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*Special Issue: Quagga Mussels in the Western United States*

**Management in Practice**

# Interagency Monitoring Action Plan (I-MAP) for quagga mussels in Lake Mead, Nevada-Arizona, USA

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**Editor's note:**
This paper was prepared by participants attending the workshop entitled "Quagga Mussels in the Western United States – Monitoring and Management" held in San Diego, California, USA on 1-5 March 2010. The workshop was organized within the framework of the National Shellfisheries Association, American Fisheries Society (Fish Culture Section) and World Aquaculture Society's Triennial Conference. The main objective of this workshop was to exchange and share information on invasive quagga mussels among agencies. The data presented in this special issue provide critical baseline information on quagga mussel monitoring and management at the early stages of introduction in the western United States.

## Abstract

Following the discovery of quagga mussels in Lake Mead, Nevada-Arizona, USA, a variety of federal, state and regional agencies set up monitoring programs to evaluate and gain information to help minimize the impacts, or potential impacts, of quagga mussels to their facilities and lake ecology. While the agencies have worked closely and shared monitoring data and findings from the beginning of the infestation, there has been no documented comprehensive monitoring program to describe and record the various quagga mussel-related monitoring needs. *Ad hoc* interagency quagga mussel meeting representatives established an Interagency Monitoring Action Plan (I-MAP), which outlines agency objectives related to quagga mussel monitoring and provides approaches to realize these objectives. I-MAP team members and their respective agencies provide technical, logistical, and financial support in monitoring quagga mussels and their environmental impacts to Lake Mead. The goal of this effort is to develop a long-term, cost-effective, and consistent monitoring plan for quagga mussels in Lake Mead to inform various agencies and to gain efficiencies from shared operations and information. The plan attempts to build upon current monitoring activities and capabilities, identifies the next steps that can occur within existing capabilities and, finally, outlines gaps and areas of future need.

**Key words:** *Dreissena bugensis*, Colorado River System, program design, mitigation, prevention, infrastructure, sport-fishery, education

## Introduction

On January 6, 2007, the quagga mussel [*Dreissena bugensis* (Andrusov, 1897)] was found in Boulder Basin of Lake Mead, Nevada-Arizona; they quickly spread to Lake Mead's other basins by the end of 2007. This discovery extended the U.S. range of this non-native species more than 1,609 km west of previously known populations in the Great Lakes. The invasion of dreissenid mussels (i.e., zebra and quagga mussels) to lakes and rivers of North America has already resulted in severe ecological and economical impacts (Nalepa and Schloesser 1993; Connelly et al. 2007). For example, following the 1988 invasion of the Great Lakes by zebra mussels, it is estimated that regional economic damages in the order of $4 billion were incurred in the first 10 years, largely from sport fishery losses (Roberts 1990). Before quagga mussels were found in western states, the economic loss due to the invasion of zebra and quagga mussels was already thought to be as high as $1 billion per year in the U.S. (Pimentel et al. 2005). It is estimated that, between 1989 and late 2004, approximately $267 million was

spent on preventing dreissenid mussel infestation of electricity-generation and water-treatment facilities in North America (Connelly et al. 2007).

Part of the Lower Colorado River system, Lake Mead is the largest reservoir by volume in the USA (LaBounty and Burns 2005), storing drinking water for more than 20 million people in Nevada, Arizona and California. It is also a primary feature of the Lake Mead National Recreation Area, providing high quality recreational experiences to more than eight million visitors annually. Upon discovery of this emerging issue in Lake Mead, a variety of federal, state and regional agencies, including National Park Service (NPS) Lake Mead National Recreation Area (LMNRA), U.S. Bureau of Reclamation (Reclamation), Southern Nevada Water Authority (SNWA), Nevada Department of Wildlife (NDOW), Arizona Game and Fish Department (AZGFD), Metropolitan Water District of Southern California (MWD), U.S. Fish and Wildlife Service (USFWS) and U.S. Geological Survey (USGS), set up monitoring programs to evaluate and gain information to help minimize the impacts or potential impacts of quagga mussels to their infrastructures, facilities and ecosystems. Some of the following actions have already been employed in, or may be used for, coping with quagga mussels in Lake Mead:

1. Establishment of educational and disinfection programs for recreational boaters to prevent introduction to new waters;
2. Chemical treatment of drinking waters;
3. Application of coating materials for water intakes and associated equipment, or new intakes;
4. Physical removal of quagga mussels colonizing water pipes, dam gates, boats or other highly infested infrastructures;
5. Setup of monitoring programs to assess the impacts and potential impacts on drinking water, infrastructure and the ecosystem;
6. Contracts with consulting companies to evaluate means to minimize the impacts;
7. Research projects addressing the need to monitor, control and prevent quagga mussels;
8. Meetings and workshops to update and share information on quagga mussels with other agencies.

