# Risk Assessment and Response Plan for Zebra Mussels (*Dreissena polymorpha*) and Quagga Mussels (*Dreissena bugensis*) in Lake Elsinore and Canyon Lake

DRAFT FINAL REPORT

*Submitted to:*
Lake Elsinore & San Jacinto Watersheds Authority
Riverside, CA 92503

*Submitted by:*
Michael A. Anderson
Riverside, CA 92504

19 January 2010

## Table of Contents

## List of Figures

## List of Tables

# EXECUTIVE SUMMARY

Section 2302 of the California Fish and Game Code requires any district or authority that owns or manages a reservoir where public recreational, boating or fishing activities are permitted to (i) assess the vulnerability of the reservoir to infestation by dreissenid mussels, and (ii) develop and implement a program to prevent the introduction of dreissenid mussels that includes public education, monitoring and management of the recreational activities. Waters not open to the public must include visual monitoring for the presence of mussels, while water supply systems must implement measures to avoid infestation, and control or eradicate any infestation that may occur. This report was developed to assess the vulnerability of Lake Elsinore and Canyon Lake to infestation by *Dreissena spp.*, including their potential distribution in the lakes, and to review recent information about introduction, dispersal, prevention, and eradication and control methods. Results from preliminary monitoring at the lakes are also presented.

Water column conditions in Lake Elsinore and Canyon Lake are generally suitable for *Dreissena spp.* growth and reproduction, although low dissolved oxygen (DO) concentrations are likely to inhibit colonization of deeper regions of these lakes. This is particularly true for Canyon Lake, where under current management activities, the strongly anoxic hypolimnion with high $NH_3$ and $H_2S$ concentrations would exclude dressenid mussels from the deepest 60% of the lake area. Anoxic bottom sediments in Lake Elsinore, previously found to cover 50-70% of the lake area, would also limit the spatial extent of invasive mussels to shallower regions of the lake. Operation of the recently installed diffused aeration system will potentially expand the range of mussels in the lake, however. In a similar way, installation of an aeration or oxygenation system in Canyon Lake would also potentially expand the range of dreissenid mussels there, although the fine uncohesive organic sediments in the deepest parts of these lake are also expected to inhibit successful colonization.

Lake Elsinore, with its high level of public recreational boating activity, is at significant risk of introduction of mussels, while Canyon Lake is thought to be at a somewhat lower risk level owing to access restrictions and the smaller number of boats brought in from outside the community. Both lakes are also susceptible to introductions from upstream locations during periods of flow in the San Jacinto River, although neither lake was found to have veligers, juveniles or adult mussels based upon sampling conducted in October-November 2009. Comprehensive Level 3 inspection programs following Zook and Phillips (2009) are recommended, with screening interviews at the point of entry; a comprehensive watercraft/equipment inspection performed by trained inspectors of all high risk watercraft/equipment; decontamination and/or quarantine or exclusion of suspect watercraft, and possible vessel certification.

# 1. BIOLOGICAL ASSESSMENT

## 1.1 Introduction

Since the first reported siting of zebra mussels (*Dreissena polymorpha*) in Lake St. Clair in June 1988, this non-native mussel and the closely related quagga mussel (*Dreissena bugensis*) have spread rapidly through much of the U.S. Their very high filtering and reproductive rates have led to significant economic and ecological impacts throughout the midwestern U.S. and more recently here in the southwestern U.S. The purpose of this section is to provide a review of available published and unpublished information concerning the dreissenid species (specifically the quagga mussel) threatening the lakes, reservoirs and conveyances of Southern California.

## 1.2 Invasive Mussels in the Western U.S.

Quagga mussels were first identified in Lake Mead in January 2007, and were subsequently identified in Lake Mohave and Lake Havasu. They have now been identified in 19 lakes in California, 7 lakes in Colorado, 1 lake in Nevada, and 3 lakes in Arizona (USGS, 2009). Zebra mussels have, to this point, been found only in 1 lake in California (San Justo Lake, San Benito County, January 2008).

## 1.3 Ecology and Life-History of Dreissenid Mussels

Both quagga and zebra mussels are so-called “r-strategists”, i.e., species having life-history characteristics promoting rapid population growth, r (Vanderploeg et al., 2002). They accomplish this rapid population growth through broadcast spawning of very large numbers of eggs and sperms, with an adult female capable of releasing a million eggs or more. There are some reports that a small portion (<4%) of the mussels in a population can be hermaphroditic (Nichols and Kollar, 1991). The eggs are thus externally fertilized, and develop within 6-96 h into a trochophore larva (stage 1, Fig. 1.1) that is 60-120 μm in size (Ackerman et al., 1994). The free swimming trochophore develops a velum, a larval organ for feeding and swimming, and the trochophore becomes a veliger, the planktonic larval stage. It is this planktonic larval stage that distinguishes *Dreissena spp.* from other freshwater bivalves, conserving this mode of reproduction as found in marine bivalves. Within 2-9 days post fertilization, the veliger larvae secrete an unadorned D-shaped $CaCO_3$ shell from shell glands (Ackerman et al., 1994). This early larval stage veliger is thus commonly referred to as the D-shaped veliger (stage 2, Fig. 1.1) that is generally 70-160 µm in height. Within 7-9 days post-fertilization, a second more ornamented shell is secreted from the mantle tissue. It has a more pronounced umbonal region near the hinges and is round or clam-like in profile. This umbonal veliger (stage 3) is somewhat larger in size (120-280 µm) and is the last free-swimming veliger stage routinely found in the plankton (Fig. 1.1). It is at this stage that new organ systems begin to develop. Of particular importance is the development of the foot that occurs after about 10 days post-fertilization. The umbonal veliger then becomes a pediveliger (167- 300+ µm) (stage 4) (Fig. 1.1), with the foot used for both swimming and moving over surfaces. The capability to crawl over surfaces distinguishes the pediveliger from the D-shaped and umbonal veligers that are planktonic. The pediveliger will then "settle" onto a suitable substrate and secrete a byssal thread onto the surface. This generally occurs 18-90 days post-fertilization (Ackerman, et al. 1994), and once anchored, the pediveliger will undergo metamorphosis to become a plantigrade mussel (>158-500 µm) (Fig. 1.1). These plantigrade or juvenile mussels can cut their byssal threads and relocate on the bottom by moving with their foot or in the water column to a more suitable location.

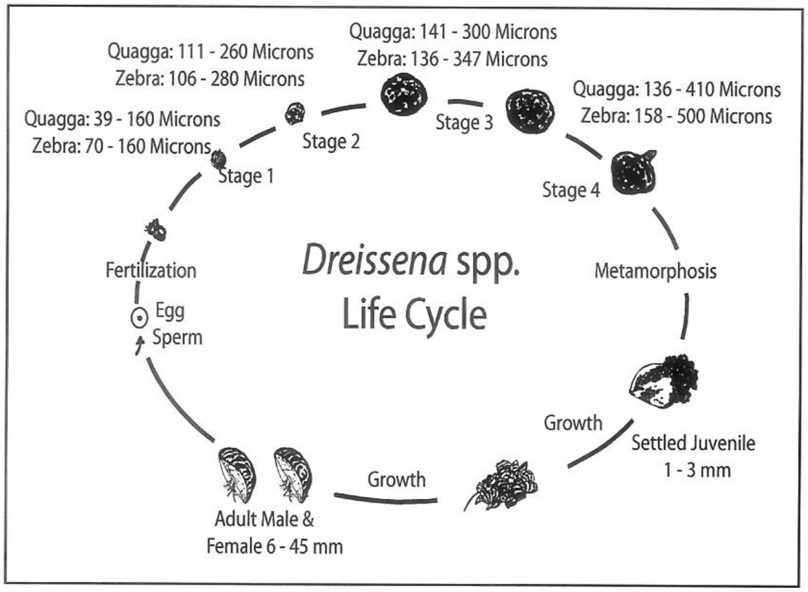


**Figure 1.** *Dreissena* spp. life cycle. Illustrated by Chris Webb, U.C. Cooperative Extension. Adapted from *http://www.fws.gov/Midwest/mussel/images/zebra_mussel_%20life_cycle.html*.

*Fig.1 1. Dreissenid mussel life history (from Culver et al., 2009).*

## 1.4 Water Column Conditions Necessary for Growth and Reproduction

The conditions necessary for growth and survival of mussels include a minimum calcium level to support shell formation and growth, and suitable pH, salinity, temperature, and dissolved oxygen (DO) levels. Calcium levels are generally considered to be the most critical water quality parameter controlling the potential distribution of mussels in North America (Cohen and Weistein, 2001). A wide range of $Ca^{2+}$ thresholds (from 12-28 mg $L^{-1}$) have been reported for zebra mussels however, while fewer studies have addressed this issue for quagga mussels.

Water temperature is another key parameter influencing survival, growth, and reproduction of dreissenid mussels. Maximum summer temperatures exceeding 30-32°C are generally thought to result in widespread mortality of mussels (Cohen, 2007). Zebra mussels appear to have a higher minimum temperature limit of 10-12 °C, while quagga mussels can survive at lower temperatures (5-6 °C). Cohen (2007) assumed the temperature range of 5 - 31°C for quagga mussels and 10-31°C for zebra mussels. Recent work on the Lower Colorado River and the Colorado River Aqueduct have found veligers present in these systems throughout the year. While some have proposed nearly continuous reproduction, populations measurements combined with size class information suggest lakes and reservoirs in the region are subject to 2-3 major spawning events each year, resulting in high abundances (often 50 veligers $L^{-1}$ or more) during the late spring and mid-late summer months (Anderson, unpubl. data). Much lower abundances (~1 veliger $L^{-1}$) are generally found through the winter. While it appears unlikely that spawning events are occurring in the winter, at least in these oligotrophic-mesotrophic waters, veligers can remain in the water column for a considerable period of time until suitable environmental conditions and substrates are present for settlement and maturation into reproductive adults.

