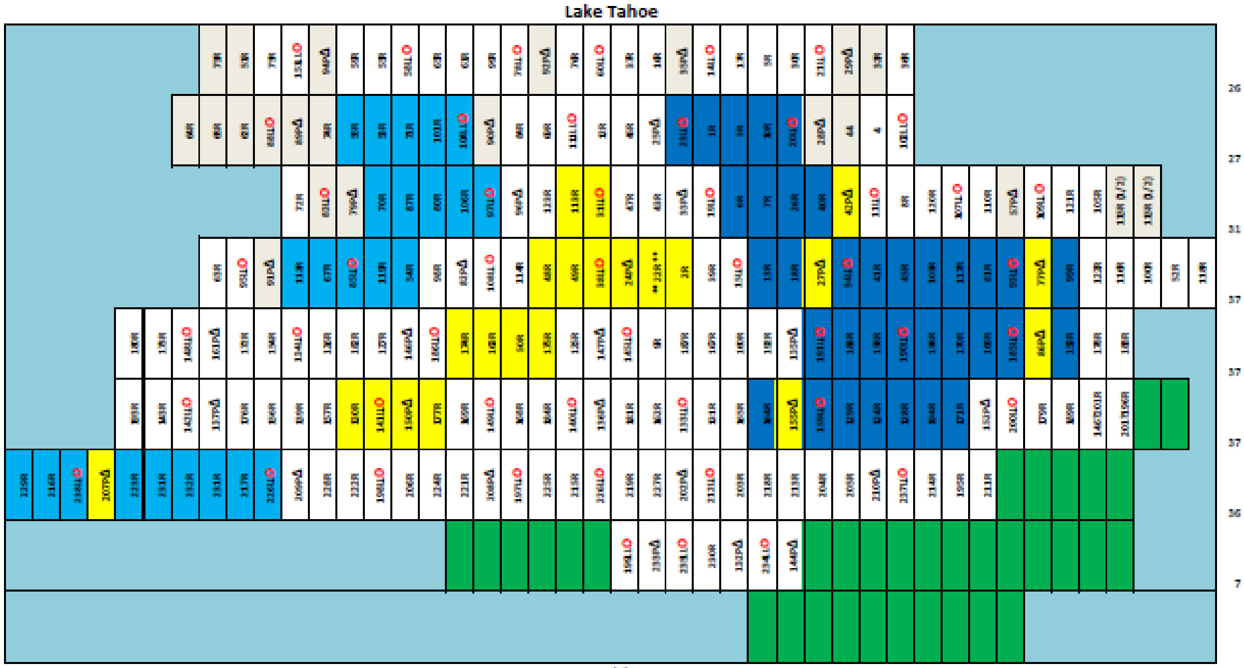
[1] More information about Curlex™ is available at http://www.americanexcelsior.com/erosioncontrol/products/netfree.php

Figure 4. SCUBA diver installation of Curlex (light material in foreground) and EPDM benthic barrier (dark material behind divers) over the sill of Emerald Bay. Photo from Zabaglo 2015.

The deployment site was inspected monthly by UC Davis to alert agencies to any movement of the benthic barriers, or compromises in the integrity of the overlapping seams. Some benthic barriers were retrofitted with luer locks (n = 50, Figure 2) to allow for diver collection of water samples from underneath the barriers. Other barriers had portals (n = 37, Figure 2) measuring 0.75 m x 0.75 m to allow diver access for collection of benthic samples from under the barriers. A 1-m^2 cover was constructed for each portal using rebar as a frame and EPDM material as a cover. Portals also were used for the deployment of dissolved oxygen sensors.

The benthic barriers were in place for approximately 700 days (December 2012 – November 2014). However, numerous benthic barriers were disturbed over the course of the deployment period, some on multiple occasions. These disturbances were due to surface water currents (see physical processes section above) and human activities (Zabaglo 2015). While only a small number of barriers were compromised at the beginning of the deployment, by October 2013 sixty-nine barriers had lost integrity with the bottom at least once during the deployment necessitating substantive repairs by the dive team. Fifteen centrally located barriers had lost integrity with the bottom three times, and eleven barriers lost integrity twice. Barrier disturbance was most often observed in the center of the boating channel. The Curlex™ material also was disturbed in several locations (Figure 5). Further, some benthic barriers were relocated part-way through the deployment period to cover clam infestation areas that were previously untreated. This resulted in a complex barrier deployment pattern (Figure 6).

Figure 5. Underwater photo showing disturbed benthic barriers (black material) and Curlex™ on the sill of Emerald Bay. The lighter-colored, Curlex™ material is mostly piled on top of the benthic barriers. Exposed open sandy bottom is also visible.



