Aquatic Invasions (2011) Volume 6, Issue 2: 125–129
doi: 10.3391/ai.2011.6.2.01
© 2011 The Author(s). Journal compilation © 2011 REABIC
Open Access

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

**Guest Editorial**

# Quagga Mussels in the Western United States: Monitoring and Management

Wai Hing Wong and Shawn L. Gerstenberger

*Department of Environmental and Occupational Health, University of Nevada Las Vegas, Las Vegas, NV 89154, USA*

*E-mail: David.Wong@unlv.edu (WHW), shawn.gerstenberger@unlv.edu (SLG)*

Received: 7 December 2010 / Accepted: 7 December 2010 / Published online: 19 December 2010

**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.

This special edition of *Aquatic Invasions* includes papers on quagga mussels in the western United States presented in a workshop entitled "Quagga Mussels in the Western United States – Monitoring and Management." This workshop was sponsored by the National Shellfisheries Association, American Fisheries Society (Fish Culture Section) and World Aquaculture Society's Triennial Conference, which was held in March 2010 in San Diego, CA, USA.

Dreissenid mussels including zebra mussel (*Dreissena polymorpha* Pallas, 1771), originating from the Ponto-Caspian area, and quagga mussel (*Dreissena rostriformis bugensis* Andrusov, 1897), originating from the mouths of the Rivers Southern Bug and Dnieper are both species native to Eastern Europe, which were accidently introduced into the Laurentian Great Lakes in North America in the 1980s in ballast water (Carlton 2008; Van der Velde et al 2010). Dreissenid mussels have created severe ecological, recreational and economic impacts on many systems because they are biofoulers and efficient ecological engineers that filter large quantities of water. Examples of these wide-ranging impacts are discussed by Turner et al. (2011) in this issue. Ecologically, invasive dreissenid species have been shown to affect a variety of changes, such as altering phytoplankton species composition and nutrient dynamics in the Great Lakes (Lavrentyev et al. 1995; Vanderploeg et al. 2001; Conroy et al. 2005; Zhang et al. 2011), impacting other organisms by direct colonization or indirect competition for food and/or space, and increasing water clarity by removing suspended particles (e.g., phytoplankton, debris, silt and microzooplankton) in the water column. The increased water clarity can then affect other ecosystem components, such as species abundance and community composition of microalgae and aquatic plant communities. The zebra/quagga mussel has become arguably the most serious nonindigenous biofouling pest introduced into North American freshwater systems (LaBounty and Roefer 2007) and one of the world's most economically and ecologically important pests (Aldridge et al. 2006). The spread of dreissenid mussels in recent years has slowed in recent years in many systems as the most vulnerable bodies of water have been colonized (Johnson et al. 2006), but will presumably continue for many years, until the entire range is filled (Strayer 2009).

Before its discovery in the Boulder Basin of Lake Mead (Nevada, USA) on January 6, 2007, the quagga mussel was primarily restricted to the Great Lakes region. The presence of quagga mussels in Lake Mead in 2007 was the first confirmed introduction of a dreissenid species in the western United States, and it was also the first time that a large ecosystem was infested by quagga mussels without previous infestation by zebra mussels. It has been postulated that quagga mussels were introduced into Lake Mead via bilge water (i.e. bait or live wells) carried by a boat from the Great Lakes region. The discovery of quagga mussels in Lake Mead extended the U.S. range of this non-native species about 3,000 km west of previously known populations in the Great Lakes. Because of these mussels' high fecundity, passively dispersed planktonic veliger larval stage, and ability to attach to submerged objects with byssal threads, they have rapidly spread to other lakes and reservoirs in the Lower Colorado River Basin. The presence of many artificial waterways for drinking water and irrigation along the Colorado River aqueduct also exacerbates the spread of quagga mussel veligers. For example, following their detection in Lake Mead in January 2007, quagga mussel veligers were found in December 2007 in Sweetwater Lake in San Diego, California. Sweetwater Lake is indirectly connected to Colorado River aquaduct and is more than 500 km southwest of Lake Mead. By contrast, in the eastern United States, zebra mussels were discovered in 1993 in New York's Hudson River, but they were not detected in Massachusetts until 2008. Although the distance between the two eastern infestation sites is comparable to that of the two western sites, the spread speed is not on the same scale (i.e., 11 months vs. 15 years). The speed at which quagga mussel has spread throughout southwestern United States is unprecedented. Apart from the Lower Colorado System, quagga mussels have also been found in lakes and reservoirs in Arizona, California, Colorado, Nevada and Utah.