The pH of a water body can also affect shell development; zebra mussels were absent in lakes with a pH below 7.3 in a survey of lakes in Europe (Ramcharan et al., 1992). A range in pH from 7.3 – 9.4 has been considered suitable for both zebra and quagga mussels (Cohen, 2007).

Salinity levels have also been found to constrain the distribution of mussels. The salinity tolerance is dependent upon temperature however, with higher salinity tolerance at cooler water temperatures. Upper threshold salinities of 6 ppt for zebra mussels and 4 ppt for quagga mussels were used by Cohen (2007). No lower level has been used, and is thus only limited by $Ca^{2+}$ concentrations. Since formation of a $CaCO_3$ shell begins shortly after fertilization following the trochophore stage, the availability of $Ca^{2+}$ can limit growth and reproduction of these invasive mussels. A study by Jones and Ricciardi (2005) noted that quagga mussels were present only at sites in the St. Lawrence River where $Ca^{2+}$ concentrations exceeded 12 mg $L^{-1}$. Since they are tolerant of a rather wide range of temperature, salinity and other conditions, dissolved $Ca^{2+}$ concentrations were recently used to estimate the potential distribution of invasive mussels in California (Cohen, 2007). Based upon that assessment, Cohen (2007) concluded that the soft-water lakes and rivers of the Sierra Nevada and in the North Coast region are likely to be safe from colonization by zebra and quagga mussels, although waters throughout much of southern California would be vulnerable to invasion.

Dissolved oxygen is another water quality parameter thought to control mussel survival, growth and reproduction. As aerobic organisms, they have a metabolic requirement for DO, although it appears they have adapted to suboxic conditions owing no doubt in part to their benthic habitat. DO concentrations <2 mg $L^{-1}$ have been reported to be lethal to zebra mussels, while quagga mussels appear to be slightly more tolerant of low DO concentrations (USFWS, 2007). DO concentrations were generally not limiting the range of quagga mussels in Cohen (2007), although anoxic hypolimnia are not suitable sites for adult mussel growth and reproduction (MWD, unpubl. data). This was clearly demonstrated in whole-lake manipulations conducted in the summer of 2008, in which the hypolimnia of two nearby reservoirs were allowed to go anoxic, resulting in mortality to adult mussels that were exposed for several weeks to low DO concentrations (near 1 mg $L^{-1}$).

Low DO concentrations are generally also associated with high $NH_3$ concentrations. $NH_3$ is known to be toxic to a wide range of organisms, including zooplankton and fish. Total $NH_3$ concentrations near 2 mg $L^{-1}$ and free $NH_3$ concentrations of about 0.05 mg $L^{-1}$ were found to limit colonization of zebra mussels in Onondaga Lake (Spada et al., 2002). Ironically, increased treatment at the wastewater treatment plant discharging to the lake in 1999 lowered $NH_3$ loading and triggered subsequent development of a dense zebra mussel population there (Spada et al., 2002). Hydrogen sulfide is another potential toxicant formed under low DO conditions, although thresholds for toxicity to invasive mussels do not appear to be available.

## 1.5 Susceptibility of Lake Elsinore and Canyon Lake to Invasion

The water column conditions identified above can be used to gauge the susceptibility of Lake Elsinore and Canyon Lake to invasion by dreissenid mussels.

### *Lake Elsinore*

Conditions in Lake Elsinore vary rather markedly depending upon interannual precipitation to the region. The lake is often relatively well-mixed vertically, with only modest variations in temperature with depth generally present. In a study conducted from July 2003 – June 2006, Lawson and Anderson (2007) found temperature differences between the lake bottom and 2 m below the surface to remain below 3ºC on all sample dates except one, with transient weak stratification through the summer (mean ΔT~0.5ºC) at low lake surface elevations (2003-2004), and slightly greater and more persistent summer temperature differences in 2005-2006 (mean ΔT~1.1ºC). Minimum lake temperatures near 10 ºC were present in December-January, while temperatures throughout most of the lake volume reached 26-27 ºC during the summer (Lawson and Anderson, 2007). Slightly warmer temperatures were found in the upper 1-2 m during the daytime. Thus, the temperature conditions in Lake Elsinore are well within the range suitable for quagga and zebra mussels (Table 1).

Table 1.1. Dreissenid mussel tolerance range and water column conditions in Lake Elsinore and Canyon Lake.

| **Property** | **Tolerance Range** | **Lake Elsinore** | **Canyon Lake** |
|---|---|---|---|
| Temperature (ºC) | 5 - 31 | 10 – 28 | 10-28 (stratification) |
| Salinity ( mg $L^{-1}$ TDS) | < 4,000 | 800 – 2,200 | 540 - 1100 |
| $Ca^{2+}$ ( mg $L^{-1}$) | > 12 | 12 – 45 | 60 - 100 |
| pH | 7.3 – 9.4 | 7.9 – 9.4 | 6.8 - 9.2 |
| DO ( mg $L^{-1}$) | > 2 | <0.1 – 18 | <0.1 - 14 |
| Total $NH_3$ ( mg $L^{-1}$) | < 2 | <0.04 - 2.1 | <0.04 - 3.2 |

Salinity levels in Lake Elsinore also vary strongly, depending upon when in the El Nino-drought cycle the region is in. The lake was in a severe drought from 1999-2004, such that the maximum lake depth had decreased to 4.5 m by the summer of 2004. Salinity at that time reached almost 2,200 mg $L^{-1}$ TDS. While this salinity level was shown to adversely affect zooplankton community structure and was also thought to impair fish reproduction, such a salinity is well within the salinity tolerance of the dreissenid mussels (Table 1). The near record rainfall in the winter of 2005 rapidly restored lake elevation (maximum depth increased to 10.5 m) (Lawson and Anderson, 2007), and reduced TDS values to about 800 mg $L^{-1}$ (Anderson, unpubl. data).

No minimum salinity is specified as a lower limit, except through the effect on dissolved $Ca^{2+}$. Dissolved $Ca^{2+}$ concentrations over this same time period varied from 12 – 45 mg L-1. As previously noted, Lake Elsinore has an unusual $Ca^{2+}$ geochemistry due to its Ca:$HCO_3$ ratio that is <1. As a result, evapoconcentration as occurs during extended periods of drought results in precipitation of $CaCO_3$ and the corresponding enrichment of the water column in $HCO_3^-$ and depletion of dissolved $Ca^{2+}$. Dissolved $Ca^{2+}$ levels thus reached a minimum of 12 mg $L^{-1}$ in the summer of 2004 (during the period of highest salinity), while runoff from the watershed the following winter diluted existing salinity but actually increased dissolved $Ca^{2+}$ concentrations in the lake to over 40 mg $L^{-1}$ (Anderson, unpubl. data). These concentrations nevertheless exceed the putative minimum $Ca^{2+}$ level needed for shell production and growth by zebra and quagga mussels (Table 1). As a result, $Ca^{2+}$ limitation, suggested for some lakes in California, is not expected for Lake Elsinore under most conditions.

pH levels in Lake Elsinore have also exhibited some variation, both interannually and, more substantially on a seasonal and even diurnal basis. High levels of algal productivity have yielded pH values exceeding 9, while turnover events have yielded lower pH values (<8) during field measurements conducted in 2002-2005. These values remain with the tolerance range for the mussels however, indicating no substantive pH constraints on growth (Table 1). More recent data from the YSI profiler at the Lakeshore Drive aeration system for the period January 1 – July 7, 2009 (downloaded from the EVMWD website) indicate a higher pH range. Data at the deepest sampling depth (5.5 m) ranged from 8.47-9.75 over this winter-early summer period. Almost 40% of the measurements exceeded the pH value of 9.4 used by Cohen (2007), although the influence of high pH on mussel growth is unclear, since $CaCO_3$ precipitation is actually significantly enhanced at higher pH values. On geochemical grounds, exceedances of pH 9.4 are not considered here to represent a meaningful constraint on metabolism or growth.

Dissolved oxygen concentrations exhibit the greatest vertical and seasonal differences. Volume-weighted DO concentrations in Lake Elsinore have exhibited regular seasonal trends, with levels near saturation (8-10 mg $L^{-1}$) during the winter months, and much lower concentrations in the summer (typically 2 – 4 mg $L^{-1}$) (Lawson and Anderson, 2007). DO concentrations near the surface of the lake were generally substantially higher than that above the sediments, with DO <1 mg $L^{-1}$ found over 50-70% of the lake area during at least part of each summer from 2003 – 2006 (Lawson and Anderson, 2007). The duration and extent of low DO concentrations above about two-thirds of the bottom sediments during this time period would be sufficient to inhibit colonization and successful growth of dreissenid mussels in Lake Elsinore. Since that time, a diffused aeration system has been installed at the lake. The system was installed in the summer of 2008, although operational challenges limited its use that year. The system was run more regularly in 2009, although the exact operational schedule is not known. YSI profilers were also installed as part of the control system; data from January 1 – July 7, 2009 were downloaded and the bottom measurement (at about 5.5 m depth) were extracted from the dataset. The January DO data was in error, but the February – June data were evaluated. Over this winter-early summer time period, 634 out of 2369 hourly measurements (26.8%) were <1 mg $L^{-1}$. It is not known whether the diffused aeration system was operational or not, nor the lateral extent of anoxic sediments, but it does appear that anoxic bottom sediments may be periodically present in Lake Elsinore. Somewhat paradoxically, maintenance of reasonable DO concentrations through successful operation of the diffused aeration system may make the lake more susceptible to invasion by quagga mussels than the conditions previously found at the lake.