Mat Key	Description	Treatment Duration (months)
	Mats in place from installation. Mats were removed in November 2014.	24
	Mats relocated in July 2014 from areas highlighted in due to damage. Original mats were in place from installation. Mats were removed in November 2014	24
	Mats in place from installation and relocated in July 2014 to areas highlighted in	19
	Mats in place from installation and relocated to areas highlighted in in July 2014.	19
	Mats inplace from installation and removed due to damage in July 2014.	19
	Mats relocated from areas highlighted in Mats were relocated here in July 2014.	5

Figure 6. Schematic showing the benthic barrier deployment pattern and the duration of deployment for different barriers. Figure from Zabaglo 2015.

The intentional and unintentional disturbance of the benthic barriers confounded water quality data evaluations. This outcome combined with the heterogeneity of the bottom substrate led us to delineate three treatment categories (Figure 7):

(1) Undisturbed benthic barriers covering substrate with reduced permeability: These barriers were located on the lakeside of the deployment area, and generally maintained good integrity with the bottom throughout the deployment period. These barriers were deployed over substrate estimated to have reduced permeability compared to substrate in other areas of the sill.

(2) Undisturbed benthic barriers covering substrate with enhanced permeability: These barriers were located on the bay side of the deployment area, and generally maintained good integrity with the bottom throughout the deployment period. These barriers were deployed over substrate estimated to have enhanced permeability compared to substrate in other areas of the sill.

(3) Disturbed barriers: These barriers were observed to have lost integrity with the bottom multiple (>2) times throughout the deployment period. The duration of integrity loss varied among disturbed barriers, depending on the repair response time. These barriers may have been deployed over substrate of enhanced or reduced permeability.