Although there are no accurate numbers describing how much money has been spent on quagga mussel management by these multiple agencies, it is clear that the impact is severe in terms of direct cost (e.g., control and prevention) and indirect loss (e.g., potential fishery decline). In any case, significant funds have been spent on quagga mussel management and control in the western states of America (Table 1). While the agencies have worked closely and shared monitoring data and findings from the beginning of the infestation, there has been no documented compre-hensive monitoring program to describe and record the various quagga mussel-related monitoring needs relative to interagency objectives for Lake Mead. *Ad hoc* interagency quagga mussel meetings attended by representatives of the above-listed agencies and others served as a springboard for gathering the information to establish an Interagency Monitoring Action Plan (I-MAP), which outlines agency objectives related to quagga mussel monitoring and provides approaches to realize these objectives. At the time of this document's publication, the I-MAP Quagga Mussel Coordination Team (Figure 1) included representatives from the following agencies: LMNRA, Reclamation, SNWA, NDOW, AZGFD, USFWS, MWD, University of Nevada, Las Vegas (UNLV), Desert Research Institute (DRI) and University of Nevada, Reno (UNR). I-MAP team members and their respective agencies provide technical, logistical and financial support in monitoring quagga mussels and their environmental impacts to Lake Mead.

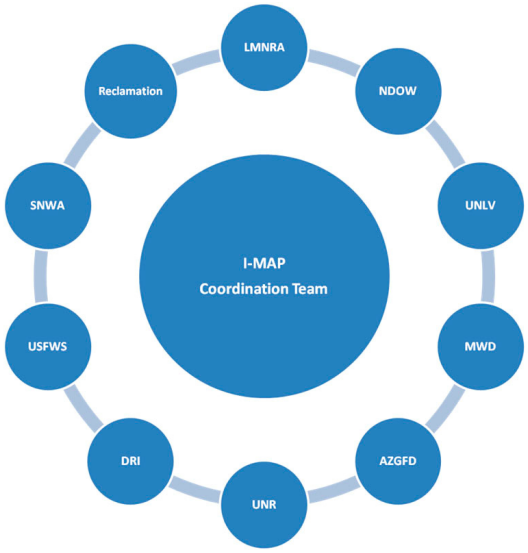



**Figure 1.** I-MAP team members (see text for abbreviations).

**Table 1.** Expenditures of four federal agencies to deal with quagga mussels in the Western United States.

| Agency | Expenditure | Purpose | Year | Source |
|---|---|---|---|---|
| NPS | $5,000,000 | Inspection | 2008 | Wirkus 2008 |
| Reclamation | $12,590,000 | Research, prevention and control, early detection, and education | 2008-2010 | Leonard Willett, personal communication |
| USFWS | $1,800,000 | Aquatic invasive species program in the West | 2008 | Wirkus 2008 |
| USGS | $200,000 | Support to deal with quagga mussels | 2008 | Wirkus 2008 |

## Agency objectives and needs

The goal of this effort is to develop a standardized, cost-effective, and consistent monitoring plan for quagga mussels in Lake Mead, to inform various agencies of the needs and objectives outlined below, and gain efficiencies from shared operations and information. The overall interagency objectives for monitoring quagga mussels and the associated ecological responses to their infestation can be delineated within three broad focus areas: (1) biology and ecology of quagga mussels; (2) impacts on fish and wildlife and water quality related to drinking water and recreational experience; and (3) quagga mussel management in terms of prevention, control and infrastructure maintenance. The subsequent sections outline current monitoring objectives within each of the three focus areas. Identified are immediate needs that the participating agencies feel they can meet with current capacities, and monitoring gaps that will require additional resources. A brief summary of these three categories is provided below.