Total $NH_3$ levels in Lake Elsinore have generally been somewhat higher than found in many lakes, but consistent with the eutrophic conditions present there. Total $NH_3$-N concentrations have ranged from <0.04 – 2.1 mg $L^{-1}$ earlier this decade. Based upon typical pH values near 8.2-8.4, free $NH_3$ would account for approximately 9-14% of total $NH_3$. Although total $NH_3$ concentrations would generally be below the range thought to inhibit mussel growth and reproduction, the concentrations of free $NH_3$ may occasionally exceed the assumed threshold value of 0.05 mg $L^{-1}$. This would be expected to be more common above the fine organic sediments with low DO concentrations and, with high $H_2S$ levels, potentially also helping to inhibit colonization in the deeper regions of the lake.

### *Canyon Lake*

Water temperatures near the surface of Canyon Lake are quite similar to those found in Lake Elsinore, with winter minimum values near 10 ºC and summer maximum values of about 28 ºC (Table 1) (Davis et al., 2005). Unlike Lake Elsinore however, the main basin of Canyon Lake stratifies in the summer, such that a cool hypolimnion near 12-14 ºC is present even when surface temperatures approach 30ºC. The shallower East Bay does not stratify except near the Causeway, and so exhibits thermal conditions similar to Lake Elsinore. Like Lake Elsinore, temperatures in Canyon Lake are not expected to inhibit quagga mussel growth and reproduction.

Salinities in Canyon Lake are consistently lower than found in Lake Elsinore (Table 1), owing to the regular flushing of Canyon Lake during moderate rainfall events in the watershed. Such salinities would not adversely affect mussel establishment in Canyon Lake. Dissolved $Ca^{2+}$ concentrations are higher than found in Lake Elsinore and also suitable for mussel growth and reproduction (Table 1).

The pH levels in Canyon Lake do vary strongly with depth. Generally high pH values consistent with waters in equilibrium with $CaCO_3$ and atmospheric $CO_2$ are present in the epiliminion (pH ~8.3), while lower pH values are found in the hypolimnion (pH ~7-7.5). The pH of the hypolimnion lies near or slightly below the lower stated pH range for dreissenid mussels, and thus may reduce their availability to secrete a $CaCO_3$ shell, although anoxic conditions in the hypolimnion are expected to more directly affect mussel viability and growth.

Specifically, while the epilimnion generally has abundant DO, the hypolimnion is absent of DO for most of the year (Davis et al., 2005). The lack of DO in the hypolimnion is thus expected to exclude mussels from colonizing much of the main basin of the lake (Table 1). High concentrations of total $NH_3$ (2-3 mg $L^{-1}$) and sulfide are also expected to exclude mussel growth within the hypolimnion. Adequate DO is generally present in the epilimnion of the Main Basin and in the East Basin.

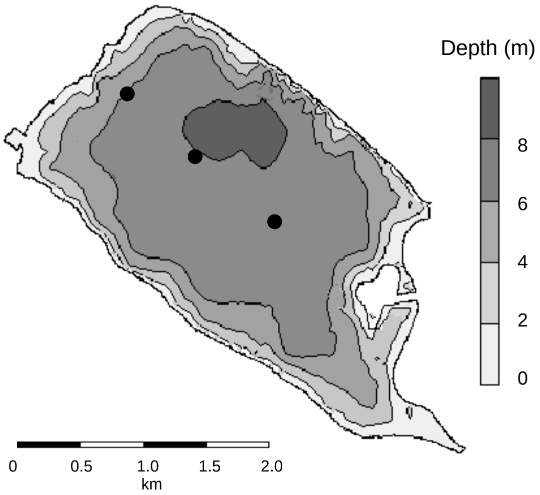
Perhaps even more so than in Lake Elsinore, aeration or oxygenation of the Main Basin of Canyon Lake will substantially improve conditions for mussels there, making the hypolimnion chemically more suitable for colonization and growth, where no growth would presently be expected.

## 2. MONITORING

A monitoring program was developed and implemented to test for the presence of dreissenid mussels in Lake Elsinore and Canyon Lake. Primary emphasis is placed on veliger sampling and analysis of samples under cross-polarized light microscopy, although tactile and visual inspection of submersed infrastructure was also conducted.

### 2.1 Lake Elsinore

Veliger samples were collected on November 17, 2009 at the 3 TMDL sampling stations using a 63 μm Wisconsin plankton net (Fig. 2.1). Three vertical tows were collected to within 0.5 m of the bottom, composited within a single wide-mouth 125 mL polypropylene bottle and preserved using 70% ethanol. Total sampled lake volume was calculated from the cross-sectional area of the net opening, the number of tows and the tow depth, and ranged from 157 – 210 L.



| Station | Latitude (N) | Longitude (W) |
|---|---|---|
| 1 | 33.67150 | 117.36568 |
| 2 | 33.66425 | 117.35738 |
| 3 | 33.65648 | 117.34628 |

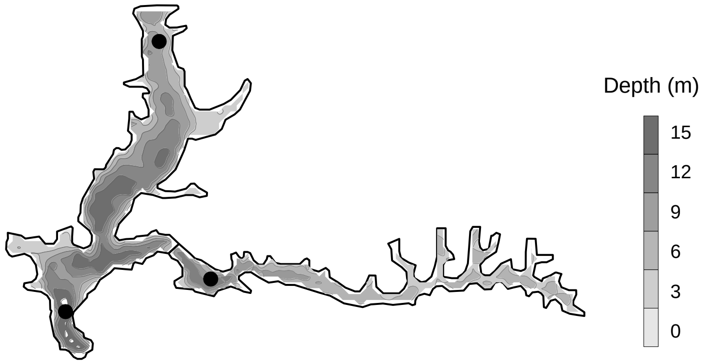
*Fig. 2.1. Invasive mussel a) sampling sites (TMDL stations) on Lake Elsinore, and b) Wisconsin net.*

All submersed surfaces of one buoy near each of the 3 sampling sites were also visually and tactilely inspected for the presence of settled juvenile or adult mussels. Although the buoys all had a well-developed biofilm of attached algae, no mussels were detected on any of the buoys. Presence of an algal-bacterial biofilm is generally considered a prerequisite to settlement and attachment of pediveligers. Secchi depths were also measured at each of the sites.

Following return from the field, the volumes of each of the samples were determined gravimetrically and then subsampled for inspection under cross-polarized light. Triplicate 1-mL subsamples were withdrawn from gently mixed samples and pipetted onto a gridded Sedgwick-Rafter cell. No dreissenid mussel veligers were identified in any of the samples. The detection limit based upon subsampled and total sample volumes and tow volumes for the 3 sites ranged from 0.14 - 0.18 veligers $L^{-1}$.

### 2.2 Canyon Lake

Sampling for veligers in Canyon Lake was conducted on October 16, 2009 at three sites on Canyon Lake (Fig. 2.2). A separate dedicated 63 $\mu$m Wisconsin net was used for sampling Canyon Lake following the procedure described above. Secchi depth measurements and brief visual-tactile inspections of submerged surfaces of buoys were also made.



| Station | Latitude (N) | Longitude (W) |
|---|---|---|
| 1 | 33.69626 | 117.26826 |
| 2 | 33.68074 | 117.26330 |
| 3 | 33.67818 | 117.27524 |

*Fig. 2.2. Invasive mussel sampling sites on Canyon Lake.*

Tow volumes ranged from 271 L at the East Bay site to 407 L near the buoy line at the south end of the lake. Hydrogen sulfide odors were evident from sampling at this site. Secchi depths ranged from 1.9 ft at the East Bay site to 3.6 ft at the site south of the North Causeway (Fig. 2.2). No dreissenid veligers were found in any of the samples. The detection limit for the 3 sites ranged from 0.013 – 0.019 veligers $L^{-1}$.

These results corroborate the findings from recent DFG sampling of the lake that found no evidence of veligers in the lakes using PCR. DFG also provided invasive mussel training on June 27, 2009 to volunteers at Canyon Lake, and provided artificial substrates for use by residents and others for monitoring. Based upon the comprehensive training provided by DFG, no additional training was provided as part of this project. Additional veliger sampling will be conducted at each of these lakes in the spring and summer of 2010, when veliger abundances typically peak.

## 3. POTENTIAL DISTRIBUTION OF MUSSELS IN LAKES

The colonization and distribution of mussels in lakes are a function of local water quality conditions (described in Section 1.4) and bottom characteristics. Zebra and quagga mussels attach to substrates using byssal threads, and are generally found associated with comparatively hard surfaces, such as rocks, gravel, concrete, and other man-made surfaces, although quagga mussels can also attach to somewhat softer sediments and even biological surfaces. For example, we have found quagga mussels attached to native and nonnative clams within relatively soft sediments and, to a limited extent, also on aquatic vegetation (e.g., tules and cattails). Widespread colonization onto aquatic vegetation has not been observed, however.

