

Invasive Quagga Mussel Impacts on the Lake Havasu Ecosystem

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Peer Review

Bureau of Reclamation Research and Development Office Science and Technology Program

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Acronyms and Abbreviations

AZDEQ	Arizona Department of Environmental Quality
AZGFD	Arizona Game and Fish Department
BLM	Bureau of Land Management
CalDFW	California Department of Fish and Wildlife
CalEPA	California Environmental Protection Agency
CEDEN	California Environmental Data Exchange Network
EPA	Environmental Protection Agency
MCHD	Mohave County Health Department
Reclamation	Bureau of Reclamation
USGS	US Geological Survey
WQP	Water Quality Portal

Measurements

°C	degree Celsius
μg/L	microgram per liter
mg/L	milligram per liter
μg d.w./L	microgram dry weight per liter
μm³/L	cubic micrometer per liter
mV	millivolts
μS/cm	microsiemens per centimeter

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Executive Summary

Invasive quagga mussels (*Dreissena rostriformis bugensis*) were first discovered in Lake Havasu, Lake Mead, and Lake Mohave in 2007. Since then, mussel infestations have been located at other sites on the Lower Colorado River, as well as at reservoirs in Arizona and California. The mussel populations in many of these locations have expanded rapidly since first introduction. Large mussel populations pose a significant threat to Reclamation because of their ability to settle on infrastructure and slow the movement of water, but they can also change the natural ecosystem of a reservoir and harm ecological communities.

The ecological impacts of invasive dreissenid mussels have primarily been investigated at natural, temperate lakes in the eastern United States, and the response of ecological communities in western reservoirs remains an unanswered question. This study was an initial analysis of ecological data for Lake Havasu that has been collected in the past. Water quality data from federal and state agencies was retrieved from the EPA Water Quality Portal. Zooplankton survey data collected since 2009 was provided by the Lower Colorado Region, Resource Management Office. Although a large amount of data exists, collection methods, times, and locations have not been standardized which makes drawing conclusions difficult.

The Lake Havasu zooplankton community composition appears to have changed slightly since 2009. Rotifers now constitute a larger percentage of the community, while cladoceran biomass has declined. This result is somewhat unexpected, given previous reporting that dreissenid mussels reduce rotifer populations via predation. Phytoplankton data is limited to 2013 to 2016 and shows a slight upward trend in total biovolume.

Assessing the impact of quagga mussels on various water quality parameters is confounded by the influence of other outside factors, such as water level fluctuations, climatic conditions, and human activity. The presence of mussels may be shifting some nutrients, such as phosphorus, to different locations in the lake, while increasing the amount of nitrate-nitrogen and chlorophyll *a*. The oxidation reduction potential of Lake Havasu also appears to be lower than it was before quagga mussels were discovered. A low oxidation reduction potential will limit the ability of bacteria to efficiently breakdown detritus in the lake.

Additional components of the Lake Havasu ecosystem should be assessed to create a more complete picture of the impacts of quagga mussels. Data pertaining to fish populations may be available through BLM or another agency, but was not accessed for this scoping study. Dreissenid mussels often impact macroinvertebrates and aquatic plants in invaded ecosystems, so efforts should be made to assess these communities. Developing a full understanding of quagga mussel impacts to Lake Havasu will require a long-term, standardized monitoring program that incorporates many different aspects of the ecosystem.

1. Introduction

Invasive quagga mussels (*Dreissena rostriformis bugensis*) were first discovered in Lake Havasu, Lake Mead, and Lake Mohave in 2007. Since then, mussel infestations have been located at other sites on the Lower Colorado River, as well as at reservoirs in Arizona and California. The mussel populations in many of these locations have expanded rapidly since first introduction. Large mussel populations pose a significant threat to Reclamation because of their ability to settle on infrastructure and slow the movement of water, but they can also change the natural ecosystem of a reservoir and harm ecological communities. The ecological impacts of invasive dreissenid mussels have primarily been investigated at natural, temperate lakes in the eastern United States, and the response of ecological communities in western reservoirs remains an unanswered question.

1.1 Potential Ecological Impacts

The ecological impacts of invasive mussels may change based on the natural environment of the waterbody and the size of the mussel population (Nalepa 2010). Waterbodies that are degraded by drought, pollution, or climate change, may be more susceptible to large changes.

1.1.1 Transfer of Energy

Mussels filter large quantities of water and deposit organic matter as feces or as pseudo-feces (Gergs et al. 2009). This can transfer energy from the pelagic-profundal (open water) region to the littoralbenthic (near shore and bottom) (Miehls et al. 2009, Higgins & Vander Zanden 2010). The feeding process separates particle bound nutrients and increases the availability of soluble nutrients, particularly phosphorus (Higgins & Vander Zanden 2010), which is redirected to the benthic region (Hecky et al. 2004). Concentrations of soluble phosphorus, nitrate-nitrogen, silica, and chloride have increased after some zebra mussel invasions (Holland et al. 1995) but declines in phosphorus and chlorophyll *a* have also been documented (Cha et al. 2013).