1. Monitoring and understanding the biology and ecology of quagga mussels. This category covers monitoring the abundance and distribution of quagga mussel veligers and adults in Lake Mead, as well as the *in situ* life history of this species. A cost-effective, standardized and long-term monitoring protocol needs to be implemented (Wong et al. 2011).
2. Understanding and quantifying the effects of quagga mussels on fish and wildlife and water quality. Several areas of critical monitoring or research needs include maintaining healthy populations of fish and wildlife under variable conditions, evaluating bioaccumulation and biomagnfication of organic and inorganic contaminants in quagga mussels, and monitoring drinking water quality including nutrients, odor, cyano-bacteria and clarity.
3. Quagga mussel prevention, control and infrastructure maintenance needs. Preventing quagga mussel attachment to boats, recreational and water-service facilities, and other structures; stopping spread to other water bodies; performing public education and outreach activities to inform boaters; and implementing infrastructure maintenance to prevent severe infestation on dams and docks and clogging of water intakes and pipelines.

## Current monitoring summary

Since the discovery of quagga mussels in Lake Mead, LMNRA, Reclamation, SNWA and NDOW have actively adopted programs to monitor and minimize the impacts of these invasive species on Lake Mead. Current monitoring activities and anticipated environmental impacts are depicted in Figures 2 and 3. The following sections summarize some of the finished and ongoing projects carried out by the different agencies. Through these actions, critical baseline information on early invasion of quagga mussel into Lake Mead has been collected, programs on minimizing quagga mussel infestation on drinking water facilities and recreational facilities have been designed and successfully implemented, and a Lake Mead quagga mussel network has been established among multiple agencies.

### *National Park Service Lake Mead National Recreational Area (NPS LMNRA)*

Monitoring actions:

1. Early detection of quagga mussels: Divers examined selected locations within all of Lake Mead's marinas, and areas deeper than 30 m were assessed with the aid of a Remotely Operated Vehicle (ROV).
2. Adult and juvenile samples were collected from 138 locations to estimate the density of quagga mussels across Lake Mead in 2007. Results from this work showed that Boulder

Basin was the first location where quagga mussels invaded. Preliminary analysis showed that the average lakewide density in 2007 was 505±667 mussels/$m^2$ (N = 138). There were more mussels in rocky areas than in silty areas. The density in both areas increased with depth, down to approximately 21 m; density decreased at depths deeper than 21 m.
3. Different artificial substrates were set up in marinas to monitor the status of quagga mussels.
4. Although they were not detectable in Lake Mead's South Cove in March 2007, by September 16, 2008, quagga mussel density in this location was found to be 54,242 mussels/$m^2$.

Control actions:
1. Inspection of incoming boats from mussel-infested states.
2. Boats slipped and moored within Lake Mead marinas are required to be inspected and washed with portable hot water pressure sprayers before leaving Lake Mead. Five large boat-wash facilities are being installed at marinas to facilitate access to this service.
3. A boat cleaning training course was offered to all marina workers, and quagga mussel disinfection workshops were offered to concerned staff.
4. Use of the "Clean, Drain and Dry" public message campaign (and others) was adopted to encourage boaters to prevent the spread of quagga mussels.

Sponsored research and studies:
1. Age and growth analysis of early invasive quagga mussels.
2. An ongoing quagga mussel thermal tolerance study.
3. Development of a suitable substrate-monitoring device for early detection of quagga mussels (co-sponsored with SNWA).
4. Impact of quagga mussel invasion on Lake Mead shad population and diet composition.
5. Impact of quagga mussel invasion on Lake Mead benthic community.

Information sharing and management:
As stated previously, the NPS LMNRA formed an *ad hoc* quagga mussel information network, the Interagency Quagga Mussel Team, with representatives from multiple agencies. A quarterly meeting continues to serve as a platform for sharing information among multiple agencies and coping with this emergency issue in Lake Mead and other areas in the western states facing the challenge of quagga/zebra mussel invasion. The number of participants attending this meeting has grown, with additional representation—joining the agencies mentioned above—from the following organizations: Arizona Department of Water Resources, Basic Water Company, City of Henderson, Coachella Valley Water District, Cornell University, Imperial Irrigation District, Lake Havasu City, Lake Las Vegas Resort, Las Vegas Valley Water District, Portland State University, San Diego County Water Authority, and University of California, Davis.