### 3.1 Lake Elsinore

It was noted that the conditions present in Lake Elsinore generally fall well within the tolerance range for dreissenid mussels. Temperature conditions, dissolved $Ca^{2+}$ concentrations, salinity, ammonia and pH levels are all suitable for growth and reproduction. Dissolved oxygen levels do periodically fall below the tolerance range, however (Table 1.1). Low DO concentrations have been found to exclude mussels from colonization, and upon exposure, result in mortality (W. Taylor, pers. comm.). Thus, as previously noted, anoxia across 50-70% of the lake bottom as found during the summer in 2003-2006 would keep adult mussels from successfully colonizing the deeper region of the lake. In addition to low DO concentrations, the fine organic sediments are thought to be too soft and uncohesive to serve as a suitable substrate for colonization. These soft organic sediments also release the greatest amount of $NH_3$ and $H_2S$. It is thus expected that, under these conditions, mussel colonization, growth and reproduction would be restricted to relatively shallow sites with at least limited DO and slightly firmer and coarser-textured sediments (Fig. 3.1). This map is thus based upon previous sediment characterization (Anderson, 2003) in conjunction with measurements of DO following installation of the axial flow pumps (Anderson 2005). Sixty percent of the sediment samples collected using a regular staggered-start sampling grid were found to have high water contents, as well as high clay and organic matter with little sand, and also coincided with the 50-70% sediment area with anoxic sediments.

*Fig. 3.1. Projected areal extent of suitable conditions for dreissenid mussels in a) Lake Elsinore and b) Canyon Lake.*

The installation and operation of the diffused aeration system is expected to expand the region of the lake where adequate DO concentrations are present to allow mussels to grow, although a detailed synoptic survey as to the distribution of DO during operation of the diffused aeration system has not been conducted. Fortunately, extensive colonization of the soft organic sediments in the deeper regions of the lake remains unlikely. Thus, even with the diffused aeration system in place, sediment characteristics are expected to limit colonization to the shallower regions of the lake. Provision of DO through operation of the diffused aeration system nonetheless does expand the likely range of quagga mussels in the lake. Moreover, physical infrastructure in the lake would expected to be colonized if mussels were introduced into the lake, including all docks, buoys, diffuser and axial flow pump hardware away from the mixing hardware.

The impacts of mussel colonization in the shallower regions of the lake and infrastructure would be substantial. The mussels have rather sharp edges that can cut fingers and hands, so anyone wading or working on hardware in the lake could be mildly injured. The interannual variation in water surface elevation experienced at Lake Elsinore may result in eventual replacement of sandy beach areas to areas with mussel shells during low lake levels.

Perhaps more significantly, a large population of mussels in the lake would no doubt alter the overall ecology and water quality there. Adult mussels filter water at a rapid rate (2-4 L $\text{mussel}^{-1}$ $d^{-1}$) (Wildridge et al., 1998). This filtration rate can be compared to that of *Daphnia*, a beneficial zooplankton that also serves as forage for larval and juvenile fish and zooplantivorous adult fish species. Filtration rates typically range from <5-50 mL *Daphnia*$^{-1}$ d$^{-1}$ (e.g., Wetzel, 2001; Thompson et al. 1982) and increase markedly with size of the individual. Large copepods and other cladocerans can also filter water, but typically at a slower rate (<1-10 mL individual$^{-1}$ day$^{-1}$) (Thomspon et al., 1982). Estimates of mussel and zooplankton abundances can be used with filtration rates to compare the relative filtration efficiency of these two groups of organisms. The density of adult mussels can reach 30,000-70,000 m$^{-2}$ under favorable conditions, although densities closer to 6000 mussels m$^{-2}$ have been reported in Lake Michigan (Nalepa et al., 2009), with lower densities in the more recently invaded Lake Mead (505 m$^{-2}$ in 2007) (Moore et al., 2009). We do not have enough information to make projections about possible abundance levels in Lake Elsinore, although the extremely high productivity of the lake makes it likely that it could support higher local populations than the less productive Lake Michigan or Lake Mead.

As a conservative estimate, one can estimate a lakewide filtration rate due to quagga mussels using density values from Lake Mead. The lakewide filtration rate $k_f$ (d$^{-1}$) can then be estimated from the estimated area of colonization in the lake $A_c$ (m$^2$), multiplied by the mussel population M (# m$^{-2}$) and the individual mussel filtration rate $F_m$ (L individual$^{-1}$ d$^{-1}$) normalized to the lake volume V (L). That is:

$$k_f = \frac{MA_cF_m}{V} \tag{3.1}$$

The estimated filtration rate attributed to mussels can then be compared with the estimated lakewide filtration rate due to the native zooplankton population. While the zooplankton population has varied widely depending upon lake level, salinity and intensity of predation, we will use a typical population found in 2004 (Veiga-Nascimento, 2005) as our reference. Using the current lake level of about 1240', we estimate the total lake volume (V) to be about 4.7x107 m$^3$. Assuming a large-bodied zooplankton population of 15 L$^{-1}$ and assuming an average individual rate of filtration of 5 mL d$^{-1}$ ($F_z$), one calculates a lakewide filtration rate of 0.075 d$^{-1}$ and filtration time of 13.3 days (Table 1).

This value can be compared with that predicted assuming mussels colonize 40% of the lake area to an average density of 505 m$^{-2}$. At an individual filtration rate of 2 L d$^{-1}$, this corresponds to a lakewide filtration rate of 0.101 d$^{-1}$ and a lake filtration time of 9.9 days (Table 1). Thus, we see that colonization by mussels would, under these circumstances, result in a biological rate of filtration that is 33% faster than that predicted for zooplankton. As a result of their increased filtration capacity, dreissenid mussels are generally recognized to compete with zooplankton for available algal resources, and shift the food web from a pelagial (open-water) system to one driven by benthic processes. The ecological implications of this will be discussed shortly, although one would expect the increased filtration rate to result in greater water clarity; increases in water clarity have in fact been found in a number of productive systems in the midwestern US (MacIsaac et al., 1992; Fishman et al., 2009).

Table 3.1. Estimated filtration rates and relative chlorophyll concentrations comparing zooplankton and invasive mussels in Lake Elsinore (principally for illustration).

| | **Phytoplankton** | **Zooplankton** | **Mussels** |
|---|---|---|---|
| Grazer Population (# $L^{-1}$ or # $m^{-2}$) | 0 | 10 | 505 |
| Lake Filtration Rate (d-1) | 0 | 0.075 | 0.101 |
| Lake Filtration Time (d) | 0 | 13.3 | 9.9 |
| Relative Chlorophyll Concentration | 100 | 50 | 32.6 |

While it is not possible to predict in detail the influence of dreissenid mussel invasion on Lake Elsinore, some simple calculations may offer some perspective on potential impacts to water clarity. Specifically, assuming a steady lake volume and stable grazer populations (mussels and zooplankton), the Lotka-Volterra form of the carrying-capacity model allows phytoplankton growth in response to nutrient availability and simultaneous removal by filtration by zooplankton (Z) and mussels (M):

$$\frac{dC}{dt} = \frac{\mu C(K-C)}{K} - \left(F_z Z + \frac{MA_c F_m}{V}\right)C \qquad (3.2)$$

where C is the concentration of phytoplankton (C), $\mu$ is the phytoplankton growth rate constant ($d^{-1}$) and t is time. A value of 300 $\mu g\ L^{-1}$ chlorophyll was used as the carrying capacity for the lake, and a growth rate constant of 0.15 $d^{-1}$ was assumed in this calculation (Thomann and Mueller, 1987). Based upon these values, the phytoplankton population asymptotically reached 95% of the carrying capacity within about 30 days. Inclusion of zooplankton grazing lowered the relative chlorophyll concentration by 50%; thus we can see the beneficial influence provided by zooplankton grazing upon phytoplankton in lakes. The colonization by mussels of the nearshore region of Lake Elsinore at a relatively low density is predicted to have greater effect on chlorophyll levels than zooplankton, reducing in this example the predicted chlorophyll level by 67% (Table 2). Thus, presence of mussels could actually improve water clarity in the lake, although the magnitude of any increase is difficult to predict with any real confidence. As a result, these calculations are offered only as an example and possible outcome.

## 3.2 Canyon Lake

As previously noted, the main basin of Canyon Lake is strongly stratified during the summer, with an anaerobic hypolimnion present from April-October. With an absence of DO, and accumulation of $NH_3$ and $H_2S$ to high levels, successful populations of mussels would not be expected there. Thus, these chemical conditions would trump any favorable sediment characteristics that might be present below the thermocline of the lake. Using the thermocline as the boundary defining suitable chemical habitat, one estimates that over 60 % of the lake area would *not* be suitable for mussels under present conditions (Fig. 3.1b). Much of the suitable area would be in east bay

Installation and successful operation of a diffused aeration or hypolimnetic oxygenation system would eliminate the anoxic hypolimnion in the main basin, so the chemically defined boundaries would be lost. Sediment characteristics (hardness, cohesiveness) would then govern adult mussel distribution within the lake. Sediment characterization conducted in 2002-03 identified very soft organic sediments in about 30-40% of the lake bottom, so it is hypothesized that mussels could potentially colonize the remaining approximately two-thirds of the lake. As with other lakes, they would readily colonize the many docks, concrete walls, buoys and other infrastructure in the lake. These man-made surfaces could possibly account for the majority of attached mussels in the lake.