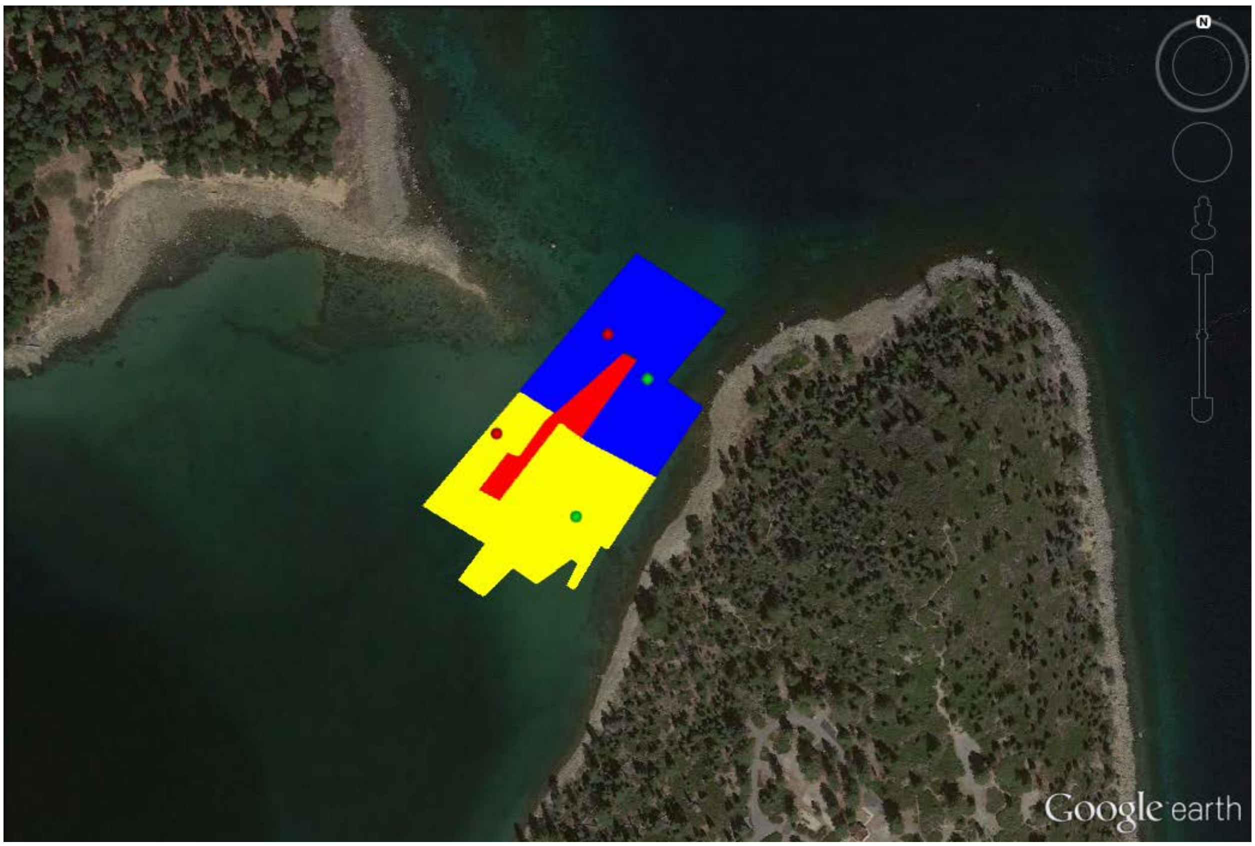


Figure 7. Aerial image of the Emerald Bay sill area with color polygons showing the approximate location of the three benthic barrier treatment categories. The blue polygon defines the approximate area of undisturbed benthic barriers over substrate with reduced permeability. The yellow polygon defines the approximate area of undisturbed benthic barriers over substrate with enhanced permeability. The red polygon defines the approximate area of disturbed benthic barriers. The red and green dots represent the approximate locations of the channel navigation buoys. See Figure 10 for the locations of intentionally moved benthic barriers.

These three benthic barrier treatment categories are used in the presentation and interpretation of water quality data.

III. Optimizing Benthic Barrier Effectiveness in Emerald Bay

Conclusions from the physicochemical and Asian clam studies identify the major points to consider in optimizing benthic barrier effectiveness for treating Asian clams in Emerald Bay.

A. Conclusions from the Physicochemical Studies

- The sill in Emerald Bay is a dynamic and variable physical environment. Two-way water motion across the sill and through the sill is driven by baroclinic (water temperature) and barotropic (wind) forces. Water motion and substrate permeability affected both the integrity of the benthic barriers, and the ability to establish and maintain hypoxic conditions underneath the barriers. Details from the investigation of water motion are provided in Appendix C.
- Changes in nutrient concentrations underneath the benthic barriers were limited, and nutrient concentrations underneath the barriers rarely differed significantly from the ambient control. This is likely due to the low densities of benthic infauna (including Asian clams) occurring throughout the Emerald Bay sill. We think the deployment of Curlex™ below the benthic barriers as an augmentation of organic material had little effect on *in situ* nutrient concentrations.
- Taken together, results from the monitoring of DO saturation and water temperature suggest:
    - A subset of the benthic barriers deployed in Emerald Bay (i.e., undisturbed barriers covering substrate with reduced permeability) was able to achieve sustained hypoxia, as well as shorter periods of anoxia in the summer. Hypoxic conditions also occurred under undisturbed barriers covering substrate with enhanced permeability, and disturbed barriers; however, both the magnitude and duration of these conditions were reduced compared to the undisturbed barriers over substrate of reduced permeability. Anoxic conditions under undisturbed barriers covering substrate with enhanced permeability, and disturbed barriers also were reduced in frequency and duration.
    - The June – October period when water temperatures are $\geq$ 10°C is the most effective time to kill Asian clams in Emerald Bay using benthic barriers to induce hypoxic conditions.
    - Substrate permeability and the resulting potential for hyporheic flows affected the ability of the benthic barriers to induce hypoxic conditions. Substrate permeability must be considered in developing expectations

for the performance of benthic barriers, particularly in areas such as sills where variations in bottom slope are pronounced.

- o The benthic barriers demonstrated the ability to perform well as a physical barrier over nearly two years of deployment. However, more work is needed to develop improved anchoring methods, particularly where dynamic physical conditions predominate, and rapid response to barrier movement is not always possible.
- o Changes in DO saturation levels under the benthic barriers could not be attributed to the addition of Curlex™. However, it is unknown if this amendment of organic material either produced little to no measurable effect on biochemical oxygen demand, or if the effect was overwhelmed by the effects of barrier integrity (i.e., disturbed vs. undisturbed) and substrate permeability.

B. Conclusions from the Asian Clam Studies

The large scale deployment of gas impermeable benthic barriers in Emerald Bay, Lake Tahoe significantly reduced the density and caused significant mortality in the population of Asian clams. However, complete eradication from the area was not achieved and is highly improbable. The data suggest that the stress caused from the benthic barriers forced clams to put less energy into reproduction and more into survival and metabolism. Finally, the presence of benthic barriers did not affect the sediment carbon content. These results suggest that gas impermeable barriers can be used to control for Asian clams, however many variables, such as upwelling, wave action, and temperature contribute to the success of these barriers.

C. Integrated Finding and Recommendations

Reanalysis of the data presented in Appendix A, Figure 4 shows that Asian clam mortality during the summer period was significantly greater under the three barrier treatment categories, compared to clam mortality at the control site (Kruskal-Wallis nonparametric analysis of variance; $H = 12.158$, $p < 0.01$; Figure 8). Clam mortality during the winter period was not significantly different. Clam mortality rates during the summer period were the highest and very similar under the two undisturbed barrier treatments (reduced and enhanced permeability), while lower levels of clam mortality occurred under the disturbed barriers.

