# California's Response to the Zebra/Quagga Mussel Invasion in the West

**Recommendations of the**

**California Science Advisory Panel**

**Prepared for the**

**California Incident Command**

**California Department of Fish and Game**
**California Department of Water Resources**
**U.S. Fish and Wildlife Service**
**California Department of Food and Agriculture**
**California Department of Boating and Waterways**

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## Executive Summary

Zebra mussels, in the form of *Dreissena bugensis*, also known as quagga mussels, have now, for the first time, established a beachhead west of the continental divide. The significance and potential impact of this event cannot be overstated. Zebra mussels are harmful fouling organisms: they attach by the millions to submerged objects, fill and block water pipes, and clog protective screens. Zebra mussels are efficient filter feeders: they strip food from the water that is needed to sustain other aquatic life. Direct economic costs are on the order of $100 million a year in eastern North America; unquantified secondary and environmental costs could be substantially larger. Impacts in California and the West could be as great or greater than those in the East. California cities, industries and farms depend on the transport of huge quantities of water across very large distances through a complex and vulnerable system of canals, pipes, reservoirs and pumping stations. It is thus critical that aggressive, concerted efforts be undertaken immediately to ***eradicate, contain and monitor*** the zebra mussel infestation in the lower Colorado River system.

## Report Summary

On January 6, 2007, Eric Virgin was making some underwater repairs at a Lake Mead boat harbor when he noticed a small, striped and unfamiliar mussel attached to a steel cable—which is how we discovered that the zebra mussel *Dreissena bugensis* had established a beachhead west of the Continental Divide. Subsequent surveys found the mussel throughout Lake Mead's lower basin, with smaller numbers at a few sites downstream in Lakes Mojave and Havasu and the Colorado River. If not eradicated or contained, these populations will seed secondary invasions across Western North America. The potential impacts include hundreds of millions to billions of dollars in direct economic costs, along with large but unquantified indirect economic and environmental costs.

California quickly set up an Incident Command system, and appointed a Science Advisory Panel to plan its response to the invasion. This report presents the Advisory Panel's recommendations in three operational areas: **control and eradication** in currently infested waters; **containment** within those waters; and **monitoring** to detect new infestations.

The goal of these recommendations is to protect California waters and water supply systems, but they include critical actions that must be taken in infested waters outside the state's boundaries. If the State of California cannot implement needed actions directly in these cases, it should facilitate their implementation by providing assistance or funding, or through persuasion or political action.

The Advisory Panel's core recommendations are:

### ERADICATION / CONTROL

- A determined effort should be undertaken to eradicate the infestations in the lower Colorado River system. The population in Lake Mead will be the most challenging, but feasible methods exist if applied persistently on a large scale. The potential for enormous, long-term economic and environmental impacts both in the infested waters and across Western North America warrants a very aggressive response.

- Field trials of treatment methods should begin immediately in Lake Mead.

- Methods of reducing the downstream flow of live larval stages (veligers) through Hoover Dam and dams further downstream should be investigated and, if feasible, implemented.

### CONTAINMENT

- The infested waters should be closed to boating until the eradication effort is completed.

- If the lakes are not fully closed to boating, then any boat that spends more than 24 hours in the Lake Mead National Recreation Area (NRA) should be cleaned by NPS staff before leaving. All boats leaving the NRA should be inspected by NPS staff. Similarly, boats leaving Lake Havasu and other downstream waters on the lower Colorado River system should be inspected, and cleaned if necessary.

- All 16 California border check stations, and an added station on US Route 95, should operate 24/7 and inspect all boats. Boats with live or dead mussels should be cleaned by state staff before being allowed to proceed.

- California and federal agencies should institute a mandatory boat inspection and cleaning system before allowing entry to high priority water bodies in California where access is under state or federal control. California and federal agencies should work with local entities to implement inspection and cleaning at other waters.

- Hatcheries that take water from an infested water body should switch to an uninfested source such as groundwater. If not possible, then fish from these hatcheries should not be planted into uninfested waters; any plantings should use appropriate fish transport protocols to minimize the spread of veligers.

- Protocols to prevent the accidental transport of zebra mussels should be implemented by all relevant activities in infested waters, including eradication/control, research and recreational activities.

### DETECTION MONITORING

- California and federal agencies should institute a core monitoring program for early detection of zebra mussels at high priority water bodies; and should work with local entities to augment the level of monitoring and extend it to other water bodies.

### OTHER RESEARCH PRIORITIES

- Within 30 days, California should conduct an initial analysis of the potential direct economic costs of the invasion (based on scaling from costs in the East), and an initial review of the potential environmental impacts of the invasion in California and in the West.

- California should also conduct more detailed assessments of the potential direct and indirect economic costs and environmental impacts in California.

- California should conduct an assessment of the vulnerability of California waters to colonization by zebra mussel species, including assessments of environmental requirements, a survey of calcium concentrations in California waters, and a survey of boat movements from infested waters into California.

- California and federal agencies should support research on promising control alternatives that need longer-term development.

## Introduction and Scope

In January 2007, a species of zebra mussel, *Dreissena bugensis*, was found in waters west of the Continental Divide. The significance and potential impact of this event can hardly be overstated. The zebra mussel invasion[1] in the lower Great Lakes has, in less than two decades, dramatically altered the composition and functioning of the largest freshwater ecosystems in North America. Zebra mussels are major fouling organisms; attaching by the millions to submerged objects, they form enormous masses that fill and block water pipes and clog protective screens and filters. Covering the bottoms of lakes and reservoirs, zebra mussels strip from the water critical portions of the food chain needed to sustain other aquatic life. As a result, water supply, power generation, navigation, shipping, commercial and sport fishing, and a variety of other activities have all been heavily impacted. Direct economic costs are on the order of $100 million annually in eastern North America; unquantified secondary and environmental costs could be substantially larger. Economic and environmental impacts in the Western U.S. could be as great or greater than those in the East.

California by itself hosts the eighth largest economy in the world, an economy which is highly dependent on the transport of large quantities of water across large distances through a large and complicated system of canals, pipes, pumps and other facilities. California agriculture is likewise dependent on the transport and distribution of vast quantities of irrigation water. Efforts to protect the state's aquatic ecosystems, which are already suffering from a variety of stresses, often involve restrictions on the storage, transport and diversion of water. Large-scale colonization of these waters and this infrastructure by zebra mussels would disrupt the state's water system and could impose significant restraints on the California economy.

The North American zebra mussel invasion has now, for the first time, established a beachhead in the transmontane West. In determining the appropriate scale of response we must consider the ultimate impact, across the entire West, of not containing and eliminating this beachhead—including the large-scale and long-term alteration of Western aquatic ecosystems, the primary economic impacts on irrigated agriculture, municipal water supply and power generation, and the secondary economic impacts affecting roughly one-quarter of the continental United States.

[1] The Great Lakes and other waters in eastern North America have been invaded by two species of freshwater European zebra mussels, *Dreissena polymorpha* and *Dreissena bugensis* (the latter sometimes known as the quagga mussel). Each species in turn has had enormous impacts on the Great Lakes.

## Background and Status of the Invasion

Zebra mussels, comprising several related species, are native to the Black, Caspian, and Aral sea drainages in eastern Europe and western Asia. Shipping canals constructed in the 18th and 19th centuries allowed them to spread, on the hulls of boats and barges, to other watersheds. In the 1980s, two species of zebra mussels appeared in the North American Great Lakes, having crossed the ocean in ships' ballast water: *Dreissena polymorpha*, discovered in Lake St. Clair in 1988, and *Dreissena bugensis* (also known as the quagga mussel), discovered in Lake Erie in 1989. Within 5 years of its initial sighting, *D. polymorpha* had spread to all five Great Lakes and the Hudson River in New York. By the end of 1996, zebra mussels had invaded waters in 20 states and two Canadian provinces, and reached west to the Oklahoma River and south to New Orleans. *D. bugensis* spread later and not as far, but wherever it has gone it has tended to displace *D. polymorpha*. Thus many zebra mussel populations in the lower Great Lakes which were primarily *D. polymorpha* are now dominated by *D. bugensis*.