The influence of mussels on water clarity would vary between the main basin and east bay in a complex way based upon available area for colonization and basin volume. The limited exchange between the two basins during the summer will help maintain local differences in water quality. At current surface elevation, the areas of the main basin and east bay are estimated at about $7.5\text{x}10^5$ and $2.8\text{x}10^5$ $m^2$, while volumes are $5.8\text{x}10^6$ and $1.2\text{x}10^6$ $m^3$, respectively. These values yield mean depths of approximately 7.7 and 4.3 m for main basin and east bay. The areas available for colonization under current conditions (i.e., without aeration or oxygenation) are estimated near $2.1\text{x}10^5$ $m^2$ and $2.2\text{x}10^5$ $m^2$ for the main basin and east bay, respectively. The corresponding volumes above the summer thermocline are $3.8\text{x}10^6$ and $1.1\text{x}10^6$ $m^3$. The net effect of the larger fraction of east bay where oxic conditions exist is that a greater number of mussels can occupy and filter a smaller relative volume compared with the main basin, assuming that the sediment substrates are suitable for colonization (Table 3.2). At the same time, east bay also has greater relative internal loading of nutrients and a correspondingly higher carrying capacity so it difficult to estimate the relative chlorophyll concentrations; nonetheless, east bay is likely to see somewhat greater relative increases in water clarity than the main basin.

Table 3.2. Filtration rates and times in Canyon Lake comparing the main basin and east bay.

| | **Main Basin** | **East Bay** |
|---|---|---|
| Mussel Population ( # $m^{-2}$) | 505 | 505 |
| Lake Filtration Rate ($d^{-1}$) | 0.056 | 0.202 |
| Lake Filtration Time (d) | 17.9 | 5.0 |

## 3.3 Related Ecological Impacts

Part of the difficulty in predicting these impacts stems from reported cases where mussels have shifted the phytoplankton species to less desirable blue-green forms through selective rejection in pseudofeces (Vanderploeg et al., 2002). In such a case, filtration efficiency of zooplankton and mussels is reduced such that total chlorophyll levels may not ultimately change all that much, and rather only changes in the phytoplankton community may result.

Other ecological impacts have also been noted. In addition to the indirect effects of dreissenid mussels on zooplankton through resource competition, mussels can directly affect microzooplankton populations by filtration and ingestion (MacIsaac et al. 1995; Wong et al. 2003). This is especially true for protozoa and small zooplankton that have insufficient motility to avoid being drawn into the siphon. Mussels also remove other particles from the water column, including inorganic and organic suspended solids, increasing clarity through this mechanism as well (MacIsaac, 1996). The increased clarity, as well as the reduced nutrient uptake by phytoplankton, result in more favorable nutrient and light conditions for benthic algae and plants, thus, as previously noted, shifting the flow of energy, nutrients and carbon from pelagial to benthic environments. At the same time, the adult mussels alter the benthic environment, displacing native clams and mussels and potentially competing with other benthic invertebrates.

Evidence for some food web adaptations to the growth of large mussel populations has been witnessed. For example, ducks have been suggested as being responsible for reductions in mussel populations in some midwestern lakes. Through stomach content analyses, we have confirmed grazing upon adult quagga mussels by redear sunfish, bluegills, catfish and carp in the reservoirs receiving waters from the Colorado River. Small bluegills have also been found to consume larval quagga mussels. Diving ducks have, in some cases, been found to graze heavily upon dreissenid mussels, especially in Europe. In the Rhine River, diving ducks and coots consume up to 97% of the standing zebra mussel crop each year, but the high reproduction rate has maintained the population there (Iowa DNR, 2009). In systems of varying productivity then, food webs appear to be adapting to this new food resource. Thus, some top-down grazing pressure may help limit mussel population growth, although pressure sufficient to dramatically lower populations is not expected. Eradication and control methods are discussed later in this report.

## 4. METHODS OF INTRODUCTION AND DISPERSAL OF MUSSELS

The initial introduction of quagga mussels into waters of the western US has been attributed to recreational boat(s) launched in Lake Mead. Since first being identified in January 2007, the mussels have spread rapidly throughout southern Nevada, Arizona and Southern California (Fig. 4.1) (USGS, 2009). Mussels have been identified on at 6 trailered boats within California as of November 6, 2009 (USGS, 2009), confirming this mechanism for dispersal. Boater-mediated jump dispersal of quagga mussels within the Great Lakes was also inferred from the genetics of subpopulations that did not conform to an isolation-by-distance model (Wilson et al., 1999).

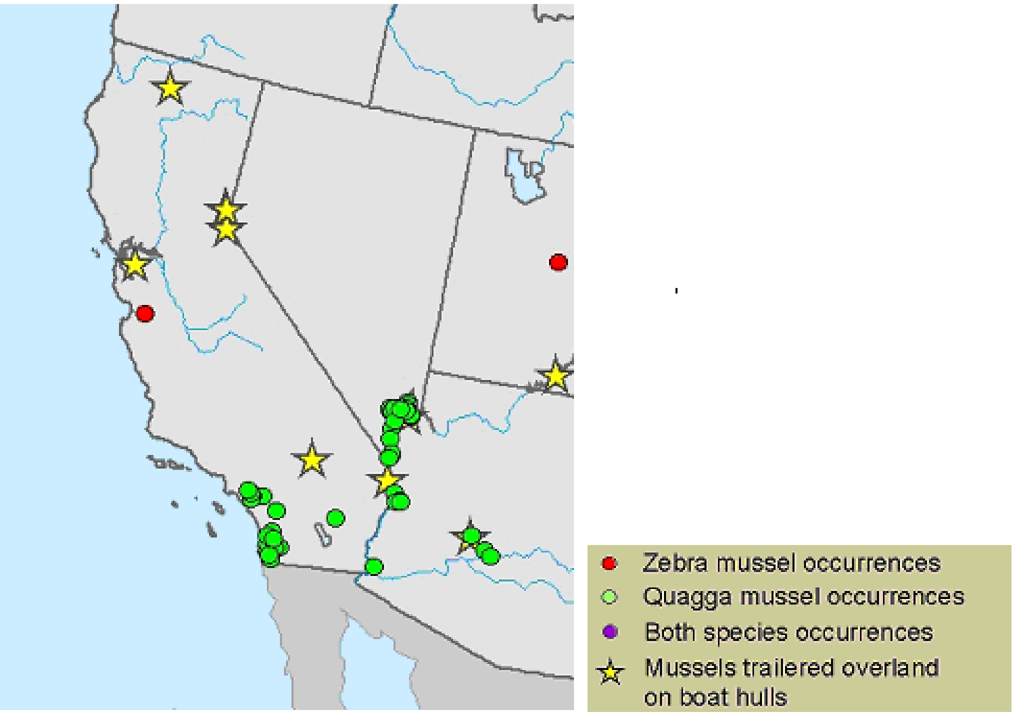


*Fig. 4.1. Dreissenid mussel occurrences in the southwestern US (USGS, 2009).*

Following the initial introduction into Lake Mead, however, the dominant mechanism by which quagga mussels have been dispersed within southern California has been in the source drinking water delivered through the Colorado River Aqueduct and the associated conveyances. The mechanism by which zebra mussels were introduced into San Justo Reservoir in Northern California is not known, although it has no connection with any known infested waters. The vulnerability of a lake is thus a function of water supply, recreational boat use, and other inadvertent introductions.

## 4.1 Water Supply

The principal water supply for both Lake Elsinore and Canyon Lake is the San Jacinto River. The river drains a 1,980 km$^2$ watershed, with its headwaters in the San Jacinto Mountains, and flows through Canyon Lake prior to entering Lake Elsinore (Fig. 4.1). The watershed includes a mix of wildlands in the headwaters (73.8%), while agricultural and urban-suburban land-uses dominate the valleys and account for 18.2 and 8.0%, respectively (Carter et al., 2006). There are no traditional point discharges in the watershed, while nonpoint inputs come from agricultural lands, dairies, feedlots, and from residential and urban areas. The lakes would both be potentially at risk from mussels introduced upstream in the watershed during the winter rainfall and runoff season. Lakes upstream in the watershed include Lake Perris, Lake Hemet and the San Jacinto Reservoir.