To address this emerging issue in the Southwest, federal, state, and local agencies, such as National Park Service Lake Mead National Recreation Area, U.S. Bureau of Reclamation (USBR, also termed Reclamation or BOR), U.S. Fish and Wildlife Service, Nevada Department of Wildlife, Southern Nevada Water Authority, California Department of Fish and Game, Metropolitan Water Reclamation District of Southern California, Arizona Game and Fish Department, as well as other agencies, began to monitor quagga mussel populations in the water bodies within their jurisdictions and seek ways to manage them in their facilities from early 2007. Several significant outcomes in response to this emerging issue include an Interagency Monitoring and Action Plan (I-MAP) for quagga mussels in Lake Mead National Recreation Area led by the National Park Service stemmed from an Emergency Response Plan produced by the National Park Service (Turner et al. 2011); the I-MAP includes a quagga mussel information network with representatives from multiple agencies. A quarterly meeting continues to serve as a platform for information sharing and responding to the challenges quagga mussels present in Lake Mead and the Colorado River. The U.S. Bureau of Reclamation established an early detection monitoring program for selected lakes and reservoirs in the West by utilising a suite of analytical methods including cross-polarized light microscopy, scanning electron microscopy, flow cell cytometry, and polymerase chain reaction (Johnson 1995; Hosler 2011). It also tested different methods to control quagga mussels on critical infrastructure, such as a filter straining and ultraviolet (UV) light systems installed at Hoover Dam. Protecting coatings were also evaluated at Parker Dam and at intakes for the Metropolitan Water District of Southern California and the Central Arizona Project, as well as a self-cleaning ballast filter that can remove all mussels and veligers from water installed at Parker Dam's domestic water intake. The Southern Nevada Water Authority installed a pre-chlorination system to prevent veligers from attaching to their equipment. With support from the American Water Workers' Association, Southern Nevada Water Authority and Metropolitan Water District of Southern California sponsored a workshop to explore strategies for responding to the presence of quagga mussels in the Lower Colorado River. The Metropolitan Water District of Southern California expects to spend between $10-15 million per year to address the quagga mussel infestation in its 242-mile Colorado River aqueduct and reservoirs. The U.S. Fish and Wildlife Service is active in preventing the spread of aquatic invasive species through the 100th Meridian Initiative (Mueting and Gerstenberger 2011) and the "Stop Aquatic Hitchhikers" national public awareness campaign. The U.S. Fish and Wildlife Service, working in concert with the Western Regional Panel on Aquatic Nuisance Species Task Force, also developed a "Quagga-Zebra Mussel Action Plan (QZAP) for western U.S. Waters" to respond to the westward spread of quagga and zebra mussels. Many western states have passed legislation requiring boat inspection and decontamination to keep invasive mussels out of their waters. There is no accurate estimate on how much money has been spent on quagga mussel control, prevention, monitoring, and education in the western United States of America, but it is known that significant funds have been spent (Turner et al. 2011).

