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A standardized design for quagga mussel monitoring in Lake Mead, Nevada-Arizona

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Abstract

The discovery of quagga mussels (Dreissena rostriformis bugensis) in Lake Mead, Nevada-Arizona, on January 6, 2007 is the first known occurrence of dreissenid species in the western United States. This study developed elements of a cost-effective and standardized quagga mussel-monitoring program for Lake Mead using preliminary data to arrive at statistically based numbers of sampling sites. To represent the abundance of adult/juvenile quagga mussels in Lake Mead’s heterogeneous floor with 95% confidence, a stratified simple random sampling design revealed a requirement of 41 samples from hard substrates (i.e., rocky areas) and 97 samples from soft substrates (i.e., sandy and muddy areas). A simple random sampling design demonstrated that 42 samples from the lake’s water column are necessary to represent veliger abundance with 95% confidence. Other important elements of the sampling program, such as standardization of protocols and processes and suggested data analyses, are discussed. The monitoring program, which is based on reconnaissance data, is intended to be optimized with data from its first year’s samples. The sample number-selection approach and the other elements of this plan can be easily implemented by lake managers and can also be adapted to other locations where dreissenid mussel monitoring is needed.

Key words: Dreissena rostriformis bugensis, Colorado River system, interagency, Simple Random Design, Stratified Simple Random Design

Introduction

Lakes Mead and Mohave, reservoirs within the Colorado River system, store drinking water for more than 20 million people in Nevada, Arizona, and California, and provide waters for agricultural irrigation, flood control, and power generation. As primary features of Lake Mead National Recreation Area, these water bodies also provide high quality recreational experiences to more than eight million visitors annually. On January 6, 2007, quagga mussels [Dreissena rostriformis bugensis (Andrusov, 1897)] were found in Las Vegas Boat Harbor within Boulder Basin of Lake Mead, Arizona-Nevada, USA (Figure 1). This is the first known occurrence of an established dreissenid population in the western United States and the first known North American quagga mussel infestation of a water body not previously infested by zebra mussels [Dreissena polymorpha (Pallas, 1771)]. In early 2007,
quagga mussels were found primarily in Boulder Basin (Figure 1), but, by the end of the year, they had rapidly spread throughout the lake, which is the largest reservoir by volume in the United States and is the second largest in terms of surface area (660 km²; LaBounty and Burns 2005). Having spread throughout Lake Mead and beyond, quagga mussels are now clogging water pipelines, attaching to boats, colonizing dam gates and fouling other substrates (Figure 2). Based on the experience of the Great Lakes region with invasive dreissenid impacts to ecosystems and economy (Nalepa and Schloesser 1993; McIsaac 1996; O’Neill 1997; Mills et al. 1996; Pimentel et al. 2005; Wilson et al. 2006), invading quagga mussels are likely to have profound, permanent, and economic impacts on not only Lake Mead’s ecosystem (Figure 3), but also on the region through their spread. In the Great Lakes and other areas of North America, it has been estimated that $1 billion is spent each year to monitor and control *Dreissena* populations (Pimentel et al. 2005).

To address this emerging issue in the lower Colorado River system, federal, state, and local agencies, such as the National Park Service, U.S. Bureau of Reclamation, U.S. Fish and Wildlife Service, U.S. Geological Survey, Nevada Division of Wildlife, Arizona Game and Fish Department, and Southern Nevada Water Authority formed an interagency group and began to monitor quagga mussels and assess ways to minimize impacts to water quality, aquatic resources, and facilities in Lake Mead with consideration to other downstream water bodies (Turner et al. 2011). A primary interagency goal, within a larger effort, was to establish a monitoring program to reveal both the abundance and distribution of Lake Mead quagga mussels to help understand how they might impact the reservoir’s biotic resources (e.g., fisheries, benthos, and planktonic community) and its cultural (e.g., water quality and water-delivery facilities) and recreational values (e.g., need for and cost associated with boat disinfection, unfavorable odors from decaying quagga mussels, etc.).