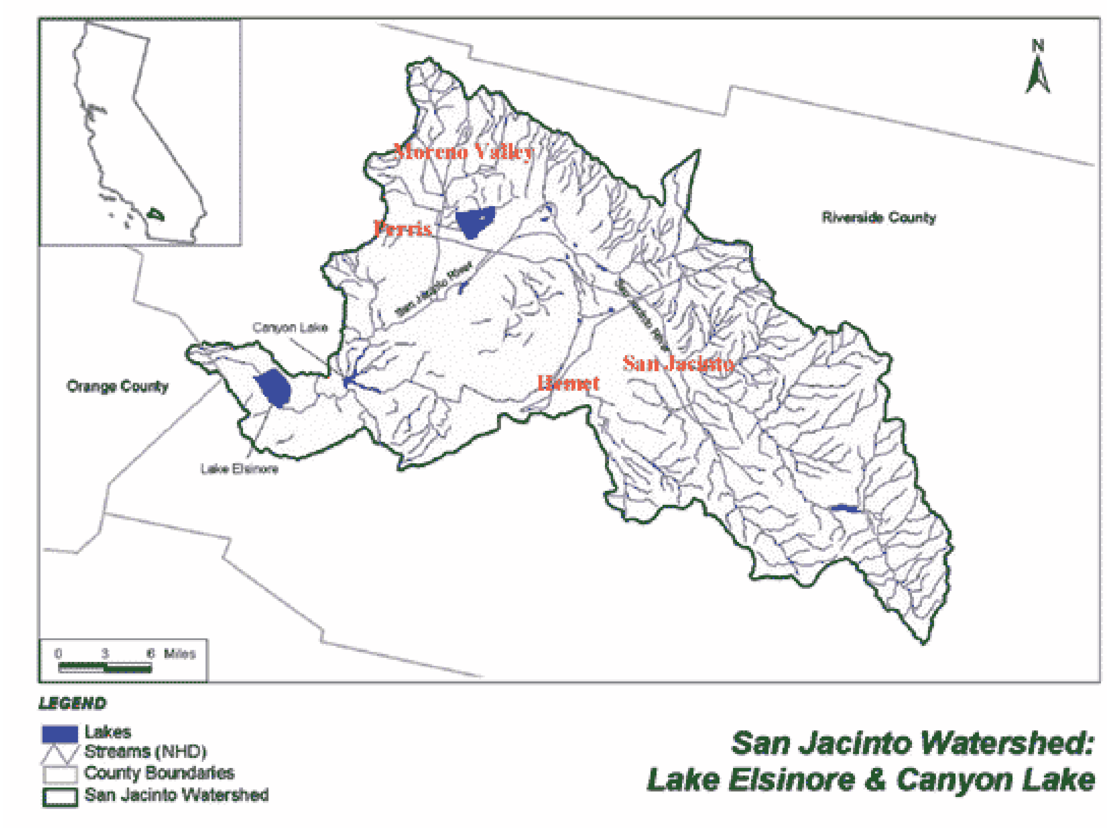


*Fig. 4.2. The San Jacinto River watershed (Carter et al., 2006).*

Lake Perris is a very popular recreational lake that can also serve as a source drinking water storage reservoir, although it is rarely used as such due to generally unfavorable water quality conditions. Importantly, Lake Perris receives State Project Water from northern California through the East Branch of the California Aqueduct, rather than Colorado River water delivered through the Colorado River Aqueduct. As a result, it is not presently at risk from importation of mussel veligers with water deliveries, since no mussels have been found in the State system. High levels of use by fisherman, water-skiers, and jet skiers make it susceptible, however, to invasion by mussels transported by boats from other infested lakes. A boat inspection program was implemented in April 2009.

Lake Hemet is a smaller 8100 af water storage reservoir on the South Fork of the San Jacinto River that is owned and operated by the Lake Hemet Municipal Water District. Recreational activities at the lake include boating; a boat inspection program was initiated at Lake Hemet earlier this year as well.

The San Jacinto Reservoir is not part of the San Jacinto River system per se, and has in the past served as a storage basin for water delivered through the San Diego Aqueduct. Its current level of use and water source is not clear, although if it does still receive some water from the San Diego Aqueduct, then it would possibly be infested with mussels. It could then serve as a source of quagga mussel veligers to the San Jacinto River in the event of any incidental release from the reservoir or potentially from other parts of the San Diego Aqueduct, although chlorination by MWD has substantially reduced veliger levels in their system.

At the same time, water has occasionally been imported from MWD into Canyon Lake to help maintain the water supply in times of drought. For example, approximately $1.3\text{x}10^6$ $m^3$ was imported in April 2002 (Davis and Anderson, 2005). Any water imported from the Colorado River Aqueduct would potentially introduce quagga mussels into Canyon Lake and, during periods of runoff and overflow, also to Lake Elsinore. Differences in recreational use thus distinguish these two water bodies.

## 4.2 Recreational Use

### *Lake Elsinore*

There are a number of boat launch ramps on Lake Elsinore, including 2 operated by the City of Lake Elsinore as well as several others associated with private marinas and RV parks. The annual number of boat launches is not known precisely, although the lake receives heavy use by water-skiers, powerboaters and, to a lesser extent, fisherman throughout the summer. A boat inspection program has not yet been adopted, although the City has initiated a public outreach campaign at their launch ramps and online at www.lake-elsinore.org/index.aspx?page559. The website further references related quagga mussel control efforts recommended by the California Department of Fish and Game.

### *Canyon Lake*

Canyon Lake is a multiple-use source drinking water reservoir with fishing, water-skiing, wakeboarding and related water recreational activities. Since the City of Canyon Lake is a gated community that surrounds the main basin and east bay of the lake, public access to the lake is restricted to city residents and others granted special access. As a result, almost all boat use is by residents, with anecdotal evidence that comparatively few of the boats are ever launched at other water bodies. Moreover, rigorous security at the main entrances to the city regulates all access to the community, including the lake. Because of these factors, Canyon Lake is thought to be at less of a risk from incidental introduction of invasive mussels than Lake Elsinore.

## 5. PREVENTION

Prevention of the introduction of dreissenid mussels into uninfested waters is a high priority for water resource managers and agencies in California and throughout the western US. The economic impacts from dreissenid mussels are staggering, with USFWS estimates of \$500M $yr^{-1}$ for the Great Lakes region alone. Potential economic impacts to water treatment plants in the western US has been estimated at \$250M $yr^{-1}$ (DeLeon, 2008). Substantial costs are also expected to be incurred by the US Bureau of Reclamation and other agencies and power utilities.

In an effort to blunt the ecological and economic assault by these invasive mussels, the Western Regional Panel on Aquatic Nuisance Species recently completed an action plan for western US waters (WRP, 2009). In that document, a number of actions were identified to prevent introduction of mussels into new areas and to maximize containment of existing populations, including:

1. Implementation of mandatory inspection and decontamination stations at infested water bodies
2. Expand mandatory watercraft inspection and decontamination capacity in uninfested regions
3. Establish and implement strong, consistent law enforcement programs in each western state
4. Develop programs to intercept contaminated materials and equipment

Earlier this fall, Zook and Phillips (2009) of the Pacific States Marine Fisheries Commission prepared for the Western Regional Panel on Aquatic Nuisance Species a document defining recommended uniform minimum protocols and standards for watercraft interception programs in the western US. Recognizing funding and other limitations, it was acknowledged that it may be necessary to dedicate efforts to waters with the highest risk of contamination, including those with suitable water quality and with high amounts of watercraft activity that are proximal to dreissenid-infected waters. Three levels of inspections were described by Zook and Phillips (2009) depending upon risk level and individual agency/organization capacity. Text from that document is excerpted below:

### 5.1 Level 1 (Self-Inspection)

*Relatively low cost program for low risk waters or on higher risk waters where organization or physical capacity prevents a more aggressive approach.*

As an example, we recommend either a voluntary or mandatory self-inspection program similar to the one developed by the Utah Division of Wildlife Resources and in use at over 100 secondary risk waters in that state. Mandatory programs work best if the authority to enforce provisions of the program are in place (*e.g.,* authority to require that all watercraft operators complete and post self-certification form). In the absence of that authority, a voluntary program should be implemented.

This type of program involves the dissemination of an inspection form which can be made available at either an entry station, kiosk or message board with boldly printed instructions for the watercraft/equipment operator to answer all the questions and inspect all designated areas and equipment. The form is then placed in or on the transport vehicle where it can be easily seen. If the program is mandatory, spot checks by enforcement personnel can reinforce compliance.

Self-inspection programs can be implemented for under $1,000/year in most areas and for under $25,000/year for an entire state. Including staff time for verifying and/or enforcing compliance can add to both effectiveness and cost.

### 5.2 Level 2 (Screening out high risk watercraft and equipment)

*Moderate to high risk waters where budget or other issues prevent a more comprehensive (Level 3) program.*

We recommend a program that includes a screening interview to identify high risk watercraft and/or equipment, an inspection to verify interview information and exclusion of any watercraft/equipment that remain high risk following screening and inspection.

This type of program can often be incorporated into an existing entry station operation that is set-up to collect access fees, confirm reservations or provide use information and regulations. Current entry station staff can be easily trained to conduct verifying inspections and the number of watercraft excluded would normally be expected to be low on waters where this type of program would be implemented. Because a rigorous inspection is not required and no decontamination or quarantine facilities are required, this is a relatively low cost option for some agencies/organizations. Programs like this typically cost between $5,000 and $50,000 a year to operate per water body and are a relatively low cost option.

### 5.3 Level 3 (Comprehensive)

*High risk waters and wherever possible.*

We recommend this type of program for all high risk waters. A Level 3 program should include screening interviews at the point of entry; a comprehensive watercraft/equipment inspection performed by trained inspectors of all high risk watercraft/equipment; the decontamination and/or quarantine or exclusion of suspect watercraft, and may include vessel certification.

This type of program may require construction or modification of entry facilities, purchase of a hot water power wash and wastewater containment system, hiring trained inspectors and decontamination operators and provision of a quarantine facility, along with a set of policies and rules that allow all of the above actions. Programs like this can cost between $50,000 and $250,000 per waterbody per season to operate depending on the size of water involved, type of equipment and facilities used, hours of operation and the number of access points.

*NOTE ON LEVEL 1 AND LEVEL 2 PROGRAMS:* Level 1 and Level 2 programs are options for local jurisdictions when the capacity to implement more aggressive and effective programs is lacking. These programs, however, do not provide the level of security required for any type of cross-jurisdictional reciprocity because they do not offer any assurance that watercraft and/or equipment subjected to either type of program are, to the extent practical, free of mussels or other aquatic nuisance species (ANS).

(*End of excerpt from Zook and Phillips, 2009*).

### 5.4 Recommendations for Lake Elsinore and Canyon Lake

The physical, sedimentological and chemical conditions, as well as intensity of recreational use put Lake Elsinore and Canyon Lake in a high risk category. This is especially true for Lake Elsinore due to its intense summer recreational use. The controlled access and limited number of launches of boats from offsite places Canyon Lake at a lower overall risk of invasive.