This special issue of *Aquatic Invasions* is focused on Lake Mead, Nevada-Arizona: the first and one of the most severely quagga mussel infested water bodies in the western United States. Lake Mead is therefore a sentinel system to study quagga mussels and test solutions designed to prevent and control quagga mussels in the West. Lake Mead, formed in 1935 following construction of Hoover Dam, is the largest reservoir in the United States by volume ($3.5 \times 10^{10}$ $m^3$) (Holdren and Turner 2010). Lake Mead National Recreation Area is the oldest and one of the largest national recreation areas (nearly 1.5 million acres of land and water) managed by the National Park Service. Hoover Dam and Lake Mead levels are managed by the U.S. Bureau of Reclamation to provide water resources to Nevada, Arizona, and California. The Southern Nevada Water Authority provides treated drinking water to metropolitan Las Vegas and manages water resources to ensure adequate future water supplies for the Las Vegas Valley. This multi-use reservoir also provides waters for agricultural irrigation and is used for flood control, power generation, recreation, and navigation. The health of the Lake Mead ecosystem could be subject to profound and permanent changes due to the presence and spread of the invasive quagga mussel. Based upon the data from other experiments in North America and Europe, quagga mussels can potentially impact any trophic level or limnological parameter in Lake Mead, such as primary production, phytoplankton composition, suspended particles (i.e., silt and detritus), water transparency, zooplankton biomass, dissolved nutrients, aquatic vegetation, oxygen, benthic organisms, fishery, and contaminants (Wong et al. 2011 and references therein). From 2007 to 2009, water clarity has increased significant (+13%) in Boulder Basin of Lake Mead, mainly due to the reduction in chlorophyll concentrations (- 45%) (Wong et al. In review), but the zooplankton community (i.e., rotifers, daphnia, and copepod) has not had any significant change yet (Wong et al. 2010). While no detectable changes in threadfin shad abundance (Loomis et al. 2011), the gizzard shad found in Lake Mead in 2007 has experienced exponential increase since then (Herndon 2010). As benthic organisms are major food components for gizzard shad (Judge 1973), their dominance in the fish community may be associated with the invasive quagga mussels in Lake Mead. The size structure of quagga mussels in their early stage of invasion into Lake Mead in 2007 is described in this issue (McMahon 2011). For monitoring and prevention, early detection of quagga mussels with artificial substrates is critical for many agencies (Hosler 2011). Chen et al. highlight that substrates with rougher surfaces in locations with slow flow velocity (< 3 cm/s) were found to have higher colonization/settlement rates (Chen et al. 2011). This emerging issue in the western United States could be worse than in the East because this region's climate, geology, and resultant physical and chemical characteristics of water provide an ideal environment for these invasive mussels; such as warm water, localised high calcium concentrations and related suitable pH, rocky substrates and sufficient dissolved oxygen (Cross et al. 2011), as seen from the unprecedented speed of spread in the region exacerbated by many artificial waterways. Cross et al. (2011) estimate the maximum carrying capacity of the Boulder Basin of Lake Mead to be approximately $10^{12}$ adult quagga mussels. For improved monitoring of quagga mussels in the region, Turner et al. (2011) give an example on how multiple agencies can benefit from working together through an I-MAP for quagga mussels in Lake Mead - a comprehensive, 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. As part of the I-MAP, stratified random and simple random sampling designs have been used to select monitoring sites for adult/juvenile mussels and veligers and also standardized approaches to collect and quantify quagga mussel samples (Wong et al. 2011).

The control and prevention of infestation by dreissenid mussels are major concerns to managers of any type of water delivery system because these mussels have profound ecological, recreational and economic impacts. Unfortunately, tools for effective, cost-efficient, and ecologically sound quagga and zebra mussel control are limited. Many methods have been tested or are being developed for dreissenid mussel control, such as chemical treatment, physical killing, mechanical removal, and biological control. These methods can be combined to more effectively control and manage the population size, depending on the development stage of the mussel and the specific situation of the lakes and rivers. In this issue, it is found that quagga mussel veligers were killed when exposed to a 3% solution of Sparquat 256® for 10 minutes (Britton and Dingman 2011), but more rigorous evaluation of the effectiveness of various sanitation solutions in killing quagga and zebra mussels under different ambient temperatures are needed in order to validate and refine the sanitation protocol for firefighting equipment and other applications. Natural resource interest groups and regulatory agencies have made it clear that safe and non-chemical alternatives for controlling mussel fouling are preferred. Biological control of invasive dreissenid mussels is more desirable, because it is less damaging to the environment and human health.

Given the difficulty of controlling mussels once introduced to an ecosystem, the best control is prevention. Mueting and Gerstenberger (2011) found that, the 100th Meridian Initiative established by the U.S. Fish and Wildlife Service, does help prevent the spread of aquatic nuisance species through boater education and research on boater movement patterns and behaviors. Although the 100th Meridian Initiative does not successfully prevent the introduction of quagga/zebra mussels into the West, this program must have postponed the arrival of these invasive mussels for a couple of years. The 100th Meridian Initiative not only increased the boaters' awareness on invasive species, but also collected relevant data on where efforts should be focused to avoid future mussel invasions.