These two species exhibit some modest differences in appearance and physiology. *D. polymorpha*'s keeled shape is more specifically designed for attachment to hard surfaces, while *D. bugensis*' rounder profile works well on both hard substrates and on sediment. *D. bugensis* also has a greater depth range, becoming abundant at substantial depths as well as near the surface. *D. bugensis* spawns at significantly lower temperatures, though its populations may suffer higher mortality at high temperatures.[2]

Until January 2007, when *D. bugensis* was discovered in Lake Mead, zebra mussels had not been found in any waters west of the Continental Divide. Within Lake Mead, *D. bugensis* occurs throughout Boulder Basin (the lake's lowest and western-most basin) and in the western end of the Virgin Basin (Figure 1 and Appendix A). The density generally appears to be low, with a maximum of perhaps a few hundred mussels per square meter at some sites. (In comparison, densities of over 100,000 zebra mussels per square meter have been reported in the Great Lakes.) Most of the records are shallower than 70 feet, but mussels were found down to 100-150 feet at a few sites,[3] and there is an unconfirmed report of mussels below 200 feet at one site.

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[2] MacIsaac 1994; Mills *et al.* 1996; Roe and MacIsaac 1997; Claxton and Mackie 1998; Thorp *et al.* 1998.
[3] National Park Service divers were limited to maximum depths of 100 feet, but a few surveys by U.S. Bureau of Reclamation divers and ROV and by Southern Nevada Water Authority divers went deeper.

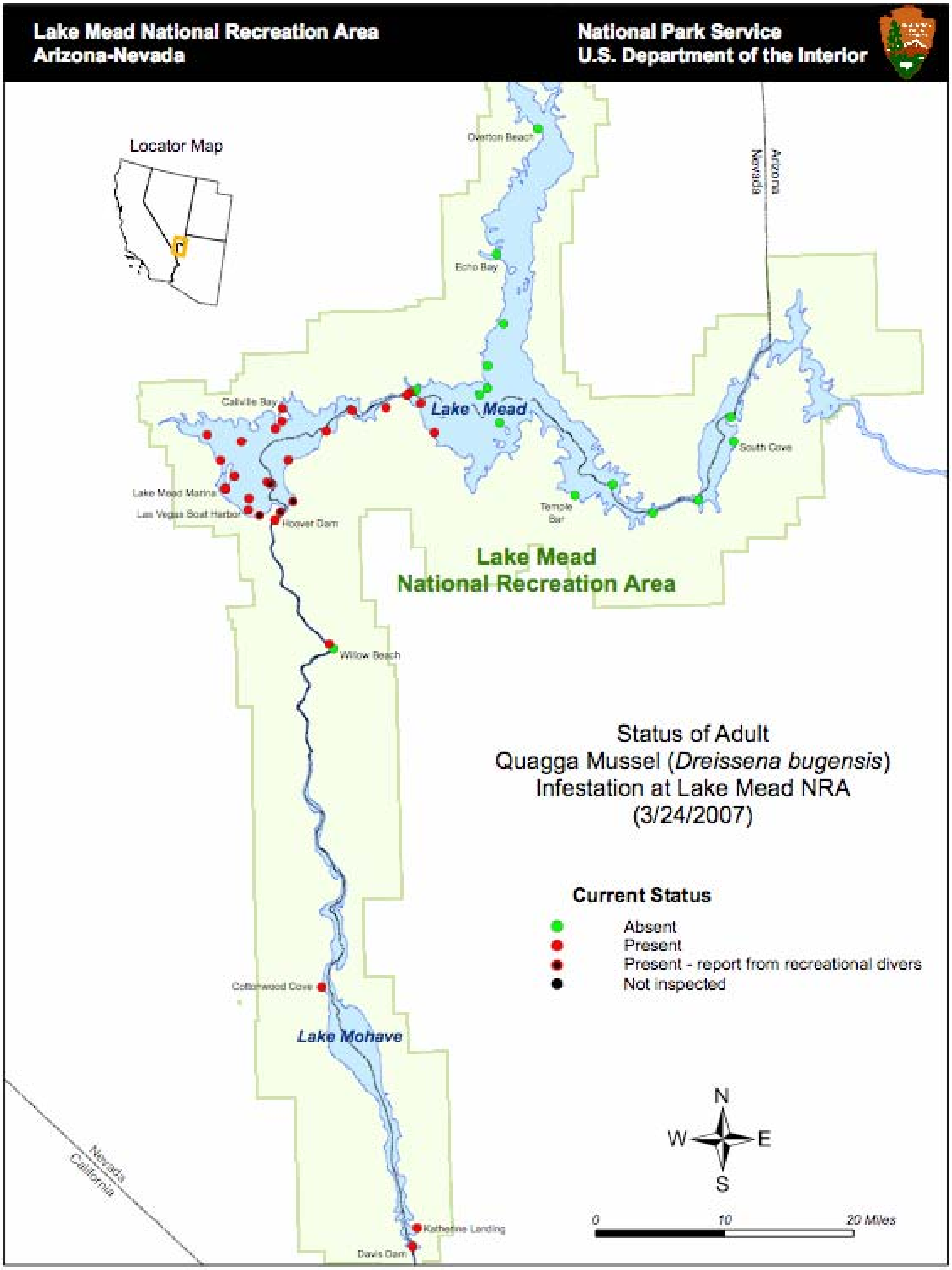


**Figure 1**. *Dreissena bugensis* records, Lake Mead to Lake Mojave (source: National Park Service map at http://www.100thmeridian.org/mead.asp).

Few mussels have been found downstream of Lake Mead. From Hoover Dam to the California border, mussels were reported in three marinas, in a fish hatchery and at Davis Dam, along with a single mussel in the river immediately below Hoover Dam, but only a few surveys have been conducted in this section. Much more extensive surveys downstream along the California border found a total of 934 mussels (Figure 2).[4] All were in the lower portion of Lake Havasu or in the first 21 miles of the Colorado River Aqueduct, which draws water from lower Lake Havasu, and nearly all were removed.[5] Extensive surveys elsewhere in California have found no mussels.[6]

[4] In January-February 2007, the California Department of Fish and Game, Metropolitan Water District of Southern California (MWD), Central Arizona Project and U.S. Bureau of Reclamation conducted at least 30 dive surveys and 40 surface surveys along the Colorado River between Needles and Yuma. MWD also conducted extensive surveys in the Colorado River Aqueduct system, including dewatering and examining portions of the aqueduct.
[5] A few mussels were dropped and lost during collection.
[6] These included 141 surface surveys conducted by the California Incident Command throughout the state in February-March 2007.


**Figure 2**. *Dreissena bugensis* records in the Colorado River between Nevada and Mexico (source: California Department of Fish and Game).

## Potential Impacts

Since *D. polymorpha* arrived and spread through the Great Lakes first, early reports attributed all of the impacts to this species. However, *D. bugensis* subsequently displaced *D. polymorpha* in much of the lower Great Lakes, and the economic and environmental impacts in these waters are now mainly due to *D. bugensis*.