On that basis, a comprehensive Level 3 inspection program is recommended for Lake Elsinore. Canyon Lake would also benefit from a comprehensive Level 3 inspection program; elements of such a program are currently under consideration there (P. Johnson, pers. comm.).

## 6. ERADICATION AND CONTROL METHODS

It is generally acknowledged that complete eradication and removal of invasive mussels from a water body is difficult if not possible under many circumstances. A large number of strategies have been proposed and in some cases field tested for their ability to remove large populations of mussels from waters. These methods include physical, chemical and biological treatment.

### 6.1 Physical Methods

The physical methods for control of dreissenid mussels vary widely in their approach and effect. In some cases, physical methods simply inhibit or prevent settlement by pediveligers and juvenile adults onto surfaces, and in other cases result in complete mortality (Table 6.1). In some situations, simple mechanical removal can be conducted as needed to limit excessive colonization. This often involves shutting down some part of a water conveyance system, use of scuba divers, and other actions that may or may not be practical. Other mechanical-physical methods include vibration and cavitation. Vibration techniques are generally unsuitable for many settings due to negative effects upon structural integrity of infrastructure (Table 6.1). Ultrasound and lower frequency sound has in some cases been tried as well, although availability of electrical power can be limiting.

Dessication and oxygen starvation are two techniques used by the MWD to manage juvenile and adult mussels in the Colorado River Aqueduct. Short-term shutdown and desiccation of the aqueduct has been shown to effectively control populations there, while reservoir drawdown has also been used to reduce adult populations in the upper region of Lake Mathews. At the same time, allowing an anoxic hypolimnion to develop has reduced populations in the deeper parts of both Lake Mathews and Lake Skinner. As a result, drawdown in combination with oxygen deprivation narrowed the depth interval for viable adult quagga mussels in these reservoirs, although recolonization was observed to occur following restoration of lake level and aeration (W. Taylor, pers. comm.).

Freezing can also be used to kill larval and adult mussels, and is useful in a laboratory setting, although this is not practical on a field scale, especially here in the southwestern US. Benthic mats can in some instances be useful as a means to remove settled adults from an area, but can be unwieldy and labor intensive to deploy and retrieve. More exotic radiation and electric field-based techniques have also been evaluated, but require power and sophisticated equipment and are thus not widely applicable (Table 6.1).

Table 6.1. Physical treatment methods for controlling dreissenid mussels (US Bureau of Reclamation, 2008).

| **Method** | **Life Stage** | **Effectiveness** | **Duration of Treatment** | **Notes** |
|---|---|---|---|---|
| Mechanical removal | Juveniles, adults | Variable | N/A | |
| Vibration | Veligers, juveniles | 100% | Pulsed 200-kHz & 10-100 kHz | Structural integrity threatened |
| Cavitation | All | 100% | Veligers in sec; adults in few h | May affect other species; need power |
| Ultrasound | All | 100% | Veligers in sec; adults in 19-24 h | May affect other species; need power |
| Low freq sound | Juveniles | Inhibits settling | 4-12 min @20 Hz-20 kHz | Not lethal |
| Freezing | Juveniles | 100 % | 2 days @ 0ºC | Must dewater system |
| | Adults | | 5-7 h @ -1.5ºC | |
| Dessication | Juveniles | 100% | Immediate @ 36ºC | Must dewater system |
| | Adults | | 2.1 d at 25ºC | |
| Oxygen starvation | All | | 2 weeks+ @ 0 mg L-1 | Must isolate population |
| Benthic mats | Juveniles, adults | Up to 99% | 9 weeks | Promising for limited infestations |
| UV radiation | All | 100% | Juveniles in 4 h; adults continuous | Lethal to many species; limited by turbidity |
| Low voltage | Adults | Prevents settling | Immediate @ 8V AC | Not lethal |
| Plasma pulse | Juveniles, adults | Prevents settling | Pulsed high energy | Not lethal |
| Electric field pulse | Juveniles, adults | Lethal | seconds | May affect other species, need power |
| | Adults | Inhibits settling | Continuous | |

## 6.2 Chemical Methods

The use of chemicals is the most widespread approach for dreissenid mussel mitigation (Costa et al., 2008). At the same time, chemical control methods can result in harmful impacts to nontarget organisms, and can also be quite expensive. Current efforts are on the development of more efficient and selective chemicals and improved application and delivery methods (Aldridge et al., 2006). Molluscidal agents include KCl (Wildridge et al., 1998), copper (Kennedy et al., 2006; Prasada and Khan, 2000), Rotenone, Clamtrol CT-1, Calgon H-130, Bayer 73, Salicylanilide I, and 3-trifluoromethyl-4-nitrophenol (Fisher et al.1994). Broad spectrum chemical oxidants are often used as well. Chlorination is the most frequently used means to control mussel larvae entering water systems (Rajagopal et al., 2002). For example, MWD has been continuously chlorinating at the outfall from Copper Basin Reservoir into the Colorado River Aqueduct since mussels were identified in Lake Havasu, and have also upgraded chlorination facilities at the outlets of Lake Mathews and Lake Skinner (DeLeon, 2008).

Some chemical treatment methods and their effectiveness were recently summarized by the US Bureau of Reclamation (2008) (Table 6.2). Most of these chemical treatment methods non-specific, resulting in mortality to nontarget organisms as well as larval, juvenile and adult dreissenid mussels (Table 6.2). Moreover, high doses and long exposure times are often required, especially for the non-oxidizing chemicals. $CuSO_4$ has a lower effective dose and contact time than the potassium and chloride salts, but is lethal to algae, zooplankton and other organisms at comparatively low doses.

The oxidizing chemicals are generally effective at much lower concentrations, often making them a more cost-effective control strategy, although most chemical oxidants exert toxic effects on other species and often have special handling requirements. Whole-lake treatment is generally not feasible nor prudent, owing to the large volume of water that would need to be treated, handling and application challenges, the potentially deleterious impact on the aquatic ecology of the system, and in the case of source drinking water reservoirs, the in situ formation of undesirable disinfection byproducts.

Table 6.2. Chemical treatment methods for control of dreissenid mussels (US Bureau of Reclamation, 2008).

| **Method** | **Life Stage** | **Effectiveness** | **Contact time, Concentration** | **Notes** |
|---|---|---|---|---|
| ***Non-Oxidizing Chemicals*** | | | | |
| Copper ions | Veligers | 100 % | 24 h @ 5 mg L$^{-1}$ | Lethal to other species |
| KOH | All | 100% | <10 mg L$^{-1}$ | As above |
| $KH_2PO_4$ | All | 100% | Continuous 160-640 mg L$^{-1}$ | As above |
| KCl | Juveniles, adults | Prevent settlement | Continuous 50 mg L$^{-1}$ | Lethal to other mussel species |
| | All | 95-100% | 3 wks @95-115 mg L$^{-1}$ | |
| Chloride salts | Veligers, juveniles | 95-100% | 6 h @10,000-20,000 mg L$^{-1}$ | Low cost, high dosage rates |
| $CuSO_4$ | All | 50% | 48 h 2-2.5 mg L$^{-1}$ @17 ºC | Lethal to other species |
| ***Oxidizing Chemicals*** | | | | |
| Chlorine | Veligers | 100% | 0.25-5 mg L$^{-1}$ 1-9 d | Lethal to other species |
| | All | 90% | 2.0 mg L$^{-1}$ continuous | |
| | Adults | 95% | 0.3 mg L$^{-1}$ 14-21 d | |
| $ClO_2$ | Veligers | 100% | 0.5 mg L$^{-1}$ 24 h | Successful on veligers |
| Chloramine | Veligers | 100% | 1.2 mg L$^{-1}$ 24 h | Less toxic to other aquatic life than $Cl_2$ |
| $H_2O_2$ | Veligers | 100% | 6 h | High dose required |
| Ozone | Veligers | 100% | Veligers 5h @ 0.5 mg L$^{-1}$ | Lethal to other species |
| | Adults | 100% | Adults 7d @ 0.5 mg L$^{-1}$ | |
| $K_2MnO_4$ | All | 90-100% | 2 mg L$^{-1}$ 48 h | Lethal to other species |

## 6.3 Biological Methods

Biological controls are generally thought to be less damaging to aquatic ecosystems than chemical control methods. The ecologically preferred strategy for control of any invasive species is simply to have a natural predator, parasite or disease that will keep the invader population in check. Natural predators of dreissenid mussels capable of exerting strong top-down control on their populations have not been identified, although some diving ducks and fish species will feed on mussels. We have found bluegills (*Lepomis macrochirus*), redear sunfish (*Lepomis microlophus*), catfish (*Ictalurus spp.*) and carp (*Cyprinus carpio*) taken from a Colorado River reservoir with large quantities of adult mussels in their stomachs. Redear sunfish, also known as shellcrakers, are well-recognized for their ability to eat native as well as invasive mussels and clams (Table 6.3). With this in mind, the Salt River Project in Arizona has stocked redear sunfish in their canals with the hope of the fish offering some control over the mussels. Thus, it is clear that aquatic food webs here in the southwestern US do adapt to invasion by quagga mussels, although grazing pressure from natural predators is apparently not intense enough to keep mussel populations in check.