**Methods**

Dreissenid bivalve mollusks have two major life stages: the larval veliger stage (planktonic), which gives way to the juvenile/adult stage (benthic) through metamorphosis (as reviewed in Ackerman 1995). Adult mussels cause the most obvious destructive economic and ecological effects by clogging public facilities, producing odor problems, fouling other benthic organisms, and affecting the ecosystem (Figure 3). Yet, veligers are also important to monitor. For instance, seasonal patterns of veliger abundances would indicate the most appropriate time to treat facilities to prevent biofouling. Therefore, two monitoring protocols are necessary: one for adults and juveniles living in the benthic community and attaching to different substrates, and another for planktonic veligers located in the water column.

**JUVENILES/ADULTS**

Considerations for sampling juvenile/adult quagga mussels in Lake Mead

The volume of Lake Mead is $36.7 \times 10^9$ m³ at 100% capacity, and its limnological characteristics are heterogeneous among the different basins (LaBounty and Burns 2005). There is likely to be variability in the preference for settlement and colonization at a given site based on which substrate type is present, especially in the early stages of colonization when there is more choice available. In previous infestations, such as in the Great Lakes, quagga mussels have been shown to colonize both hard and soft substrate types (Dermott and Munawar 1993; Dermott and Kerec 1997; Claxton et al. 1998; Mills et al. 1996; Stoeckmann 2003). Although preference determination can be confounded in water bodies already physically and chemically altered by zebra mussel colonization, it has been shown that dreissenid settlement depends on substrate-material type,
A design for monitoring quagga mussels

Figure 1. Presence and absence of quagga mussels in Lake Mead National Recreational Area in January 2007 as revealed by a National Park Service-conducted survey.
Figure 2. (A-D) Examples of quagga mussel fouling at Lake Mead, Nevada-Arizona. Water intake (A); boat hull exterior (B); dam gate (C); and a portion of a sandal (D). Photos A and B by Bryan Moore; photo C by Dave Arend; and photo D by David Wong.

Figure 3. Potential ecological impacts of quagga mussels on Lake Mead ecosystem (Wong et al. 2009). Negative (blue font) and positive (red font) effects are diagrammed. Solid and dashed lines represent direct and indirect impacts, respectively. The wider the line, the more profound the impact. Briefly, quagga mussels have potential to reduce the biomass and change the species composition of phytoplankton and zooplankton communities. Decreases in suspended solids and oxygen would increase water clarity. An increase in dissolved inorganic phosphorus and nitrogen would facilitate aquatic plant growth. Benthic production is expected to increase, which would positively impact some fish species.

exposure to light, and texture (Mills et al. 1996, Bailey et al. 1999, Wilson et al. 2006) and that quagga mussels prefer hard substrate, including the shells of other mussels, and dark areas, corners, and crevices (Marsden 1992). For Lake Mead, which was not previously infested by zebra mussels, hard, irregularly shaped substrates (i.e., rocks and stones) were expected to provide the first-choice substrate over those with less compaction such as silt and mud. Thus, it was important to sample both hard and soft substrate in representative proportions of Lake Mead’s subsurface substrate types to be able to address possibly different substrate preferences and to properly monitor population dynamics and colonizing rates in Lake Mead. The simple
random sampling method yields unbiased estimates of population abundance independently of distribution (Thompson 1992; Eaton et al. 2005). A heterogeneous universe (in this case, areas featuring different bottom substrates) necessitated the use of a stratified random sampling design (Eaton et al. 2005) where separate randomization is generated for each stratum.

Simple Random Sampling Formula

To statistically limit the sampling regime to establish the number of sampling sites (# of sampling sites) required to represent the abundance of juvenile/adult quagga mussels in Lake Mead at three confidence intervals and a 35% level of precision, a stratified simple random sampling design (Eaton et al. 2005) was used. The number of juvenile/adult samples required from the areas representing each of the two major strata (soft and hard Lake Mead substrate types), the preliminary mean densities for each substrate type were entered into Equation (1), which was calculated at confidence intervals of 95%, 98%, and 99%.

\[
\text{# of sampling sites} = \left( \frac{t \times SD}{D \times \text{Mean}} \right)^2
\]

Where \( t \) = tabulated \( t \) value at \( \alpha \) level with the degrees of freedom of preliminary survey (generally \( \alpha = 0.05 \)), SD = standard deviation of preliminary samples, Mean = mean density of preliminary samples, and D = required level of precision expressed as a decimal; investigators deliberately choose a value of D based on their objectives, the resources that are available to them, and the constraints of the study site). Eaton (2005) states that 0.30 to 0.35 usually yields a statistically reliable estimate. We chose a precision rate of 35% meaning that the population abundance that can then be estimated with the data collected from the calculated number of sampling sites lies within a range of the actual abundance ± 35%.