Zebra mussels of either species are costly fouling pests that cause the greatest economic damage when infesting the pipes, pumps or other components of municipal and industrial water supply systems or power plant cooling water systems. Mussel populations on these and similar structures can build up astonishing densities of up to 750,000 individuals per square meter in layers more than a foot thick. Affected facilities include the intakes, conveyance structures and treatment plants of municipal drinking water systems; industrial cooling, flushing and process water systems; cooling water and service water systems in nuclear, fossil fuel and hydroelectric power plants; dams and impoundments, including inflow and outflow conduits and water level control mechanisms; surface and subsurface agricultural irrigation systems; golf course and park irrigation systems; fire-fighting (hydrant) distribution systems that use untreated surface water; institutional chilled water air conditioning systems that use a surface water supply for makeup water; locks, buoys and other navigation facilities and equipment; and ballast intake and service water systems on cargo vessels that take in fresh water. In treatment plants, impacts can include "loss of intake head, obstruction of valves, blockage of rotating screens, cavitation-mediated wear on pump bells and impellers, putrefactive decay of proteinaceous mussel flesh and the related methane gas production...and increased electrocorrosion of steel and cast iron pipelines resulting from bacterial growth around the mussels' byssal attachments."[7]

Zebra mussels have caused a variety of ecological impacts on invaded waters. They consume and reduce populations of phytoplankton (the microscopic drifting plants that are an important component of aquatic food webs);[8] this is often followed by reductions in zooplankton,[9] some

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[7] O'Neill 1996.

[8] Phytoplankton were reduced by >90% in Lake St. Clair, 60-90% in Lake Erie and 85% in the Hudson River following the establishment of large populations of zebra mussels (MacIsaac *et al.* 1995; Caraco *et al.* 1997).

[9] Rotifers were reduced by 50-75% in western Lake Erie, and zooplankton by 70% in the Hudson River (Leach 1993; MacIsaac *et al.* 1995; Pace *et al.* 1998). Zooplankton are suppressed both directly (by being eaten) and indirectly (by depletion of phytoplankton).

crustaceans[10] and fish.[11] The removal of phytoplankton increases water clarity, which in some areas has led to an explosive growth of bottom algae.[12] Overall, invasion by zebra mussels tends to shift primary and secondary production from pelagic (in the water column) to benthic (bottom) zones of lakes and large rivers. By concentrating metals and organochlorines in their tissues, zebra mussels contribute to the accumulation of toxic contaminants in food chains.[13] Finally, zebra mussels pose a threat to the nearly 300 native species of freshwater clams in North America, most of which were already rare or declining.[14] Zebra mussels preferentially settle on clam shells, often in sufficient numbers to impair feeding and respiration in the clams they settle on, and ultimately starving them; and indirectly harm native clams by depleting their food resources.[15]

Published estimates of the costs of the American zebra mussel invasion vary greatly, and the actual cost remains uncertain.[16] Extrapolating from surveys

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[10] The zebra mussel invasions in Lakes Erie, Ontario, Huron and Michigan were followed by large declines in the ecologically important amphipod *Diporeia*, which had dominated benthic biomass and productivity in the colder, offshore regions of the lakes (Pothaven *et al.* 2001; Nalepa *et al.* 2005).

[11] As zebra mussels increased in Saginaw Bay, yellow perch's zooplankton food decreased by two-thirds and the commercial catch of yellow perch dropped precipitously (Jude 1996). In the Hudson River, significant declines in open water fish, especially shad (*Alosa sapidissima*) and white perch (*Morone americana*), coincided with the invasion by zebra mussels (Strayer *et al.* 2004). In Lake Michigan, lake whitefish (*Coregonus clupeaformis*) suffered a change in diet as its major prey, *Diporeia*, declined, resulting in reduced growth and poorer body condition (Pothaven *et al.* 2001); abundance, growth rates and body condition have declined in Lake Ontario (Nalepa *et al.* 2005). Alewives (*Alosa pseudoharengus*) also fed less on the declining population of *Diporeia* and more on other food sources with lower energy values, leading to alewives with 23% lower energy density and 50% less lipid content, which in turn can be expected to affect Chinook salmon (*Oncorhynchus tshawytscha*), the predominate alewife predator in the lake (Madenjian *et al.* 2006).

[12] With subsequent taste and odor problems in drinking water systems.

[13] For example, higher concentrations of organic contaminants, which can reduce egg size and increase embryo mortality, are found in the tissues of diving ducks that had fed on Lake Erie zebra mussels than in ducks that had not (De Kock and Bowner 1993).

[14] Schloesser *et al.* 1998.

[15] In the United States, all clam species coexisting with zebra mussels suffer from at least low to medium levels of infestation. Nearly 100% mortality of native clams was observed in western Lake Erie (Schloesser and Nalepa 1994), along with large population declines and several species extirpated in southern Lake St. Clair, the Detroit River, eastern Lake Erie, the St. Lawrence River, and other lakes and rivers outside of the Great Lakes region (Schloesser *et al.* 1996, 1998; Ricciardi *et al.* 1996; Strayer and Malcolm 2007). In many sites, unionid mussel populations declined by >90% in 4-8 years after initial colonization by zebra mussels (Schloesser *et al.* 1998; Ricciardi *et al.* 1998). In the Hudson River, however, initial steep declines of native unionids (Strayer and Smith 1996), was followed by stabilization or recovery of the most common species (Strayer and Malcolm 2007).

[16] For example, the U.S. Congressional Office of Technology Assessment projected U.S. costs of $3.4 billion in 1991 dollars over 10 years (OTA 1993), or somewhere around $550

conducted in 1995 of a portion of affected facilities, the retrofitting, operations and maintenance costs to facilities in eastern North America appears to be somewhere around $100 million per year—not including secondary economic costs or environmental costs.

A few general considerations will shape efforts to extrapolate from estimates in the East to projections of costs in the West. Strayer's rough early map of *D. polymorpha*'s potential distribution in North America showed ranges that included most of the United States (including nearly all of California except for the southeastern portion of the state) and much of southern Canada.[17] Strayer noted that low calcium concentrations might limit zebra mussels within this range, and subsequent studies have confirmed this.[18] The U.S. alkalinity map shows low levels of alkalinity over many large areas of the East (especially in New England and the Southeast), but in fewer and smaller areas in the West.[19] Alkalinity is a reasonably good proxy for calcium concentrations,[20] so it appears that in the West a substantially larger portion of the region is chemically suitable for zebra mussels than in the East.[21]

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million per year in 2007 dollars. An often cited figure of $5 billion—given as $5 billion in the U.S. through 2000 by Miller *et al.* 1992, as $5 billion in the Great Lakes through 2000 by Ludyanskiy *et al.* 1993, and as $1-5 billion *annually* in the U.S. by Aldridge *et al.* 2006—is apparently based on a projected cost of $4.82 billion in North America over 10 years, of which $2.11 billion was for impacts to facilities and vessels and $2.71 billion was for impacts to Great Lakes fisheries (C.R. O'Neill, pers. comm.). Other published figures include a projection of $2 billion in the Great Lakes region over 10 years (McMahon *et al*. 1993), and in two frequently cited reviews of the costs of invasions in the U.S., estimates of $100 million per year (Pimental *et al.* 2000) and $1 billion per year (Pimental *et al.* 2005). In most cases it's not clear what these estimates and projections are based on, and whether they are limited to facilities costs or include secondary or environmental costs.

[17] Strayer 1991. Strayer's projection was based on the air temperatures that coincided with the limits of *D. polymorpha*'s range in Europe, and thus should be used as only a general guide to its potential distribution in North America. As noted above, *D. bugensis* is less tolerant of high temperatures and better adapted to low temperatures than *D. polymorpha*, so its range limits may lie a little further north.