From a resource management perspective, accessibility to shared data and formal information resulting from I-MAP monitoring and research studies will be crucial to management decision making. The I-MAP program is part of a larger NPS LMNRA limnology and aquatic resource research and monitoring initiative for Lakes Mead and Mohave that was likewise designed with input from multiple agencies with managerial responsibility for these water bodies. This larger initiative is intended to take a broader, ecosystem view in making use of all available data, including those on stressors such as invasive species, to answer research and monitoring questions of joint interest and to meet stated research priorities. The initiative prescribes regular data analysis with annual data summaries, 5-year summaries, information syntheses and organization of other relevant information around these priority research and monitoring questions. Future web pages will serve as the framework to organize and make these materials accessible. As data is gathered and more information becomes known, the initiative itself, and its component programs, such as the I-MAP, are expected to be adapted over time.

*Southern Nevada Water Authority (SNWA)*

Monitoring actions:
1. Concrete-backed boards were used in early detection of settled juveniles and their growth rates.
2. Raw water veligers from intake pumping stations were counted.
3. Veligers within Lake Mead water samples were counted weekly (Table 2). In the vicinity of water intakes, veliger counts can be >100/L (LaBounty and Roefer 2007) and

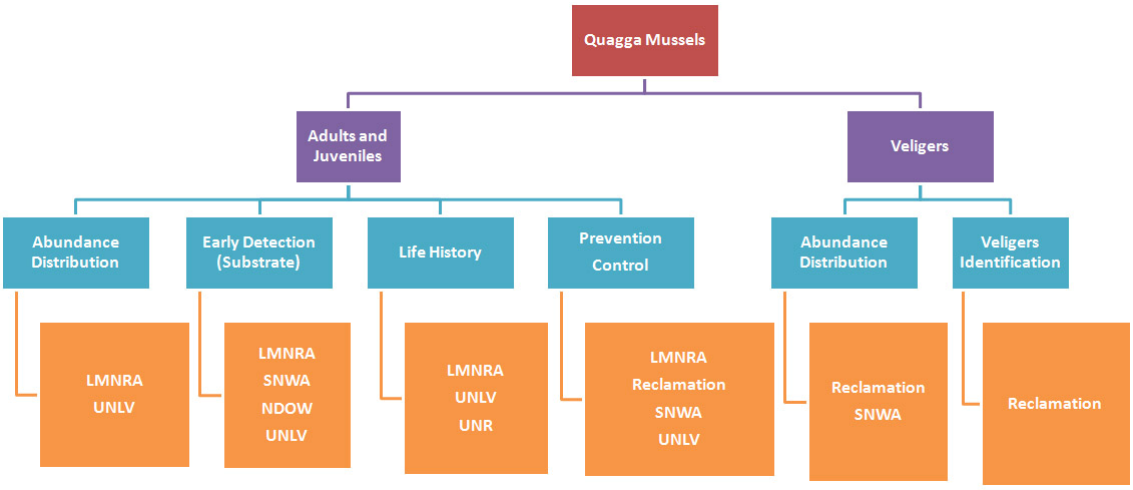
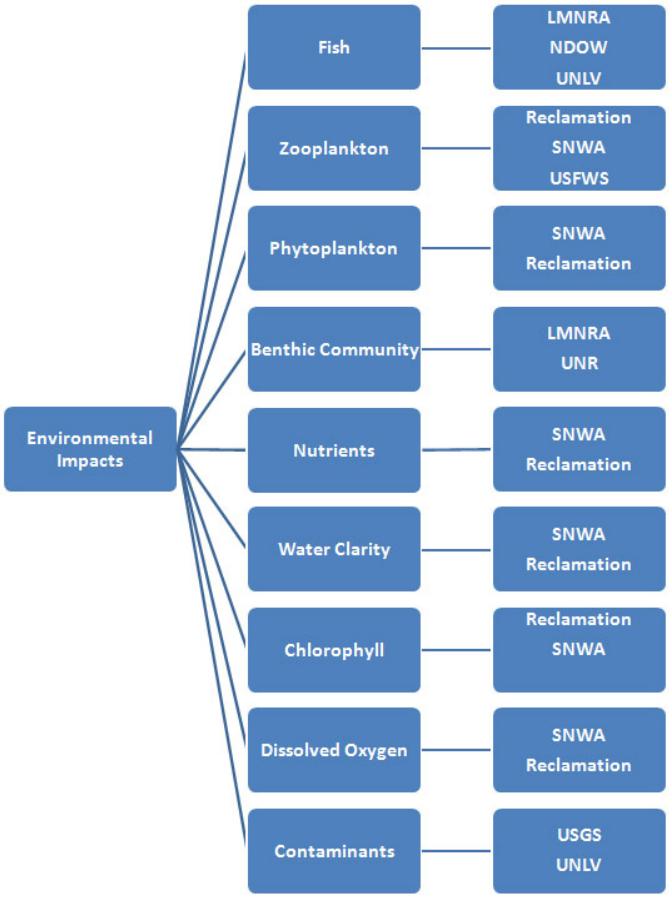