Stratification

Based on U.S. Geological Survey sediment-type data for Boulder Basin, the rock (hard), sand and gravel (alluvial; soft), and mud (soft) comprise 44.4%, 26.7%, and 24.3%, respectively, of the lake-floor surface; for the remainder (4.7%) no data were obtained (Twichell et al. 1999). Therefore, we divided the bottom substrates of Lake Mead into two relatively homogeneous strata: hard and soft.

Use of preliminary data to determine abundance of juveniles/adults

To determine the abundance of juveniles/adults, preliminary data collected by the National Park Service (NPS). As part of NPS’ early response effort, divers used a 1-m² quadrat frame in rocky, sandy, and muddy areas throughout Lake Mead and the average density in the rocky areas (hard substrate) was 624 individuals/m², while the average density in the sandy and muddy areas (soft substrate) was 79.6 individuals/m² (Bryan Moore, unpublished data). The overall mean density of juvenile/adult quagga mussels in 2007 was 505.6 individuals/m² and the range was from 0 to 3,368 individuals/m² (Bryan Moore, unpublished data). These preliminary data derived from 138 samples collected from 138 sites representing all the major basins of Lake Mead in areas (Sentinel Island, Indian Canyon Cove, Black Island, Stewart Cliffs, Boulder Islands, The Temple, and Cormorant Point) where recreational activities are most likely to take place. Also calculated were standard deviation and \( t \) at each of the three confidence levels; calculations at the 95% confidence interval, which is the target of this monitoring plan, are shown (Table 1).

VELIGERS

Considerations for sampling quagga mussel veligers in Lake Mead

The abundance and distribution of planktonic veligers are affected by many environmental factors such as temperature, food, current, and wave action (Claxton and Mackie 1998). Even minor changes in surrounding conditions can cause a substantial difference in the timing of production of ripe gametes and the subsequent development of planktonic veligers (Nichols 1996). Accordingly, the abundance and distribution of veligers is affected by the timing of adult reproduction, although the precise timing of quagga mussel reproduction and development in Lake Mead is not yet known. LaBounty and Burns (2005) reported that the average water temperature in the epilimnion of Lake Mead’s Boulder Basin ranged between
12°C in early February to 27°C in early August. The metalimnion average water temperature was between 12°C and 18°C and the average temperatures within the hypolimnion were 12–12.5°C. These temperatures are well within the quagga mussel spawning range of > 9–10°C (Claxton and Mackie 1998). Indeed, quagga mussel veligers have been observed in Lake Mead year round (Holdren 2008), but their distribution has varied in Lake Mead likely due to environmental factors, such as food availability and flow hydrodynamics. Thus, it is possible, for example, to have a high abundance of veligers in Boulder Basin but fewer in Gregg Basin, due to the differences in conditions between these two basins. Although the basins are limnologically heterogeneous, quagga mussel veligers were collected from the water column, which is relatively homogeneous. Therefore, a standard simple random sampling design (Eaton et al. 2005) is sufficient for veligers; stratification is not necessary.

To statistically limit the sampling regime to establish the number of sampling sites (# of sampling sites) required to represent the abundance of quagga mussel veligers in Lake Mead at three confidence intervals and a 35% level of precision, a simple random sampling design (Eaton et al. 2005) is sufficient for veligers; stratification is not necessary. To determine the abundance of quagga mussel veligers, preliminary data collected from the U.S. Bureau of Reclamation, as part of the NPS early response effort (specified by NPS 2007) were used. These preliminary data derived from 64 samples collected from 4 Lake Mead sites [Sandy Point, Echo Bay, Temple Bar, Hoover Dam (tow at 0-10 m), and Hoover Dam (tow at 0-30 m)] representing all of the major basins of the Lake from March to September in 2007 and from January to June in 2008. The mean density of quagga mussel veligers was determined by that effort to be 1.44 veligers/L and the range was from 0 to 18.96 veligers/L (Chris Holdren and Denise Hosler, unpublished data). Also calculated were standard deviation and $t$ at each of the three confidence levels; calculations at the 95% confidence interval, which is the target of this monitoring plan, are shown (Table 1). These calculations were repeated for each group at each of the three confidence levels and then entered into Equation (1).