[18] Cohen and Weinstein 2001. *D. bugensis* is thought to have similar or perhaps slightly higher calcium requirements than *D. polymorpha* (Zhulidov *et al.* 2004, cited in Karatayev *et al.* 2007).

[19] Omernik and Powers 1983.

[20] For example, see Whittier *et al*. 1995.

[21] In contrast, the one other published study of zebra mussels' potential distribution over continental U.S. reaches the opposite conclusion. Drake and Bossenbroek (2004), using three GARP models based on the mussels' existing distribution in the East, conclude that nearly all of the West is "uninhabitable for zebra mussels." There are several problems with this study that make this conclusion doubtful: (1) the model variables are either unrelated or only indirectly related to the environmental factors known to affect zebra mussel distributions; (2) some of the input data are wrong: sites where mussels were reported only once and that appear to be unsuitable for zebra mussels were included as if they were sites where zebra mussels are established; (3) the models weren't validated with independent data, they were "tested" only by comparing model results to other model results; and (4)

Regarding comparative economic impacts, there are no nuclear power plants in California that draw cooling water from surface freshwater systems (in the East, nuclear plants incurred the highest costs of any type of facility[22]), and there is no inland freshwater system of barge canals, barge and ship locks, or a freshwater cargo fleet. However, California has a much larger and more far-reaching water transport and delivery system,[23] a much greater reliance on agricultural irrigation systems, and a much larger number of hydroelectric power plants. Its economy is more deeply dependent on keeping large volumes of water moving over long distances than is that of any eastern state.

California also has one of the highest concentrations of rare freshwater fish, amphibians, and aquatic invertebrates of any state in the country, many of which are already stressed from pollution, habitat fragmentation and exotic species. In the upper part of San Francisco Bay and the western Delta, the clam *Corbula amurensis* has depleted phytoplankton blooms and probably contributed to the decline in pelagic organisms that is the latest crisis in this ecosystem. If *D. bugensis* became established in the Delta,[24] combining its efficient plankton filtration with that of *Corbula*, the results could be devastating.

Given the probably greater vulnerability of western waters, the greater dependence on transporting water long distances, and the highly stressed aquatic ecosystems, the overall economic and environmental impacts of zebra mussel invasion are likely to be at least as great and possibly greater than the impacts in the East.

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the outputs are inconsistent with well-known biological requirements of zebra mussels. It is telling that all three of the models predict zero chance of invasion in Lake Mead.

[22] O'Neill 1996.

[23] The State Water Project and Central Valley Project alone have over 1,600 miles of aqueducts and canals.

[24] As noted below, the Delta is one of the leading destinations for boat leaving Lake Mead.

## Recommendations

### Overview

The operational response to the zebra mussel invasion in the West can be divided into five elements or stages:

- *Initial Assessment*: Characterize the mussels' initial distribution and abundance.

- *Eradication/Control*: Assess eradication and control options in currently infested waters, determine feasibility, and implement as appropriate.

- *Containment*: Prevent overland spread to other water systems.

- *Detection Monitoring and Rapid Response*: Implement a monitoring program to detect any new infestations at an early stage, and respond rapidly to contain and eradicate or control them.

- *Mitigation*: Minimize the effects of infestations on facilities and ecosystems.

The initial assessment of the invasion was completed by the National Park Service, California Quagga Mussel Incident Command, Metropolitan Water District and others. We here recommend a set of fundamental steps regarding the **eradication and control** of the mussels in currently infested waters, **containment** within those waters, and **monitoring** to detect new infestations. We do not make any specific recommendations here regarding rapid response, although many of the same issues—technical, administrative, financial and regulatory—that affect eradication, control and containment in currently infested waters will also apply to new infestations. We did not consider specific mitigation measures—such as changes in infrastructure, operations or maintenance at facilities, or changes in ecosystem management—that could reduce the impacts from infestations that are not prevented or eradicated; but we suggest that agencies should proceed with advance planning for such measures.[25]

[25] For example, see Tippit 1993.

## Eradication / Control

The largest *D. bugensis* population occupies the Boulder Basin and the western end of the Virgin Basin in Lake Mead. This is also the most upstream population, providing a supply of veligers to initiate or augment downstream populations. If the Lake Mead population were eradicated, then the smaller downstream populations would be relatively easy to remove and, especially in the river sections, would tend to die out over time once the upstream source of veligers was eliminated. We first discuss eradication in Lake Mead, then possible approaches for reducing the downstream flow of veligers, and last the eradication of populations below Lake Mead.

Lake Mead

After eight years of drought, Lake Mead is currently (4/25/07) 106 feet below its full surface elevation, holds 50% of its maximum volume and covers 61% of its maximum surface area. The mussel-infested areas appear to cover a little under a third of the lake, or about 30,000 acres. This is a large area, but there are several technically feasible eradication methods that would have a strong chance of success if they were promptly and diligently applied at an appropriate scale. The Panel believes that this can be done at a reasonable cost relative to the economic and environmental costs of not acting, and recommends that a determined effort be made to eradicate *D. bugensis* from Lake Mead.

An efficient eradication effort will likely use a number of methods in combination. We here describe six distinct approaches for killing or removing settled mussels, in the order of their individual effectiveness as ranked by the Panel.

- *Dewater*: In experimental treatments, *D. bugensis* lives for only a few days out of water,[26] so lowering the lake level is a sure method of killing mussels.[27] Hoover Dam has two intake towers on the Nevada side of the lake and two on the Arizona side. From these, water can be withdrawn through tunnels located at 76 feet and 227 feet below the current water surface. This water is usually discharged through the penstock and the power plant turbines, but can also be discharged directly through the jet flow gates under emergency or flood conditions or to empty the penstocks for maintenance work. Assuming mean 2006 net rates of

[26] All *D. bugensis* died within 5 days of aerial exposure in warm conditions (20° C at 10-95% relative humidity), and within 15 days in cold, humid conditions (10° C and 95% relative humidity) (Ricciardi *et al.* 1995).

[27] At the same time, increasing the discharge from Lake Mead while veligers are present would transport larger numbers of veligers downstream. This trade-off would need to be considered carefully.

inflow, releasing water at the maximum rate of discharge would lower the lake by about 120,000 acre-feet a day.[28] Because of impacts to the City of Las Vegas' water supply, it may not be feasible to lower the lake surface below Southern Nevada Water Authority's (SNWA) upper or lower water intakes.

Lowering the lake surface to either the upper SNWA intake or the upper Hoover Dam intake would take about 7 weeks at maximum discharge, and would drop the water by 73-76 feet, reduce the current surface area of the lake by one quarter, and reduce the current volume by almost 40%. This would kill the majority of *D. bugensis* in the lake,[29] and would make the treatment of the remainder considerably easier as they would be closer to the surface and distributed over a smaller area. In addition, a large part of the remaining area is covered by fine lake-bottom sediments that have accumulated since the construction of Hoover Dam,[30] which provides a relatively poor substrate for the mussels. If it proved feasible, lowering the lake 123 feet to the lower SNWA intake would require about 11 weeks total, and would reduce the lake to about 55% of its current area and 30% of its current volume; lowering it 227 feet to the lower Hoover Dam intake would take about 16 weeks and would reduce the lake to about 30% of its current area and 15% of its current volume.

- *Isolate and Treat*: Mussel populations can be isolated behind barriers or under coverings and then killed with an appropriate biocide. The "killer algae" *Caulerpa taxifolia* was eradicated from two southern California lagoons by covering the infested areas with plastic mats and pumping liquid sodium hypochlorite or placing chlorine-releasing tablets under the mats.[31] Plastic isolation curtains, hanging from floats and anchored to the bottom, have frequently been used for herbicide treatments of aquatic weeds. Similar barriers have been used to contain sediment generated by construction or dredging activities and to contain chemical spills.