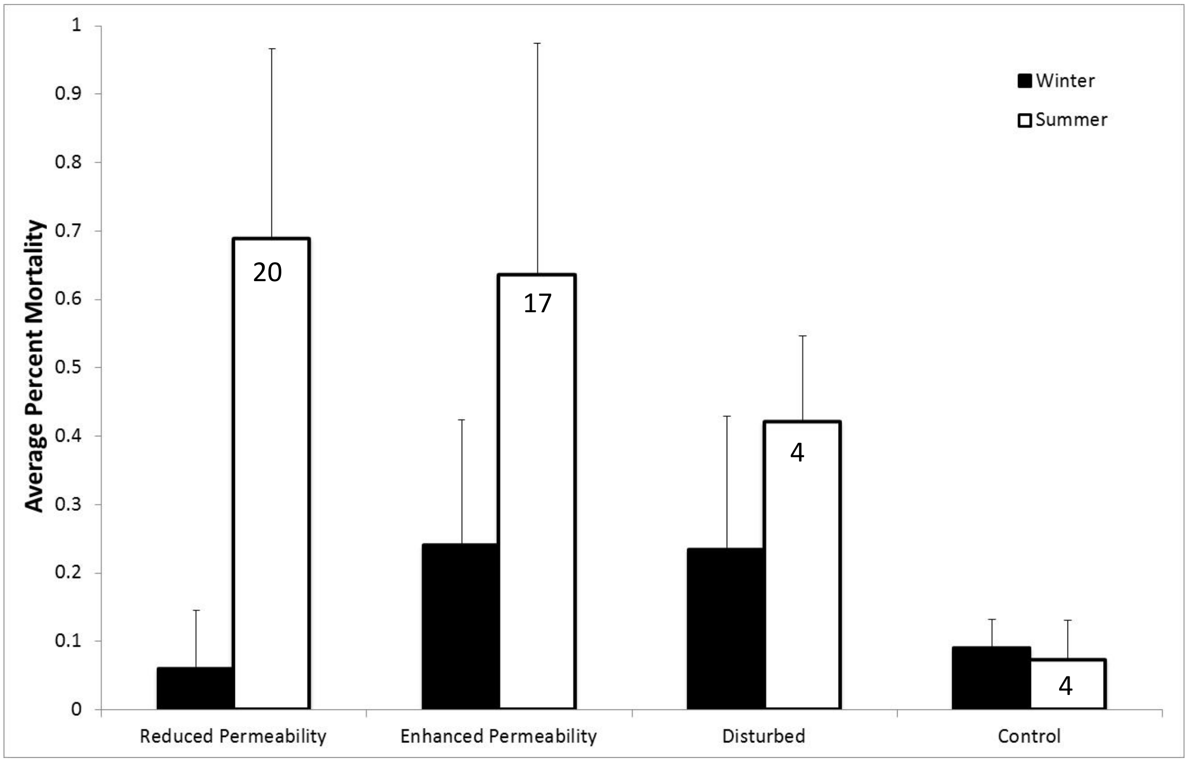


Figure 8. Average percent Asian clam mortality during the winter and summer periods in samples taken from the control site, and in samples taken from the three benthic barrier treatment categories: undisturbed barriers over substrate of reduced permeability, undisturbed barriers over substrate of enhanced permeability, and disturbed barriers. Numbers at the top of the summer values indicate the sample sizes. Vertical error bars are one standard deviation.

It seems reasonable to expect that the future treatment of Asian clams in the sill area of Emerald Bay using benthic barriers would attain average clam mortality rates of between 45% and 70% during the summer period, with short-duration mortality rates exceeding 90%. Duration times of heightened mortality would likely increase with improved barrier integrity as discussed above. It may be appropriate to extend benthic barrier treatment into the winter period for logistical reasons, but the contributions to overall clam mortality during this period are insufficient to justify targeted treatment.

The addition of an organic amendment is considered unnecessary to attain clam mortality in Emerald Bay. Excluding an amendment may help to both reduce costs and to optimize barrier performance by reducing the potential for water motion disturbance; thus reducing the variability in water quality.

It may be possible to obtain higher levels of clam mortality overall by combining the use of benthic barriers with other physical treatment techniques. Pursuing an integrated treatment strategy incorporating multiple techniques represents a fruitful area for further testing.

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Personal Communications:

Daniel Shaw, CA State Parks and Recreation, Sierra District, Tahoma, CA. Contacted on May 12, 2014.