The calculated numbers of sites were then arrayed over the area of Lake Mead based on the significance of certain locations. Some of sites had been used for the preliminary quagga mussel monitoring in 2007 and most of them are sites that multiple agencies (Turner et al. 2010, this issue) have interest in for drinking water quality, recreational, or cultural value.

**Results**

The number of juvenile/adult sampling sites required for Lake Mead hard substrates was 41 at a 95% confidence interval to estimate the actual population density in Lake Mead (Table 2). For Lake Mead soft substrates, the number of samples was 97 at the 95% confidence interval (Table 2). To increase confidence (to 98% or 99%) in the ability of the data collected from the sampling sites to estimate actual density, additional samples are required (Table 2). Based on preliminary data for quagga mussel veligers in five Lake Mead locations [Sandy Point, Echo Bay, Temple Bar, Hoover Dam (tow at 0-10 m), and Hoover Dam (two at 0-30 m)] from March to September in 2007 and from January to June in 2008 (Chris Holdren and Denise Hosler, unpublished data), using 42 sampling sites in Lake Mead was determined to provide a representative result falling within a 95% confidence interval (Table 2). For higher confidence intervals of 98% or 99% on the final estimates of mean density, 76 or 114 sampling sites would be needed, respectively (Table 3) for quagga mussel veligers.

**Discussion**

The herein described approach both considers the whole of Lake Mead and accounts for variability through representative sampling. Within the subsections below we discuss, in addition to our findings, the various elements of constructing an interagency quagga mussel-monitoring plan for Lake Mead. As with any monitoring study, the more samples taken, the more representative the results become. However, economic and physical realities of sampling the largest reservoir by volume in the U.S. quickly set in. Therefore, it was necessary to set limits on the number of samples required using the simple random sampling formula (Eaton et al. 2005) for veligers and stratifying it to eliminate any substrate-preference bias for
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Table 1. Summary of variables calculated and values set for use in Equation (1) at the 95% confidence interval.

<table>
<thead>
<tr>
<th>Adults/Juveniles</th>
<th>t</th>
<th>SD</th>
<th>D</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>hard substrates</td>
<td>1.983</td>
<td>707</td>
<td>0.35</td>
<td>624</td>
</tr>
<tr>
<td>soft substrates</td>
<td>2.045</td>
<td>133.9</td>
<td>0.35</td>
<td>79.6</td>
</tr>
<tr>
<td>Veligers</td>
<td>2.78</td>
<td>1.17</td>
<td>0.35</td>
<td>1.44</td>
</tr>
</tbody>
</table>

Table 2. Number of sampling sites required for estimating juvenile/adult quagga mussels at different confidence intervals in the hard and soft substrates of Lake Mead.

<table>
<thead>
<tr>
<th>Confidence Interval</th>
<th>Hard Substrates</th>
<th>Soft Substrates</th>
</tr>
</thead>
<tbody>
<tr>
<td>95%</td>
<td>41</td>
<td>97</td>
</tr>
<tr>
<td>98%</td>
<td>58</td>
<td>140</td>
</tr>
<tr>
<td>99%</td>
<td>72</td>
<td>175</td>
</tr>
</tbody>
</table>

Table 3. Number of sampling sites needed for estimating quagga mussel veligers at different confidence intervals in Lake Mead.