[28] The calculations on draw-down rates are based on data from the U.S. Bureau of Reclamation at http://www.usbr.gov/dataweb/ and provided by Carly Jerla.
[29] All of the mussels reported in the Virgin Basin and Boulder Canyon, and most of the mussels reported in the Boulder Basin were at less than 70 feet deep.
[30] Twichell *et al.* 1999.
[31] Anderson 2005; Merkel & Associates 2006.

A number of biocides are available that would be effective in killing *D. bugensis*.[32] Potassium chloride was used to eradicate *D. polymorpha* from a 12-acre quarry pond,[33] and copper sulphate and sodium hypochlorite were used to eradicate the related black-striped mussel, *Mytilopsis sallei*, from three boat basins in Australia.[34]

- *<u>Cover</u>*: Plastic mats laid on the bottom are routinely used to kill aquatic weeds. Field trials applying this technique to *D. polymorpha* produced over 99% mortality in 9 weeks. Mortality was apparently due to hypoxia, though accumulation of waste products, lack of food or other stresses may have contributed to the effect.[35] Covering *D. bugensis* on the bottom, or tightly wrapping them where they occur on structures, could be an effective, biocide-free technique.[36]

- *<u>Heat</u>*: Water heated to 40° C (104° F) kills *D. polymorpha* on contact.[37] The invasive seaweed *Undaria pinnatifida* was eradicated from the hull of a vessel sunk in the ocean off Chatham Island, New Zealand, by using electric heating elements inside a shroud fixed to the hull and treating small, inaccessible areas with a modified cutting torch.[38] Superheated steam has been applied to benthic populations of *Undaria*.[39]

- *<u>Batch Treatment</u>*: Batch treatment means treating the entire infested area with a biocide—either all of Lake Mead, or Boulder Basin alone if it can be isolated from the upper part of the lake by a temporary barrier. California has conducted some large batch treatments—including applying rotenone to Lake Kaweah, Frenchman's Lake and Lake Davis to kill white bass and northern pike—but treating Lake Mead would involve a much larger volume of water.

- *<u>Mechanical Removal</u>*: Various mechanical techniques have been used to remove mussels and other fouling from structures such as water intakes

[32] Metallic salts (potassium and copper ions), oxidizing agents (chlorine, chlorine dioxide) and various nonoxidizing molluscicides were effective biocides in tests on *D. polymorpha* (McMahon *et al.* 1994; Netherland *et al.* 1998).
[33] Bax et al. 2002.
[34] USFWS 2005.
[35] Braithwaite *et al*. (undated); S. Nierzwicki-Bauer, pers. comm. In anaerobic conditions, *D. bugensis* survives longer than *D. polymorpha* at 4° C, but dies quicker than *D. polymorpha* at 20° C (O'Brien 2006).
[36] A variant of this technique would be burying the mussels.
[37] McMahon *et al.* 1994. *D. bugensis* generally has a slightly lower tolerance for high temperatures than *D. polymorpha* (*e.g.* MacIsaac 1994; Mills *et al*. 1996; Thorp *et al*. 1998). Lower temperatures would be effective with longer exposures, or if mussels are acclimated to lower temperatures (Payne 1992; McMahon and Ussery 1995).
[38] Stuart 2004.
[39] *Ibid*.

and pipes which could be employed in Lake Mead. These range from the use of handheld scrapers with attached suction hoses to abrasive blast cleaning using sand, grit or carbon dioxide pellets.[40]

The most efficient program will likely include a combination of approaches. Thus, for example, even a limited draw-down of the lake would improve the effectiveness of other approaches by reducing the area or volume to be treated. Populations could initially be covered, and those not killed by covering alone could be treated beneath the covering with appropriate biocides as regulatory permits become available. In situations where covering is difficult or impractical, heat treatment or mechanical removal may be more cost-effective. Efforts at water intakes and at marinas, boat launches or other locations where recreational boats congregate should receive the highest priority to reduce the infestation of critical infrastructure and reduce the risk of transport to other water bodies. In addition, the large-scale use of plankton tows in Lake Mead in conjunction with these approaches would reduce the further settlement of mussels during the eradication effort and reduce the number of veligers transported downstream. The eradication effort should be guided by a team that includes expertise in zebra mussel biology and ecology, reservoir/riverine hydraulics, mechanical engineering, aquatic species eradication and containment, pesticide (molluscicide) use and aquatic environmental toxicology.

Field trials of Cover, Heat and Mechanical Removal approaches, and of large-scale plankton tows to reduce veliger densities, should begin immediately in Lake Mead, along with trials of the Isolate and Treat approach as soon as regulatory approval can be obtained. Such field trials are equally needed for large-scale eradication planning in the lake, for eradication/control efforts focused on intakes, marinas and boat launches, and for developing rapid response techniques that can be used if zebra mussels are discovered in other water bodies.

Investment should also be made in promising approaches that need longer development times, such as:

- Zebra mussel-specific toxins derived from bacteria or other sources;[41]
- Encapsulating and delivering a biocide in microscopic controlled-release particles ingested by mussels;[42]

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[40] O'Neill 1996. In some cases, the most efficient mechanical approach may be to just remove the substrate from the water. For example, in an infested marina, boats and floating docks could be removed from the water for a few weeks, which would kill any mussels on them and facilitate treatment of the mussels remaining on the bottom.
[41] For example, see Mitchell and Gu 1998; Malloy 2006.

- Delivering a biocide in a gel that remains in contact with mussel populations on horizontal, sloped or vertical surfaces.

Downstream Veliger Flow

Veligers that survive passage through the Hoover Dam waterworks and into the Colorado River can drift downstream and settle in the river, in reservoirs or in water diversion systems. Methods of reducing the downstream flow of veligers should be investigated, and implemented if feasible. These could include:

- Large-scale plankton tows, as mentioned above;

- Monitoring veliger distributions in the lake and choosing the timing, location and depth of intake to minimize the number of veligers entrained through Hoover Dam;

- Treating the water drawn though Hoover Dam with a biocide with a very short contact time and a short life and/or no impact at applicable doses on important non-target organisms or public health;[43]

- Hydrocyclone or filtration to remove veligers from the water drawn though Hoover Dam.

Where they are applicable, these approaches should also be investigated at Davis Dam on Lake Mojave and at Parker Dam on Lake Havasu.

Below Lake Mead

Surveys to date indicate that populations below Lake Mead are small and limited in distribution, and eradication seems feasible with modest effort. Hand picking alone might eliminate the mussels from Lake Havasu. The approaches mentioned above—Mechanical Removal, Cover, Heat or Isolate and Treat—may suffice for the infested marinas and the hatchery in or near Lake Mojave. Any populations in the river itself are likely to be small, and would die out over time if upstream sources of veligers were eliminated.

Eliminating the populations below Lake Mead would have at least two distinct benefits:

- It would substantially reduce the supply of veligers to the Colorado River Aqueduct, the Central Arizona Project, the All American Canal and other

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[42] For example, see Aldridge *et al.* 2006.

[43] Possibilities include chlorine at 0.25-0.5 ppm, acrolein, ozone and potassium chloride.

large water systems that divert water from the Colorado River below Lake Mojave.[44]

- It would eliminate two major sources of mussels (Lakes Mojave and Havasu) for accidental transport on boats hauled to other Western waters.