**Figure 2.** Current quagga mussel monitoring activity on Lake Mead.

**Figure 3.** Existing environmental monitoring of impacts of quagga mussels on Lake Mead.



at times compose 40% of the total zooplankton.

Control actions:
1. Equipment and water intake inspection by divers and facilities will be continuously conducted until the equipment is out of service.
2. A pre-chlorination system was installed at the discharge point of each intake pumping station to prevent veligers from attaching to the equipment; and chlorine application at points preceding entrance to the pumping station at Intakes 1 and 2 started in late 2008.
3. SNWA visited Parker Dam (CA-AZ) to observe Reclamation's anti-fouling coating study.
4. SNWA and MWD representatives went to Washington, D.C. to urge Congress to invest in research-based quagga mussel eradication or management methods. SNWA and MWD sponsored a workshop to explore strategies for responding to the presence of quagga mussels in the Lower Colorado River (Zegers 2008).

Sponsored research and consultancy:
1. Risk assessment of potential impact of quagga mussels on Southern Nevada Water System drinking water treatment plants, pumping stations and intakes.
2. Development of suitable substrate device for early detection on quagga mussel (co-sponsored with NPS); the potential infestation risks on the water intakes were determined to be moderate.

*U.S. Bureau of Reclamation (Reclamation)*

Monitoring actions:
1. Monthly veliger monitoring at 5 sites in Lake Mead and at 19 other pre-established zoo-plankton monitoring stations (Table 3) with vertical plankton tows.
2. Method development for veliger identification using microscopy and polymerase chain reaction (PCR).
3. Examining the infestation status on Hoover Dam with video-enabled ROV.

Control actions:
1. A straining and ultraviolet (UV) light system was installed at Hoover Dam. The strainer removes large mussels followed by treatment with UV light to kill or disable veligers from settlement in cooling and domestic water systems at dams.
2. Initiated tests of 18 different coatings on plates at Parker Dam and at intakes for the MWD and the Central Arizona Project.
3. A self-cleaning ballast filter (50 µm) that can remove all mussels and veligers from water is being installed at Parker Dam's domestic water intake.
4. A field trial was tested for using high-pressure water to clean out grates and pipelines in October 2008.

Sponsored research and consultancy:
Risk assessment of potential impact of quagga mussels on Southern Davis Dam and Parker Dam. Denver Technical Service Center and the Lower Colorado Dams Office are testing the ability of *Pseudomonas fluorescens* (Migula, 1895) in the product Zequanox$^{TM}$ to selectively kill quagga mussels. This study has been done in the lab using lake and river water; more tests are needed for approval from the U.S. Environmental Protection Agency (EPA) before its application *in situ*.

*Nevada Department of Wildlife (NDOW)*

Since quagga mussels were discovered in NDOW's fish hatchery facilities, the stocking program has been temporarily suspended. In 2008, NDOW examined some other inland waters within Nevada and all the test results were negative (i.e., no quagga mussels found). NDOW is concerned with tracking quagga mussel spread and getting support for minimizing the potential impacts to the Lakes Mead and Mohave fishery.

*US Fish and Wildlife Service (USFWS)*

USFWS is active in preventing the spread of aquatic invasive species through the 100$^{th}$ Meridian Initiative and the "Stop Aquatic Hitchikers" national public awareness campaign. It also participated with agencies in Nevada and California in developing the education program "Don't Move a Mussel."

**Suggested monitoring over the next two years with existing resources**

With existing resources, the suggested monitoring programs over the next two years include quagga mussel monitoring, water quality monitoring, and fish and invertebrate monitoring.