Significant work has been done in the three years (2007-2009) following the initial detection of invasive quagga mussels in Lake Mead; the data presented in this special issue of *Aquatic Invasions* provide critical baseline information on monitoring and management at the early stages of quagga mussel introduction in the western United States. Long-term studies in Lake Mead, and other lakes and reservoirs along the Lower Colorado River Basin, and across the entire western United States are needed to further address this emerging issue in the coming years. It is our sincere hope that a future issue of *Aquatic Invasions* will cover the quagga mussels in this region in 3 to 5 years when more data have been accumulated. At that time, these data will also be available to compare the ecology and control techniques for dreissenid mussels in the Midwest (Nalepa and Schloesser 1993; Nalepa et al. 2010) and Europe (Karatayev et al. 2007; Lucy et al. 2008; Lucy and Muckle-Jeffs 2010; Van der Velde et al. 2010; Zhulidov et al. 2010).

## References


Aldridge DC, Elliott P, Moggridge GD (2006) Microencapsulated BioBullets for the control of biofouling zebra mussels. *Environmental Science and Technology* 40: 975–979, doi:10.1021/es050614+

Britton D, Dingman S (2011) Use of quaternary ammonium to control the spread of aquatic invasive species by wildland fire equipment. *Aquatic Invasions* 6: 169–173, doi:10.3391/ai.2011.6.2.06

Chen D, Gerstenberger SL, Mueting SA, Wong WH (2011) Potential factors affecting settlement of quagga mussel (*Dreissena bugensis*) veligers in Lake Mead, Nevada-Arizona, USA. *Aquatic Invasions* 6: 149–156, doi:10.3391/ai.2011.6.2.04

Conroy JD, Kane DD, Dolan DM, Edwards WJ, Charlton MN, Culver DA (2005) Temporal trends in Lake Erie plankton biomass: Roles of external phosphorus loading and dreissenid mussels. *Journal of Great Lakes Research* 31: 89–110, doi:10.1016/S0380-1330(05)70307-5

Cross C, Wong WH, Chen TD (2011) Estimating carrying capacity of quagga mussels (*Dreissena rostriformis bugensis*) in a natural system: A case study of the Boulder Basin of Lake Mead, Nevada-Arizona. *Aquatic Invasions* 6: 141–147, doi:10.3391/ai.2011.6.2.03

Herndon D (2010) Lake Mead preliminary gill net survey results. Interagency Quarterly Quagga Mussel Meeting, Henderson, NV

Holdren GC, Turner K (2010) Characteristics of Lake Mead, Arizona-Nevada. *Lake and Reservoir Management* 26: 230–239, doi:10.1080/07438141.2010.540699

Hosler D (2011) Early detection of dreissenid species: zebra/quagga mussels in water systems. *Aquatic Invasions* 6: 217–222, doi:10.3391/ai.2011.6.2.10

Johnson LE (1995) Enhanced early detection and enumeration of zebra mussel (*Dreissena spp*) veligers using cross-polarized light microscopy. *Hydrobiologia* 312: 139–146, doi:10.1007/BF00020769

Johnson LE, Bossenbroek JM, Kraft CE (2006) Patterns and pathways in the post-establishment spread of non-indigenous aquatic species: The slowing invasion of North American inland lakes by the zebra mussel. *Biological Invasions* 8: 475–489, doi:10.1007/s10530-005-6412-2

Judge DJ (1973) Food and Feeding Habits of Gizzard Shad in Pool 19, Mississippi River. *Transactions of the American Fisheries Society* 102: 378–383, doi:10.1577/1548-8659(1973)102<378:FAFHOG>2.0.CO;2

Karatayev AY, Padilla DK, Minchin D, Boltovskoy D, Burlakova LE (2007) Changes in global economies and trade: the potential spread of exotic freshwater bivalves. *Biological Invasions* 9: 161–180, doi:10.1007/s10530-006-9013-9

LaBounty JF, Roefer P (2007) Quagga mussels invade Lake Mead. *LakeLine* 27: 17–22

Lavrentyev PJ, Gardner WS, Cavaletto JF, Beaver JR (1995) Effects of the zebra mussel (*Dreissena polymorpha* Pallas) on protozoa and phytoplankton from Saginaw Bay, Lake Huron. *Journal of Great Lakes Research* 21: 545–557, doi:10.1016/S0380-1330(95)71065-6

Loomis E, Sjoberg J, Wong WH, Gerstenberger S (2011) Abundance and stomach content analysis of threadfin shad (*Dorosoma petenense*) in Lake Mead, Nevada: Do invasive quagga mussels (*Dreissena rostrifomis bugensis*) affect this prey species? *Aquatic Invasions* 6: 157–168, doi:10.3391/ai.2011.6.2.05