## Containment

There are three main points where the spread of *D. bugensis* into additional California waters could be blocked: at the source waters on the lower Colorado River, at the California border check stations, and at the destination waters in California. Each containment point has advantages and disadvantages. The fullest possible effort should be made at the source waters and border check stations; and a selective effort should be made by California and federal agencies at destination waters in collaboration with local authorities and the public. If additional legal authorities are needed to implement the following recommendations, they should be developed and adopted immediately.

Source Waters

The infested waters include Lakes Mead, Mojave and Havasu and the reaches of the Colorado River that run between them. Lakes Mead and Mojave are in the Lake Mead National Recreation Area (NRA), which is operated by the National Park Service (NPS). There are nine marinas in the Lake Mead NRA; three in the Boulder Basin and three in Lake Mojave have *D. bugensis* reported in or near them, while the remaining three marinas are in the upper, uninfested sections of Lake Mead. There are a few additional boat launches. There are only about a dozen roads entering the NRA, some of which are unpaved, and several of which pass through a fee station.

[44] At mean water velocities (based on U.S. Geological Survey data for 2000 to the present), the travel times on the reaches between reservoirs on the lower Colorado River range from less than a day to 3-4 days per reach. Mean retention times in the reservoirs are much longer, 9 weeks in Lake Mojave and 3-4 weeks in Lake Havasu (based on January 1, 2007 reservoir volumes, 2006 annual discharges and 2007 forecast diversions). Since *D. polymorpha* veligers can drift in the water for a period that is usually estimated at 8-10 days up to about a month (and is generally shorter at higher temperatures; estimates reviewed in Cohen and Weinstein 2001), and *D. bugensis* is assumed to have a similar planktonic period, most of the veligers released from Lake Mead would not reach the major water diversions at and below Lake Havasu, and eliminating any veliger sources downstream of Hoover Dam would substantially protect these diversions.

An average of around 700 boats use Lake Mead on a summer weekday, about 1,300 boats on a summer weekend, and about 2,500 boats on a summer holiday weekend, with similar numbers on Lake Mojave. About one-third of Lake Mead boats and two-thirds of Lake Mojave boats surveyed came from California, with most of them presumably returning there.[45] The most common destinations of boaters leaving Lake Mead include Clear Lake (#6), Lake Shasta (#7), Lake Oroville (#15) and the Sacramento-San Joaquin Delta (#19).[46]

*D. bugensis* has also been found at Laughlin Bay Marina, below Davis Dam and just south of the NRA, and at several sites in lower Lake Havasu. There are numerous boat launches and marinas in the lakes and along the river. Land ownership varies, including private land, reservation lands, a National Wildlife Refuge, an Arizona state park and a county park.

The Lake Mead NRA has advised boat owners to clean their boats before leaving Lakes Mead or Mojave for other waters; requires the owner of any boat moored in these lakes to clean and remove zebra mussels from it before leaving the NRA; and is instituting procedures to examine and possibly stop and clean boats at major boat ramps. Nevertheless, in February and March five boats that had been moored in Lake Mead were intercepted in Arizona and California with live mussels on them.[47] In April, a boat that had been moored in Lake Havasu was stopped at a California check station with live mussels on its hull. To prevent further transport of *D. bugensis* out of these waters, the following actions should be taken:

- Lakes Mead, Mojave and Havasu should be closed to boating until eradication efforts are completed.

- If the lakes are not fully closed, then before leaving the NRA all boats should be (1) cleaned by NPS staff or their certified agents and drained of any standing water, and then (2) inspected by NPS staff or their agents for the presence of standing water, zebra mussels, aquatic plants, or other fouling on the boat or trailer. Cleaning should include a careful washing or flushing of all potentially infested surfaces with water heated

[45] Hickey 2007; V. Hickey pers. comm.
[46] Based on a survey of 213 boaters at Lake Mead, results cited at http://www.100thmeridian.org/mead.asp.
[47] In late February, workers at the Pleasant Harbor Marina on Lake Pleasant in Arizona intercepted a 55-foot houseboat from Lake Mead whose hull was covered with adult mussels. Between March 1 and 23, inspectors at California's border check station in Yermo found live *D. bugensis* on four boats that had been moored in Lake Mead; and on April 25 inspectors at the Needles station found them on a boat that had been moored in Lake Havasu for six months.

to at least 40° C (104° F) and treatment of any water ballast tanks.[48] Boats that fail inspection should be re-cleaned and re-inspected. Boats that have been in the NRA for less than 24 hours and that do not have ballast tanks may be allowed to proceed directly to inspection without prior cleaning by NPS staff or their agents.

- Measures should be taken to clean and inspect boats leaving Lake Havasu and other downstream waters on the lower Colorado River system.

<u>The State Border</u>
California has border check stations on 16 major roadways entering California from adjacent states (Figure 3). These stations mainly inspect agricultural produce to prevent the entry of crop pests, but in the 1990s they began checking for zebra mussels on boats being hauled into the state. Since January 29, 2007, the three stations closest to the infested lakes,[49] which operate 24 hours a day, have been inspecting every entering boat. The other stations only inspect boats that are carried by commercial haulers; six of these stations operate around the clock, while the remaining seven stations are open intermittently. Some significant routes into California lack a check station; one of particular concern is U.S. Route 95, which runs south from the western side of Lakes Mead and Mojave, crosses the California border, and joins Interstate 40 west of the check station at Needles.

At the three stations closest to the infested lakes, 6,739 boats were inspected between January 29 and April 10, or a little under 100 boats a day. The inspectors found that about 6% of the boats held water that could carry veligers, which they drained. As noted above, five boats had live mussels from Lakes Mead or Havasu on their hulls. These boats were given a quarantine notice that required them to be cleaned of mussels and inspected by a state agent before being placed in the water.

To prevent the further transport of zebra mussels across the California border, the following actions should be taken:

- All 16 border check stations should operate 24/7, and an additional temporary or permanent station should be set up on US-95 between the

[48] Some large speedboats used for water skiing are equipped with ballast tanks, which often cannot be emptied completely. These tanks should either be drained as far as possible and then filled with water hot enough to kill any mussels in the tanks, or drained and treated with an appropriate biocide such as potassium chloride.
[49] At Yermo on Interstate 15, at Needles on Interstate 40 and at Vidal Junction on State Route 62.