**Table 2.** Quagga mussel veliger monitoring stations in Lake Mead.

| Station | Station Name | Latitude, N | Longitude, W | Agency | Sampling Frequency | Sampling Mode |
|---|---|---|---|---|---|---|
| 1 | LWLVB | 36°07' 04.19" | 114°50'56.65" | USBR/SNWA | Weekly | Zooplankton |
| 2 | LWLVB_B | 36°07'03.58" | 114°50'51.25" | SNWA | Weekly | Zooplankton |
| 3 | LVB4.15 | 36°07'00.82" | 114°49'49.50" | USBR/SNWA | Weekly | Zooplankton |
| 4 | LVB 6.7 | 36°05'46.03" | 114°47'35.27" | SNWA | Weekly | Zooplankton |
| 5 | INTAKE | 36°03'47.05" | 114°47'51.32" | SNWA | Weekly | Zooplankton |
| 6 | CR 346.4 | 36°03'41.96" | 114°44'20.88" | USBR/SNWA | Weekly | Zooplankton |
| 7 | CR348.4NW0.8 | 36°05'34.85" | 114°46'03.97" | SNWA | Weekly | Zooplankton |
| 8 | LVB3.5 | 36°07'04.92" | 114°50'33.42" | USBR | Monthly | Zooplankton |
| 9 | LVB4.95 | 36°06'34.42" | 114°49'10.66" | USBR | Monthly | Zooplankton |
| 10 | LVB7.3 | 36°05'29.39" | 114°47'14.76" | USBR | Monthly | Zooplankton |
| 11 | CR342.5 (Hoover Dam) | 36°01'09.78" | 114°43'57.59" | USBR | Monthly | Veliger/Zooplankton |
| 12 | VRLM | Variable | | USBR | Monthly | Zooplankton |
| 13 | MRLM | Variable | | USBR | Monthly | Zooplankton |
| 14 | VR25.1 | 36°26'06.90" | 114°20'48.07" | USBR | Monthly | Zooplankton |
| 15 | VR18.0 | 36°21'36.09" | 114°23'15.15" | USBR | Monthly | Zooplankton |
| 16 | VR13.0 | 36°17'23.74" | 114°23'17.07" | USBR | Monthly | Zooplankton |
| 17 | VR9.4 | 36°15'18.17" | 114°24'13.20" | USBR | Monthly | Zooplankton |
| 18 | VR6.0 | 36°12'50.34" | 114°25'03.28" | USBR | Monthly | Zooplankton |
| 19 | VR2.0 | 36°09'41.01" | 114°25'08.83" | USBR | Monthly | Zooplankton |
| 20 | CRLM_A | Variable | | USBR | Monthly | Zooplankton |
| 21 | CR394.0 | 36°06'00.70" | 114°07'00.51" | USBR | Monthly | Zooplankton |
| 22 | CR390.0 | 36°02'29.59" | 114°08'17.24" | USBR | Monthly | Zooplankton |
| 23 | CR380.0 | 36°02'48.30" | 114°16'24.09" | USBR | Monthly | Zooplankton |
| 24 | CR360.7 | 36°09'05.11" | 114°33'02.48" | USBR | Monthly | Zooplankton |
| 25 | CR355.75 | 36°08'28.97" | 114°37'41.66" | USBR | Monthly | Zooplankton |
| 26 | Echo Bay | 36°17'44.30" | 114°23'58.78" | USBR | Monthly | Veliger |
| 27 | Temple Bar | 36°02'33.36" | 114°18'38.34" | USBR | Monthly | Veliger |
| 28 | Sandy Point | 36°07'10.02" | 114°06'33.37" | USBR | Monthly | Veliger |
| 29 | Sentinel Island | 36°03'14.50" | 114°45'05.40" | NPS/UNLV | Weekly | Veliger |

**Table 3.** Transect sampling location and frequency of adult and juvenile quagga mussels in Lake Mead.

| Transect | Station Name | Substrate | Sampling | Frequency |
|---|---|---|---|---|
| 1 | CR 346.4 | Soft | Grab | Quarterly |
| 2 | LVB 7.3 | Soft | Grab | Quarterly |
| 3 | LVB 3.5 | Soft | Grab | Quarterly |
| 4 | CR351.7 | Soft | Grab | Quarterly |
| 5 | Overton Arm | Soft | Grab | Annual |
| 6 | Virgin Basin | Soft | Grab | Annual |
| 7 | Temple Bar | Soft | Grab | Annual |
| 8 | Greg Basin | Soft | Grab | Annual |
| 9 | Sentinel Island | Hard | Diving | Quarterly |
| 10 | Black Island | Hard | Diving | Quarterly |
| 11 | Boulder Island | Hard | Diving | Quarterly |
| 12 | The Temple | Hard | Diving | Annual |
| 13 | Sandy Point | Hard | Diving | Annual |

*Quagga mussel monitoring*

Baseline information on quagga mussel veligers and adults has been collected over the past 2 years. To establish a cost-effective, long-term and scientifically sound quagga mussel monitoring plan, it is recommended that the following programs be initiated or continued at existing sampling stations that multiple agencies have set up for different purposes.