<table>
<thead>
<tr>
<th>Confidence Interval</th>
<th>Veligers</th>
</tr>
</thead>
<tbody>
<tr>
<td>95%</td>
<td>42</td>
</tr>
<tr>
<td>98%</td>
<td>76</td>
</tr>
<tr>
<td>99%</td>
<td>114</td>
</tr>
</tbody>
</table>

settlement by juveniles/adults. It should be noted that even with limiting the sampling numbers with the lowest confidence level we calculated, the number of monitoring sites proposed may be financially unfeasible given the demands on limited resources available to managers to address a variety of strategic goals and emerging issues at any given time. Dive surveys are extremely time consuming and expensive; and, staff divers are limited in the number of dives they may participate in each year. Thus, although we suggest a sampling regime intended to provide data that will estimate population figures with 95% confidence, resource managers will still be able to provide a cost effective, yet statistically representative, estimate of the abundance of quagga mussel juveniles/adults and veligers in Lake Mead at a lower interval that is feasible to implement and that meets their needs.

From where should juvenile/adult quagga mussel and veliger samples be collected and how many sampling sites are enough to provide a good representation of the population?

Based on our calculations using preliminary data, 41 samples from hard substrates and 97 samples from soft substrate were determined to be the minimum needed to estimate site-specific densities of juvenile/adult quagga mussels with 95% confidence within a range of actual juvenile/adult density ± 35%. The sampling sites were arrayed within each of the major basins of Lake Mead in representative proportion to the types of substrates and with input from agencies who have interests in them. For veligers, at least 42 samples are needed in order to have a 95% confidence of representation.

How should juvenile/adult quagga mussels be collected from Lake Mead?

The sediment composition in Lake Mead necessitates use of a combination of sampling equipment: Quadrat frames on hard substrates (rocky areas) and Ponar grabs in soft sediments (muddy, silty, and sandy areas). The applicability of use of a Remotely Operated Vehicle (ROV) should be tested for estimating mussel density at hard substrate stations deeper than 30 m in Lake Mead. Since it has been determined that there are more mussels in the rocky areas, quadrats with different sizes can be used for mussel sampling. Small (0.01 m$^2$), medium-sized (0.06 m$^2$), and large quadrats (1 m$^2$) might be used for areas where the densities (individuals/m$^2$) of mussels are high (> 10,000/m$^2$), moderate (≤ 10,000 but ≥ 500 /m$^2$), and low (< 500 /m$^2$), respectively. As one sample was collected from each sampling sites during the preliminary pilot study, this program views each quadrat sample as an independent sampling point that cannot be successively sampled. Replicate quadrats samples from the broader area surrounding each site cannot be collected or analyzed due to financial limitations. It is
recommended that juvenile/adult sampling be conducted on a quarterly basis during the first year of the invasion. Preliminary growth data (Wen Baldwin, unpublished data) suggested that most mussels in Lake Mead become sexually mature (assuming >10 mm equates to sexual maturity) approximately 4 months after settlement. Therefore, sampling at 3-month intervals is likely sufficient to monitor mussel cohorts in Lake Mead. Early February, early May, early August, and early November are recommended as the quarterly sampling months according to the long-term temperature profile in Boulder Basin (LaBounty and Burns 2005).

What data are needed from the juvenile/adult samples and how should these data be collected?

To help assess the scale of potential impacts of juvenile/adult mussels, track changes in population size over time, and track cohorts of new mussels (including their mortality rates), mussel density, shell length, and biomass must be determined. Following field collections, individual adult and juvenile quagga mussels need to be separated carefully from each other and from sediments. In the laboratory, whole animals (mussel and its shell) and any complete (or nearly complete) empty shells are to be counted. Tiny juvenile mussels might be attached to the empty shells; therefore, to ensure that all individuals within the sample are counted, shells should be examined closely under microscope. Shell lengths are to be recorded for all occupied and empty shells. Following measurement, whole animals are to be frozen at -20°C or lower for future biomass analysis; and, the empty shells within the collection are discarded. There are two ways to present standing stocks of mussel populations: (1) density (number per square meter) and (2) biomass (tissue dry weight and shell dry weight per square meter). Although the first approach traditionally has been used, the second approach is becoming popular as increasing evidence shows that biomass is more useful in evaluating the impacts of dreissenid mussels and in determining growth rates and reproductive activity; furthermore, filtration rates are based on biomass units. Therefore, it is recommended that the density, shell length, and biomass of quagga mussels in Lake Mead all be recorded. If time constraints or other factors prevent immediate analysis, juvenile/adult samples may be stored frozen until the time of analysis.

How should quagga mussel veligers be collected from Lake Mead?