Lucy FE, Minchin D, Boelens R (2008) From lakes to rivers: downstream larval distribution of *Dreissena polymorpha* in Irish river basins. *Aquatic Invasions* 3: 297–304, doi:10.3391/ai.2008.3.3.4

Lucy FE, Muckle-Jeffs E (2010) History of the Zebra Mussel/ICAIS Conference series. *Aquatic Invasions* 5: 1–3, doi:10.3391/ai.2010.5.1.1

McMahon RF (2011) Quagga mussel (*Dreissena rostriformis bugensis*) population structure during the early invasion of Lakes Mead and Mohave January-March 2007. *Aquatic Invasions* 6: 131–140, doi:10.3391/ai.2011.6.2.02

Mueting SA, Gerstenberger SL (2011) The 100th Meridian Initiative at the Lake Mead National Recreation Area, NV, USA: Differences between boater behaviors before and after a quagga mussel, *Driessena rostiformis bugensis*, invasion *Aquatic Invasions* 6: 223–229, doi:10.3391/ai.2011.6.2.11

Nalepa TF, Fanslow DL, Pothoven SA (2010) Recent changes in density, biomass, recruitment, size structure, and nutritional state of *Dreissena* populations in southern Lake Michigan. *Journal of Great Lakes Research* 36: 5–19, doi:10.1016/j.jglr.2010.03.013

Nalepa TF, Schloesser DW (1993) Zebra mussels: Biology, Impacts, and Control. Lewis Publishers, Boca Raton, Ann Arbor, London, Tokyo, 810 pp

Strayer DL (2009) Twenty years of zebra mussels: lessons from the mollusk that made headlines. *Frontiers in Ecology and the Environment* 7: 135–141, doi:10.1890/080020

Turner K, Wong WH, Gerstenberger SL, Miller JM (2011) Interagency monitoring action plan (I-MAP) for quagga mussels in Lake Mead, Nevada-Arizona, USA. *Aquatic Invasions* 6: 195–204, doi:10.3391/ai.2011.6.2.08

Van der Velde G, Rajagopal S, Bij de Vaate A (2010) The Zebra Mussel in Europe. Backhuys Publishers, Leiden, The Netherlands, 490 pp

Vanderploeg HA, Liebig JR, Carmichael WW, Agy MA, Johengen TH, Fahnenstiel GL, Nalepa TF (2001) Zebra mussel (*Dreissena polymorpha*) selective filtration promoted toxic *Microcystis* blooms in Saginaw Bay (Lake Huron) and Lake Erie. *Canadian Journal of Fisheries and Aquatic Sciences* 58: 1208–1211, doi:10.1139/f01-066

Wong WH, Gerstenberger SL, Miller JM, Palmer CJ, Moore B (2011) A standardized design for quagga mussel monitoring in Lake Mead, Nevada-Arizona. *Aquatic Invasions* 6: 205–215, doi:10.3391/ai.2011.6.2.09

Wong WH, Holdren GC, Tietjen T, Gerstenberger S, Moore B, Turner K, Wilson D (2011) Effects of Invasive Quagga Mussels (*Dreissena rostriformis bugensis*) on chlorophyll and water clarity in the Lower Colorado River Basin In: Nalepa TF and Schloesser DW (eds) Zebra Mussels: Biology, Impact, and Control (accepted)

Wong WH, Tietjen T, Gerstenberger SL, Holdren C, Mueting SA, Loomis E, Roefer P, Moore B, Turner K, Hannoun I (2010) Potential ecological consequences of invasion of the quagga mussel (*Dreissena bugensis*) into Lake Mead, Nevada–Arizona, USA. *Lake and Reservoir Management* 26: 306–315, doi:10.1080/07438141.2010.504071

Zhang H, Culver DA, Boegman L (2011) Dreissenids in Lake Erie: an algal filter or a fertilizer? *Aquatic Invasions* 6: 175–194, doi:10.3391/ai.2011.6.2.07

Zhulidov AV, Kozhara AV, Scherbina GH, Nalepa TF, Protasov A, Afanasiev SA, Pryanichnikova EG, Zhulidov DA, Gurtovaya TY, Pavlov DF (2010) Invasion history, distribution, and relative abundances of *Dreissena bugensis* in the old world: a synthesis of data. *Biological Invasions* 12: 1923–1940, doi:10.1007/s10530-009-9641-y