Adult and juvenile quagga mussel monitoring: Sampling locations will be established in different areas representing Lake Mead's various geological substrates with an extensive focus on Boulder Basin. Seven transects will be sampled quarterly and 6 transects will be sampled

annually (Table 3). Annually, ≥ 41 samples in the rocky areas and ≥ 97 samples in the soft sediment (i.e., silty and sandy areas) will be collected from these locations, which can represent the population at a 95% or higher confidence level (Wong et al. 2011).

Quagga mussel veliger monitoring: Regular veliger monitoring by SNWA and Reclamation should continue. This includes SNWA's 7 regular weekly zooplankton-monitoring stations and Reclamation's 4 monthly veliger- and 19 monthly zooplankton-monitoring stations (Table 2). The Sentinel Island station sampled by UNLV will be used to investigate veliger abundance at different depths. More detailed information on veliger sampling locations is listed in Table 3. Total samples taken from these stations per year will be ≥ 42 to represent the abundance of veligers at a 95% or higher confidence level (Wong et al. 2011).

Contaminant monitoring: Like other bivalves, quagga mussels can bioaccumulate contaminants [e.g., mercury (Hg), selenium (Se), poly-chlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs)] in their tissue and transfer these contaminants to higher trophic levels, such as molluscivorous species of ducks and fish in Lake Mead. Recently, the concentration of Hg in fish tissue was approximately 3× that in quagga mussel tissue (Mueting and Gerstenberger 2010). Baseline data on Hg levels in ducks and migratory waterfowl have also been collected (Gerstenberger 2004). As such, quagga mussels are an ideal indicator species for contaminants. Sediment and water concentrations of Hg are too low to detect, but quagga mussel tissue concentrations are within the detection range of simple analytical methods. Monitoring of the contaminant transfer from quagga mussels to fish and ducks is recommended.

Substrate monitoring: Substrate monitoring needs to be established along a transect in Las Vegas Bay from Las Vegas Wash to Boulder Basin. As stated previously, quagga mussels were first found in Boulder Basin and then spread exponentially. However, there is no sign that they have been similarly successful in the inner Las Vegas Bay. Is this due to the influx, from Las Vegas Wash, of wastewater with extremely high nutrients, other toxic compounds or a particular mixture of different compounds? Alternatively, is it due to other factors, such as substrate type, rich organic materials in the sediment, or a too-high-phytoplankton biomass with less edible species? Additional research is needed to evaluate why quagga mussels are not colonizing this area of Lake Mead as severely as in other locations.

*Water quality monitoring*

In Lake Mead's Boulder Basin, SNWA and Reclamation have 15 and 7 permanent water quality and limnology (Figure 2) monitoring stations, respectively. Measured parameters include, but are not limited to, temperature, dissolved oxygen, conductivity, pH, Secchi depth, turbidity, alkalinity, total calcium, biological oxygen demand (BOD), chemical oxygen demand (COD), orthophosphate phosphorus, total phosphorus, ammonia nitrogen, nitrite nitrogen, nitrate nitrogen, Kjeldahl nitrogen, total nitrogen, bromide, perchlorate, selenium, mercury, PCBs, total organic carbon, fecal coliform bacteria [especially *Escherichia coli* (Escherich, 1885)], chl-*a*, phytoplankton biomass and species composition, and zooplankton, with sampling frequency from weekly/biweekly to monthly/ bimonthly and sampling depth from surface to hypolimnion depending on each parameter and the needs of each agency. The long-term record of these multiple parameters and future data collection will provide excellent support for studying the effects of quagga mussels on water quality parameters. The following parameters are suggested to be shared with the long-term quagga mussel monitoring plan: (1) Chl-*a*; (2) Secchi depth and/or turbidity; (3) orthophosphate and total phosphorus; (4) ammonia and nitrate nitrogen; (5) total organic carbon; (6) dissolved oxygen; (7) phytoplankton (concentration and biovolume); and (8) zooplankton. It is recommended that these monitoring programs continue.