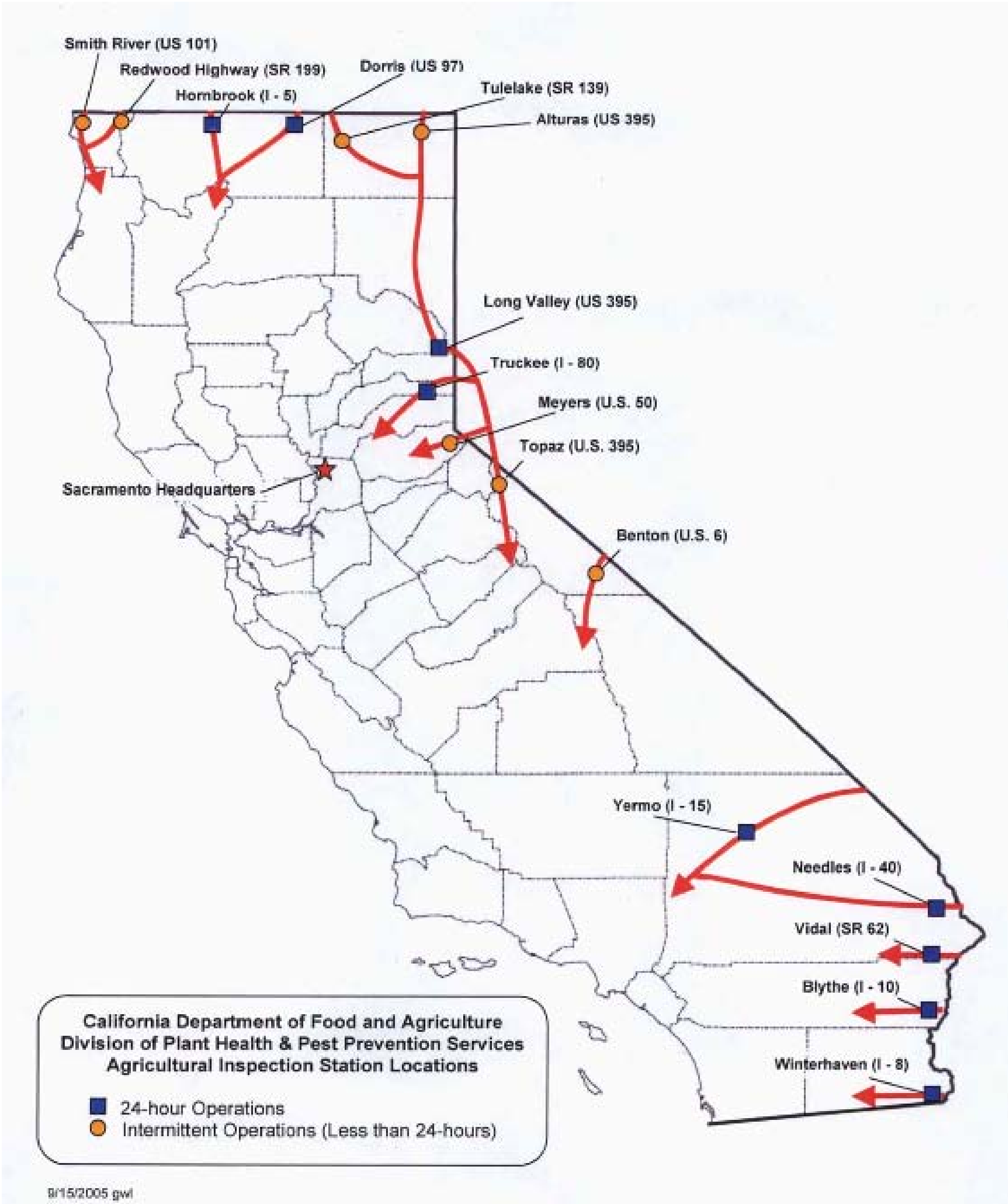


**Figure 3**. California border check stations (source: California Department of Food and Agriculture).

California border and I-40. All boats should be inspected at all of these stations, not just the boats carried by commercial haulers. In addition to the three stations currently implementing this level of effort, the highest priority are the stations at Truckee on I-80, at Meyers on US-60, at a new station on US-95, and at Blythe on I-10.

- Any standing water found during inspection should be drained before the boat is allowed to proceed. Any boat with live or dead mussels should be given a quarantine notice and not allowed to proceed until it is cleaned by state staff or their agents, either at the border station or at a designated site to which the boat is taken directly. Cleaning should include a careful washing or flushing of all potentially infested surfaces with water heated to at least 104° F (40° C) and treatment of any water ballast tanks.

- An effort should be made to assess the effectiveness of border inspections—for example, by sending through boats that have been planted with artificial or dead zebra mussels.

Destination Waters

The following actions should be taken at lakes and rivers in California:

- At high priority water bodies in California where boating access is under state or federal control, state and federal agencies should institute an inspection and cleaning program similar to that at the border check stations. The prioritization of water bodies should be based on their suitability for zebra mussels (considering such factors as salinity, calcium, temperature, etc.)[50] and the number and origin of boats arriving from other water bodies.

- At other water bodies, the state should encourage, assist and work with local authorities, marina and boat launch operators to ensure that boats are inspected and cleaned before entry.

Containment of Other Vectors

*Hatcheries.* Hatcheries should switch to uninfested source water such as groundwater. If this is not possible, then fish from these hatcheries should not be planted into uninfested waters, and any plantings should use protocols to minimize the risk of transporting mussel veligers.[51]

[50] An assessment done for *D. polymorpha* (Cohen and Weinstein 1998) could be quickly updated and recalculated for *D. bugensis*.

[51] For example, one hour pretreatment with 750 mg/L KCl, two hour treatment with 25 mg/L formalin in well water or 20-micron filtered surface water, and transfer from transport

*Research.* Any field research in infested waters should implement protocols to prevent the accidental transfer of zebra mussels to new locations on equipment or by other means. Agencies should deny access, permits, authorization and funding for research in infested waters if appropriate protocols are not implemented.

*Eradication/Control.* Eradication efforts must implement protocols to prevent the accidental transfer of zebra mussels to other locations.

*Other Activities.* Anglers, divers, marina staff and others engaged in work or recreation in infested waters should follow protocols to prevent the accidental transfer of zebra mussels to other locations.[52]

## Detection Monitoring

State and federal agencies should implement a core detection monitoring program for the early detection of zebra mussel invasions at currently uninfested water bodies; and encourage, assist and support local authorities, water supply agencies, power plants, marina operators, boating, fishing and diving groups, researchers, educators, students or others to engage in monitoring that will augment and extend this program. The program should use a variety of methods (such as settlement samplers, surface surveys, diver surveys, veliger sampling, *etc*.), with the mix depending on site characteristics, relative costs and other factors. The sampling sites should be selected based on their suitability for zebra mussels in terms of factors such as salinity, calcium, temperature, substrate, *etc*.; the number and origin of boats arriving from other water bodies; and the ease of sampling.

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truck to receiving water in dip net with no discharge of water (Edwards et al. 2002; Anonymous 2004; Anonymous, undated; Bollig, undated); or "waterless conveyance" methods, where the water is briefly drained from the trays holding the fish while they are transferred from the hatchery to the transport truck (J. Herod, pers. comm.).

[52] Carlton (1993) discusses 20 human-mediated mechanisms that could transport zebra mussels between water bodies.

## Other Research Priorities

In addition to the research described above as part of eradication and containment efforts,[53] the Panel identified several research needs (summarized in Appendix B), with the following being of the highest priority:

- We urgently need a clearer understanding of the economic and environmental costs of allowing zebra mussels to spread across the West, in order to support decisions about the appropriate level of effort to put into our response. There is currently no information on these costs, except for one study of the costs of infrastructure modifications that would be needed to mitigate zebra mussel infestations at Columbia River hydropower facilities.[54] We need a rough estimate of the overall potential costs and impacts immediately, followed by more precise assessments as soon as they can be developed. Therefore California should, within 30 days, develop an initial estimate of the potential direct economic costs of the invasion (based on scaling from cost estimates in the East) in California and in the West, and conduct an initial review of the potential environmental impacts of the invasion in California and in the West. California should follow these initial assessments with more detailed studies of the potential direct and indirect economic costs and environmental impacts in California.

- Not all waters are at equal risk of invasion, and significant cost savings and efficiencies could be gained by focusing containment and detection efforts on waters that are most at risk. California should conduct an assessment of the vulnerability of California waters to colonization by zebra mussel species, including assessments of the species' environmental requirements, a survey of calcium concentrations in California waters, and a survey of boat movements from infested waters into California.

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[53] Field trials of eradication approaches in Lake Mead; investigation of methods of reducing the downstream flow of live veligers out of Lake Mead; research on promising control methods that need longer-term development; and assessment of the effectiveness of border inspections.
[54] Phillips *et al.* 2005.