Mesh plankton nets (e.g., Wisconsin net) are most commonly used to concentrate veligers as a relatively large volume of water is reduced to a small volume. To collect samples, either the net is towed through the water or water is pumped through a hose from the water source and drained into the net. Pumping allows sampling from a discrete depth, sampling waters too shallow to tow, and avoidance of algal blooms or disturbed sediment (such as is present in large rivers) that may clog the net. For general veliger monitoring in Lake Mead, vertical tow sampling, the same method successfully used for zooplankton sampling in the water body, is recommended. Veliger size in Lake Mead is greater than 75 µm (Gerstenberger et al. 2011). Therefore, a plankton net with a standard mesh size of 64 µm is appropriate for quagga mussel veliger sampling in Lake Mead. This size is consistent with what has been used by the Southern Nevada Water Authority for zooplankton sampling during the past nine years and is also used by the U.S. Bureau of Reclamation for Lake Mead veliger sampling. In temperate areas, such as the Great Lakes region, veliger sampling is conducted weekly, a frequency that can track the peak density of veligers (Marsden 1992) and will not underestimate seasonal maximum veliger counts. In contrast to the Great Lakes region, veligers are detected year round in Lake Mead due to its warmer water temperatures (Holdren 2008). Given the cost of sampling trips, number of sampling sites, and distance between sites, it is suggested that monthly sampling data be used to calculate the abundance and densities of veligers in Lake Mead in spring and fall (Holdren 2008).

What data are needed from the veliger samples and how should they be collected?

Plotting density over time allows managers to track cohorts of quagga mussels and determine reproductive timing and survivorship of fertilized eggs. Veligers can be quantified in several ways in the laboratory. The modified enumeration method currently used by the U.S. Bureau of Reclamation for Lake Mead (Holdren 2008) is recommended. It is a combination of Standard Method (10200 G) for the examination of water and wastewater (Eaton et al. 2005), U.S. EPA Standard Method LG403 (USEPA 2007),
and a method used by the U.S. Army Corps of Engineers (U.S. Army Corps of Engineers 2010). The sample may be diluted if veligers are too abundant or, if abundance is low, the sample may be concentrated further such as by filtering them through a sieve and backwashing into a counting tray (Allen 1997). Subsamples can be taken for estimating the veliger density U.S. Army Corps of Engineers (U.S. Army Corps of Engineers 2010). Developmental staging of veliger samples would provide more complete information about the timing of veliger growth and development in the Lake Mead environment, but is beyond the scope of the current study.

**Future sampling program optimization**

The herein described monitoring program uses preliminary data collected in the early stages of infestation as part of a rapid reconnaissance effort to set the number of samples required to adequately estimate abundance. For long-term monitoring, the effectiveness of these actions undertaken in year 1 will be evaluated. It would be appropriate to optimize the sampling regime after the first year of data collection, by repeating the calculations for simple random sampling (and its stratified variation for juveniles/adults) using the year-1 data and solving for confidence level. It will be important to see how well (at what confidence level) these data will represent abundances within Lake Mead. If the calculated confidence level is found to drop below the desired confidence interval, the number of sampling sites needed to assess abundance could be increased, if feasible, to yield the desired confidence interval. With this information in hand, it will be advisable for the interagency group to review and reassess its goals for the sampling program. If, for example, the goal were limited to an assessment of the annual density change at each sampling site then conducting one sampling event per year for each fixed station would be sufficient. If its goal is, instead, to document seasonal population trends over time, then multiple sampling events per year will continue to be required.

**What information is needed to collect appropriate data to address quagga mussel population dynamics and ecological impacts?**