*Fish and invertebrate monitoring*

Threadfin shad [*Dorosoma petenense* (Gunther, 1867)] is important to the Lake Mead fishery as the primary prey of striped bass [*Morone saxatilis* (Walbaum, 1792)]; monitoring by NDOW of this important prey species should be continued to detect any change that threatens the sport fishery (Loomis 2009). Endangered species such as the razorback sucker [*Xyrauchen texanus* (Abbott, 1860)] may be in a more dangerous situation in Lakes Mead and Mohave as quagga mussels degrade their feeding and spawning

**Figure 4.** Spawning habitat (left) of razorback suckers and benthic community with soft sediments in Lake Mead. Currently, the spawning area is surrounded by quagga mussels and periphyton/submerged aquatic vegetation, but at the edge of the spawning area large colonization of quagga mussels has been found (red arrow in the left). In soft sediment areas where razorback suckers forage for benthic prey there is evidence of invasive threats from quagga mussels (red arrow in the right) (Photos by Bryan Moore).

habitat (Figure 4). Long-term datasets are necessary to track how quagga mussels impact fisheries in the Lake Mead ecosystem. Assessment of the benthic ecology of Lake Mead during the early invasion of quagga mussels should be continued to document long-term benthic invertebrate composition, abundance and production along different depth gradients in the lake.

*Infrastructure maintenance and public education*

Quagga mussel monitoring on boats, water intakes and dams should be continued. Boat inspections, boat cleaning training events and use of public messaging campaigns and other outreach activities are encouraged. Regular cleaning measures for water intakes and dams should be taken.

**Desired future monitoring plans**

The suggested ongoing monitoring program will shed light on quagga mussels' biological and ecological impingement. However, many questions will remain answered. If the program has the opportunity to expand, the following monitoring projects should be appended to the basic I-MAP quagga mussel monitoring program. The answers to these research questions may provide strategic advice to lake managers for making long-term policies to evaluate this large-scale biological invasion and maintain the water quality for millions of people depending upon the Lower Colorado River Basin.

*Reproductive behavior of quagga mussels*

Due to the favorable environmental conditions Lake Mead provides, quagga mussel reproduction has been very successful. For example, in Lake Mead's South Cove, the density of quagga mussels reached 54,000 individuals/$m^2$ in less than 1.5 years. However, there has been no systematic study on the reproductive state and recruitment rate of quagga mussels across Lake Mead or in other areas along the lower Colorado River, though it is estimated that these mussels reproduce multiple times per year. By understanding the reproductive behavior of quagga mussels at different conditions, we can explain how environmental variables such as temperature, food and water velocity can affect recruitment in Lake Mead.

*Filtration rates of quagga mussels*

Although there are filtration data available for quagga mussels in temperate waters (Baldwin et al. 2002), it is not known how filtration rate differs in this warm water reservoir or during

different seasons therein. Filtration rate is an important factor to consider in assessing how much and in what timeframe these mussels can impact the Lake Mead ecosystem.

*Impact of quagga mussels on water chemistry and phytoplankton composition*

Water chemistry and phytoplankton composition can be changed by quagga mussels through their selective feeding behavior (i.e., rejection of cyanobacteria and preference for green algae) and excretion of phosphorus and nitrogen (Conroy et al. 2005; Zhang et al. 2008). Though no significant change has yet been observed in the past 2 years, the potential for change exists and needs to be monitored.

## Summary

This program is the first step by multiple agencies to identify key needs, questions, objectives and projects related to quagga mussel infestation, basic biology and ecology, impacts on water quality and aquatic living resources, as well as prevention and control of this invasive species in Lake Mead. I-MAP team members and their respective agencies provide technical, logistical and financial support in monitoring quagga mussels and their environmental impacts to Lake Mead. The I-MAP team will coordinate monitoring activities based on this plan. The I-MAP can help develop a long-term, cost-effective, and consistent monitoring plan for quagga mussels in Lake Mead to inform various agencies and gain efficiencies from shared operations and information. The plan builds upon current monitoring activities and capabilities, identifies the next steps that can occur within existing capabilities and, finally, outlines gaps and areas of future need.

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