Table 6.3. Biological treatment methods for control of dreissenid mussels

| **Method** | **Life Stage** | **Effectiveness** | **Contact time, Concentration** | **Notes** |
|---|---|---|---|---|
| Predation | All | Low | Continuous | Need to maintain predator populations |
| *P. fluorescans* | Adult | 70-90% | Variable | No nontarget toxicity identified |
| Parasite/disease | Unknown | Unknown | Unknown | Target-specific |
| Reproduction | Larval | Unknown | Unknown | Target-specific |

A potential biological control strategy being touted is the addition of a strain of the common bacterium *Pseudomonas fluorescens* (Molloy, 2002). It is specifically a toxin produced by the bacterium that is thought to result in mortality, with dead bacteria just a effective as live bacteria in its molluscicidal properties. No nontarget mortality has been observed in tests with fathead minnows (*Pimephales promelas*), *Daphnia*, or native bivalves (Molloy and Mayer, 2007). A small field trial by the USBR is presently underway at the hydroelectric plant at Davis Dam. Preliminary results from tests conducted in March 2009 found that a 25 mg $L^{-1}$ dose of *P. fluorescens* resulted in 75±6% mortality, with 87±3% mortality at a higher (100 mg $L^{-1}$) dose (Willett, 2009). The exposure time was not specified, although previous studies by others were generally run for several days. This approach, while showing greater target specificity than other control strategies, appears to be suitable only for targeted applications, such as the infrastructure associated with hydroelectric power generation and water supply systems, such as pumps, valves, pipes and trash racks. Use for general dreissenid mussel control in lakes is not likely to be feasible. This can be demonstrated by considering the total dose that would be required to treat an established population of adult mussels in Lake Elsinore. Assuming that 40% of the lake was colonized, this would represent about 1200 acres (assuming the lake is near 1240’ elevation). Further assuming that a 25 mg $L^{-1}$ dose could be maintained for sufficient exposure time (1-3 days) near the mussels to a depth of 1 m, this (highly conservative) estimate of required *P. fluorescens* would be >121,000 kg or 121 metric tons. To treat the entire lake volume to 25 mg $L^{-1}$ would require >1,400 metric tons. Moreover, 100% mortality is typically not achieved, so rapid recolonization would be expected.

An alternative approach that is being studied is to control the mussels by disruption of their reproductive cycles (Snyder et al., 1997). The eggs are fertilized externally, so the male and female must release their gametes simultaneously. After release, the male's sperm is viable for only a short time, perhaps as short as only a few minutes. Disrupting the synchronization of spawning by males and females may thus effectively reduce the number of fertilized eggs and thus the number of trochophores, veligers and, ultimately, adults (Fig. 1.1). Researchers are studying the environmental and physiological cues that coordinate dreissenid mussel spawning activity, although such an approach remains a theoretical one at this time.

## 6.4 Eradication and Control Methods for Lake Elsinore and Canyon Lake

### ***Lake Elsinore***

As a recreational lake, critical infrastructure that would need to be protected from mussels would be limited to the boat launches and to the axial flow pumps, diffused aeration system and in situ YSI profiler installed at the lake. The tendency of mussels to associate into colonies (druses) could rapidly make wading and launching a boat difficult and even result in injury especially later in the year when lake levels have dropped. Simple mechanical removal with a powerful water jet as currently done at the boat launches to reduce attached algal growth would be sufficient to keep the boat launch area clear of adult mussels. The rate of growth seen in other lakes suggests that this would need to be done at least 2-3 times per year. Keeping the diffuser lines, axial flow pumps and 2 YSI profilers free of excessive mussel colonization would be more challenging. While veligers do not settle under high flow velocities, they do readily settle in small-scale regions of reduced flow within larger flow fields found in lakes and streams and in response to modest changes in wind conditions in wind-mixed lakes (e.g., Martel et al., 1994). Operation of the mixing systems would increase the collision frequency of veligers with associated hardware, including low flow microenvironments. Thus, colonization on the underside of the diffuser lines, float lines and supports seems likely, as does colonization onto draft tubes and submersed fencing around the axial flow pumps. Such physical obstructions would potentially greatly lower the mixing rates and flows near these devices. Mechanical removal, possibly by scuba, would presumably be needed. Similarly, the YSI profilers will need to be inspected and regularly maintained to limit biofouling by mussels.

### *Canyon Lake*

Since Canyon Lake serves both as a recreational lake and as a potable water supply, greater infrastructure is potentially at risk here. In addition to the boat launch areas that will likely require periodic mechanical cleaning to rid the launch ramps of adult mussels, the trash racks, pipes, valves and other hardware on EVMWD’s water intake would also be at risk. The average annual cost to water treatment facilities for monitoring, chemical and mechanical control, and other activities due to invasive mussels is $214,360 (O’Neill, 1997). Retrofitting of intake hardware with special anti-fouling coatings can reduce maintenance costs, but typically represent substantial hardware and installation costs. Depending upon the details of EVMWD’s water intake, periodic cleaning presumably by scuba, would be expected. Targeted cleaning with molluscicidal agents of specific zones within the water treatment plant may also be necessary.

## 7. REFERENCES

Carter, S., A. Parker, R. Whetsel and M. Norton. 2006. An analytical framework. *Stormwater*

Culver, C.S, S.L. Drill, M.R. Myers and V.T. Borel. 2009. *Early Detection Monitoring Manual for Quagga and Zebra Mussels.* California Sea Grant Extension Program. 40 pp.

Davis, K., M.A. Anderson and M.V. Yates. 2005. Distribution of indicator bacteria in Canyon Lake, California. *Water Res.* 39:1277-1288.

DeLeon, R. 2008. Testimony Before the US House of Representatives Committee on Natural Resources, Subcommittee on Water and Power. Washington, DC. June 24, 2008.

Fishman, D.B., Adlerstein, S.A., H.A. Vanderploeg, G.L. Fahnenstiel and D. Scavia. 2009. Causes of phytoplankton changes in Saginaw Bay, Lake Huron, during the zebra mussel invasion. *J. Great Lakes Res.* 35:482-495.

Lawson, R. and M.A. Anderson. 2007. Stratification and mixing in Lake Elsinore, California: an assessment of axial flow pumps for improving water quality in a shallow eutrophic lake. *Water Res.* 41:4457-4467.

MacIsaac, H.J. 1996. Potential abiotic and biotic impacts of zebra mussels on the inland waters of North America. *Am. Zool.* 36:287-299.

MacIsaac, H.J., C.J. Lonnee and J.H. Leach. 1995. Suppression of microzooplankton by zebra mussels. Importance of mussel size. *Freshwater Biol.* 34:379-387.

Martel, A., A.F. Mathieu, C.S. Findlay, S.J. Nepszy and J.H. Leach 1994. Daily settlement rates of the zebra mussel, Dreissena polymorpha, on an artificial substrate correlate with veliger abundance. *Can. J. Fish. Aq. Sci.* 51:856-861.

Molloy, D.P. 2002. *Biological control of zebra mussels.* In Proceedings of the Third California Conference on Biological Control. University of California, Davis, pp.86-94.

Molloy, D.P. and D.A. Mayer. 2007. Overview of a novel green technology: biological control of zebra and quagga mussels with *Pseudomonas fluorescens*. http://www.aquaticnuisance.org/wordpress/wp-content/uploads/2009/01/Dreissena%20Novel%20Green%20Technology%20for%20Dreissena%20Control%20%284%29%20Malloy.pdf.

O'Neill, Jr., C.R. 1997. Economic Impact of Zebra Mussels – Results of the 1995 National Zebra Mussel Information Clearinghouse Study. *Great Lakes Res. Rev.* 3:35-44.

Snyder, F. L., M. B. Hilgendorf, and D. W. Garton. 1997. *Zebra Mussels in North America: The invasion and its implications.* Ohio Sea Grant, Ohio State University, Columbus, OH. URL: http://www.sg.ohio-state.edu/f-search.html.

Spada, Michael E., Ringler, Neil H., Effler, Steven W., Matthews, David A. 2002. Invasion of Onondaga Lake, New York, by the zebra mussel (*Dreissena polymorpha*) following reductions in N pollution. *J. No. Am. Benthol. Soc.* 21: 634-650.

Thomann, R.V. and J.A. Mueller. 1987. *Principles of Surface Water Quality Modeling.* Harper & Row, Publ., New York, NY. 644 pp.

Thompson, J.M., A.J.D. Ferguson and C.S. Reynolds. 1982. Natural filtration rates of zooplankton in a closed system: the derivation of a community grazing index. *J. Plankton Res.* 4:545-560.

US Bureau of Reclamation. 2008. Draft Upper Colorado Region Prevention and Rapid Response Plan for Dreissenid Mussels.

USGS. 2009. Quagga mussel locations in lakes and reservoirs outside the Great Lakes. http://nas.er.usgs.gov/taxgroup/mollusks/zebramussel/QuaggaMusselLakeList.asp.

Vanderploeg, H.A., TF. Nalepa, D.J. Jude, E.L. Mills, K.T. Holeck, J.R. Liebig, I.A. Grigorovich and J. Ojaveer. 2002. Dispersal and emerging ecological impacts of Ponto-Caspian species in the Laurentian Great Lakes. *Can. J. Fish. Aquat. Sci.* 59:1209-1228.

Willett, L. 2009. Challenges and control activities for invasive mussels. US Bureau of Reclamation. http://www.usbr.gov/mussels/workshop/presentations/Willett.pdf.

Wong, W.H. J.S. Levinton, B.S. Twining and N. Fisher. 2003. Assimilation of micro- and mesozooplankton by zebra mussels: a demonstration of the food web link between zooplankton and benthic suspension feeders. *Limnol. Oceanogr.* 48:308-312.