Quagga mussel invasion into Lake Mead can affect the whole ecosystem (Figure 3) and, conversely, mussel populations can also be affected by limnological variables such as substrate composition, substrate texture, substrate type, depth, currents, light, temperature, pH, food quantity and quality, ionic concentration, and the composition of the existing benthic community. Therefore, to provide a more complete picture of quagga mussels populations in Lake Mead and their impact over time, the following ancillary data is also suggested for collection: (1) water-level elevation, (2) specific conductance, (3) Secchi depth, (4) calcium concentration, (5) substrate type, (6) sampling depth, (7) chlorophyll a, (8) dissolved oxygen, (9) water temperature, (10) current speed, (11) total phosphorus (TP: µg/L) and ortho phosphorus (PO4-P: µg/L), (12) total nitrogen (TN: mg/L), nitrate (NO3-N: mg/L), and ammonia (NH3: mg/L), (13) pH, (14) phytoplankton community composition, (15) zooplankton community composition, and (16) benthic macro-invertebrate assemblage. To reduce cost, data on some parameters such as nutrients and water temperature, may be acquired from the nearest water quality sampling sites in Lake Mead set up by Southern Nevada Water Authority, U.S. Bureau of Reclamation, or the U.S. Geological Survey.

**Interagency standardization and communication**

Interagency agreement on standard sampling methods and measurement units are recommended to yield directly comparable data collected by all participating agencies. Relevant communication venues such as interagency program coordination meetings (Turner et al. 2010, this issue) and other outlets to share and distribute data, information, and findings are crucial to the success of any interagency monitoring effort. A quagga mussel database is recommended to store baseline and subsequent data useful to future estimation of the impacts of quagga mussel invasion on the Lake Mead ecosystem. Resultant data and information may be useful as a reference and resource for multiple agencies as they monitor water quality and aquatic living resources that could be affected by natural phenomena and anthropogenic activities in Lake Mead.

**Plan adaption in the event of future invasion by other aquatic invasive species**

As noted above, Lake Mead was not colonized by zebra mussels prior to the quagga mussel’s
arrival. A prudent measure, over the course of implementing the quagga mussel monitoring plan, would be for monitoring staff to be well acquainted with the morphological differences (and their variabilities) between quagga mussels and zebra mussels and to be vigilant in the watch for zebra mussels (and other aquatic invasive species). Should zebra mussels or other invasive bivalves appear, it is recommended that this plan be adapted to consider the new invader. In the example of zebra mussels, a sighting would trigger a survey of all existing quagga mussel-monitoring sites, which, together, provide a representation of all Lake Mead basins. Resultant data (mean and range) should then be used to calculate, as was done for quagga mussels, the minimum number of samples needed for zebra mussel adults and veligers. If calculation results show that numbers similar to those of quagga mussels are required, then it would be sufficient to monitor for both quagga mussels and zebra mussels at the existing stations. These examinations should be planned to determine abundance, extent of colonization, and distribution of zebra mussels across the lake. Variation among sites in terms of quagga mussel vs. zebra mussel preference should be assessed. Subsequently, growth and survivorship of zebra mussels in a quagga mussel-dominated environment could be studied.

Summary

The health of the Lake Mead and other ecosystems in the lower Colorado River system will undoubtedly be altered due to the presence and exponential spread of invasive quagga mussels. It is clear that the quagga mussel population in Lake Mead is still growing. We have cooperatively designed a strategic, cost-effective, long-term, and scientific monitoring plan designed to facilitate coordination and integration of the monitoring efforts conducted by multiple agencies. Although it is unlikely that mussels will be eradicated, the fundamental biological knowledge resulting from this program will be useful in quagga mussel control and prevention, and assessment of ecological implications and risks to public facilities. For example, regular, targeted prevention and maintenance based on the natural history of the organism in the Lake Mead environment can be scheduled to coincide with identified veliger peaks to avoid reduced flows or ultimate clogging of pipes later in the year.

Preliminary data quickly collected in the immediate stages of quagga mussel infestation are useful as a starting point in cost-effectively initiating a full-scale monitoring program. Statistically determined minimum numbers of samples needed are presented along with the specific sampling frequencies that will best estimate recruitment and distribution of quagga mussels in Lake Mead. These calculations help ensure validity and cost-effectiveness of the program. As the population becomes more abundant and expands into new regions, it is expected that variability between sites will change and become more defined, and fewer sites will have zero values. After the first year of monitoring, the sampling sites and frequencies, should be reviewed and optimized with the new data to ensure the plan’s usefulness in the long term.

This approach to designing a quagga mussel-monitoring program for juveniles/adults and veligers in Lake Mead may serve as a blueprint that can be tailored for use by agencies in other areas infested with or threatened by quagga/zebra mussels, especially areas in the western United States.

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