## Concluding Thoughts

It cannot be overemphasized that the actions taken now will be watched and studied by managers and scientists literally around the world. Early detection and management programs for invasive aquatic species are in their infancy globally: how federal and state agencies respond to new infestations of major invasive species is followed closely. Zebra mussels—both *D. polymorpha* and *D. bugensis*—are widely regarded as among the most important and harmful invaders in North America. For nearly 20 years, substantial investments of time, money and effort have been made to keep these mussels from crossing the 100th Meridian. Even greater investments should now be made to eliminate the zebra mussel outpost that has recently appeared on the lower Colorado River.

In the history of invasions, proposals to eradicate or control new populations of exotic species have often been dismissed as too daunting, too expensive or too politically challenging to undertake. Eradication efforts, it is argued, may cause unacceptable, short-term interferences and interruptions to local economic activities including tourism, fishing and recreation. An invasion may occur in sites that are initially assessed as too large, too complex, too environmentally sensitive—simply too overwhelming—to deal with. In the face of such arguments, it is difficult to allow oneself to imagine the mounting of an eradication program that would substantially exceed all previous efforts in size, scale and cost.

Implementing that effort would necessarily entail large, short-term, local costs. On the other hand, declining to implement it would inevitably result in large, long-term environmental and economic costs across a large swath of Western North America. That is the stark choice that we face. The arrival of zebra mussels west of the continental divide has now been noted by invasion managers and scientists around the world, and they are waiting to see how we deal with an infamous invader that will affect the economy, lives, and welfare of the people of the West.

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## Appendix A: *D. bugensis* records in the Lower Colorado River system

| Site | Date | Zebra mussels (*D. bugensis*) observed |
|---|---|---|
| LAKE MEAD: VIRGIN BASIN | | |
| Teakettle Bay | 2/21/07 | 7 at 18-23'. |
| Stewart Cliffs | 2/19/07 | On rock wall at 20-69'. |
| Boulder Wash (west) | 2/6/07 | 2 at 40'. |
| East End Light | 1/26/07 | 2-4 on rock wall at 40-60'. |
| LAKE MEAD: BOULDER CANYON | | |
| Wishing Well Cove | 2/19/07 | On rock wall at 18-67'. |
| LAKE MEAD: BOULDER BASIN | | |
| Flamingo Reef | 1/26/07 | 50-60 on rock wall at 40-100', appeared to go deeper. |
| Indian Canyon Cove | 2/11/07 | On rock at 10-53'. |
| Callville Bay | 1/16/07 | Hundreds on houseboat in dry dock. |
| Water Barge Cove | 2/11/07 | On rocks, silt and metal pipe at 4-11'. |
| Battleship Rock | 2/11/07 | Large numbers on rock and silt at 24-54'. |
| Burro Point | 2/11/07 | Low numbers on rock and silt at 20-48'. |
| Batch Plant | 2/10/07 | A few on concrete wall (ROV survey). |
| Black Island (west) | 2/9/07 | Large numbers on rocks at 12-100'. |
| Las Vegas Bay | 2/9/07 | 6 on mud and silt at 35-65'. |
| Lake Mead Hatchery | 1/9/07 | Scattered adults on concrete walls & screens in hatchery. |
| Saddle Island | 1/20/07 | On SNWA pipe at 80-90'. Clogging BMI intake at ≈80'. |
| Lake Mead Marina | 1/14/07 | Scattered mussels on dock structures & houseboats, to 32'. |
| Government Dock | 2/8/07 | On cables and anchors, down to 45' |
| Las Vegas Boat Harbor | 1/9/07 | Scattered mussels on dock structures down to 50'. |
| Hemenway Wall | 1/28/07 | On anchor at 60' (recreational diver, unconfirmed report). |
| Sentinel Island (east) | 1/20/07 | Possibly below 200' (recreational diver, unconfirmed report). |
| Sentinel Island (west) | 2/8/07 | On rocks down to 90'(?); densest population observed. |
| Kingman Wash | 1/18/07 | Down to 110' (recreational diver, unconfirmed report). |
| Promontory Point | 1/27/07 | At 80' (recreational diver, unconfirmed report). |
| Hoover Dam Intake Tower | 1/23/07 | Scattered mussels on steel grates at 30-85' (ROV survey). |
| BETWEEN LAKE MEAD AND LAKE MOJAVE | | |
| Below Hoover Dam | 1/24/07 | 1 on a rock in bottom of river channel (ROV survey). |
| Willow Beach Hatchery | 3/1/07 | In 3 settling ponds. |
| LAKE MOJAVE | | |
| Cottonwood Cove Marina | 2/5/07 | On a houseboat in dry dock. |
| Katherine Landing Marina | 1/20/07 | On dock structures and houseboats. |
| BETWEEN LAKE MOJAVE AND LAKE HAVASU | | |
| Laughlin Bay Marina | 1/31/07 | 5 on a boat in dry dock. |
| LAKE HAVASU | | |
| Bass Cove | 1/19/07 | 4 at 31-40'. |
| Grass Bay | 1/19/07 | 1 on rock wall at 30'. |
| Marker 41 | 1/19/07 | 1 at 60'. |
| Central Arizona Project intake | 1/22/07 | About 12 on concrete at 27'. |
| Colorado R. Aqueduct intake | 1/17/07 | 114 on concrete at 20-50'. |
| COLORADO RIVER AQUEDUCT SYSTEM | | |
| Gene Wash Reservoir | 1/17/07 | 14 near outlet structure at 35'. |
| Copper Basin Reservoir | 3/6/07 | 2 on rocks at 60'. |
| Aqueduct siphons | 3/10/07 | 778 in siphons between miles 12 and 21. |

## Appendix B: Priority research questions

| Area of research | Relevant to: Eradication | Reducing veliger flow | Containing overland transport | Detection monitoring | Responding to new infestations |
|---|---|---|---|---|---|
| MOST URGENT | | | | | |
| Conduct field trials of cover, heat, mechanical removal, and isolate and treat approaches in Lake Mead | X | | | | X |
| Conduct field trials of large-scale plankton tows in Lake Mead | X | X | | | X |
| Assess the potential for reducing downstream flow of veligers through Hoover Dam by (a) veliger monitoring and intake selection, (b) biocide injection[a], or (c) hydrocyclone or filtration | | X | | | |
| Conduct an initial analysis of the potential direct economic costs of the invasion to California and the West, based on scaling from costs in the East | X | X | X | X | X |
| Conduct an initial analysis of the potential environmental impact of the invasion to California and the West | X | X | X | X | X |
| Conduct a survey of calcium concentrations in California waters, determine boat movements from currently infested waters, and assess the vulnerability of California waters to colonization | | | X | X | X |
| Field and laboratory assessments of zebra mussel environmental requirements (needed especially for *D. bugensis* and for calcium) | | | X | X | X |
| LONGER-TERM | | | | | |
| Assess the potential direct and indirect economic costs and environmental impacts of the invasion to California | X | X | X | X | X |
| Develop zebra mussel-specific biocides derived from bacteria or other sources | ? | | | | X |
| Develop more effective biocide delivery systems, *e.g*. in particles ingested by the mussels or in gel that adheres to or otherwise remains in contact with the mussels | ? | | | | X |
| Determine the relationship between mussel density and reproductive success | X | | | | X |
| Conduct genetic analysis to determine the source of the Colorado River population | | | | | |
| Assess the capacity of zebra mussels to colonize the clay walls of canals | | | | ? | |
| Assess veliger mortality in passage through pumps, high pump lifts, and other water system components | | | | ? | ? |
| Assess the potential for transporting veligers via the California water supply system from one site to another | | | | ? | ? |

[a] Includes assessing veligers' dose-response relationship to acrolein and other candidate biocides.