1.1.2 Climate

Large populations of mussels have been linked to changes the carbon dioxide dynamics of waterbodies. Lin and Guo (2016) reported an increase in CO_2 emission fluxes in Lakes Michigan and Huron, making them significant atmospheric CO_2 sources. The mussels may have altered CO_2 dynamics by decreasing primary production, increasing water clarity and photo-degradation of organic matter, and by the metabolic processes of the mussel population (Lin & Guo 2016). It is not clear, however, that mussels are fully responsible for the observed increases in CO_2 fluxes.

1.1.3 Water Clarity, Plants, & Algae

Water transparency can be significantly improved (30-50%) as suspended particulate matter is removed by mussels (Higgins & Vander Zanden 2010). Submerged macrophytes are plants that provide habitat for zooplankton, invertebrates, and fish, and are a valuable food source for many organisms. Increases in water transparency means deeper light penetration which may reduce habitat for deep-water fish that prefer low-light, or expand macrophyte coverage, creating additional habitat. Biodeposition of feces and pseudofeces also enriches sediment, providing resources to aquatic plants (Minchin & Boelens 2011), potentially increasing the coverage of submerged macrophytes increased $180\% \pm 40\%$ in lakes with mussels (Higgins & Vander Zanden 2010).

1.1.4 Plankton

Phytoplankton and zooplankton are critical components of freshwater food webs. Declines in both phytoplankton (35 to 78%) and zooplankton (40 to 77%), particularly rotifers and copepods, have occurred following dreissenid invasions (Higgins & Vander Zanden 2010). Rotifer densities can be reduced due to direct predation (Thorp & Casper 2003), while copepod populations may decline when dreissenid predation eliminates their large phytoplankton food sources (Rowe et al. 2017). In two mesocosm experiments conducted using zebra mussels, the biomass of cladocerans and copepods was not affected by the presence of mussels (Feniova et al. 2020).

1.1.5 Zoobenthos

Mussels physically alter the substrate and reallocate resources. Non-mussel macroinvertebrate biomass may increase by 160 to 210% after a mussel population becomes established (Higgins & Vander Zanden 2010). Leeches, flatworms, and small gastropods colonize mussel beds, increasing overall abundance (Ward & Ricciardi 2007, Higgins & Vander Zanden 2010). Large gastropods can be negatively impacted by biofouling from mussels, leading to reduced mobility and burrowing ability, as well as inhibited growth (Van Appledorn et al. 2007, Van Appledorn & Bach 2007).

1.1.6 Native Bivalves

Unlike other macroinvertebrates, native bivalves are often decimated following an invasion by dreissenid mussels. Pearly mussels (Unionidae) have been nearly extirpated from some waterbodies, while pea clam (Sphaeriidae) populations have suffered serious declines (Strayer & Malcom 2018). Zebra and quagga mussels affect native species directly, through biofouling, and indirectly by competing for food (Karatayev et al. 1997, Burlakova et al. 2014, Lucy et al. 2014, Strayer & Malcom 2018). Native species then suffer from starvation, resulting in reduced fitness, and eventual death (Baker & Hornbach 1997, Strayer & Malcom 2018).

1.1.7 Fish

The impact of invasive mussels on fish populations depends on the adaptability of different fish species and the resiliency of the overall food web. Correlations between the presence of dreissenid mussels and the growth, condition, and relative abundance of game fish have been documented (Nienhuis et al. 2014). However, changes caused by mussels will not affect all fish species equally. Since zebra and quagga mussels reduce the plankton in a waterbody and shift energy resources to the littoral zone, obligate planktivore and deep-water benthivore species are likely to be negatively impacted (Higgins & Vander Zanden 2010). In the Great Lakes, benthivorous lake whitefish (*Coregonus clupeaformis*) successfully shifted from deep-water to nearshore resources after mussel establishment (Fera et al. 2017). Other species that can use a variety of resources and forage in the littoral zones should maintain population sizes, and potentially expand. Smallmouth bass and muskellunge rely on submerged aquatic plants for feeding and spawning habitat. In Lake St. Clair, the abundance of smallmouth bass and muskellunge tripled after the establishment of dreissenid mussels, likely due to increased macrophyte coverage (Vanderploeg 2003).

1.1.8 HABs

Lakes with dreissenid mussels tend to see an increase in the biomass of cyanobacteria species (Higgins & Vander Zanden 2010). In a survey of 39 lakes, Knoll et al. (2008) found that lakes with zebra mussels had a 3.6-time higher biomass of *Microcystis aeruginosa*. Dreissenid mussels will selectively reject cyanobacteria and other pollutants as pseudofeces (Vanderploeg et al. 2001). Since

other phytoplankton and small algae species are consumed, the rejection of cyanobacteria increases the relative abundance of toxic species in a waterbody, potentially leading to harmful blooms.

1.1.9 Other

Dreissenid mussels can attach to the larvae of dragonflies (*Macromia illinoiensis*), impeding their ability to burrow, forage, and emerge from the water to molt (Fincke & Tylczak 2011). Because dragonflies prey upon mosquitoes and other small insects (Corbet 1999), dragonfly declines could significantly change the entomological community near the waterbody. Hard-bodied aquatic organisms are vulnerable to dreissenid colonization, and the carapace and hard appendages of crayfish are ideal attachment points. High densities of mussels have been found attached to crayfish, particularly in coastal areas with soft substrates (Brazner & Jensen 2000, Ďuriš et al. 2007). However, because crayfish molt as they grow, the effects of mussels will vary seasonally (Ďuriš et al. 2007).

Various waterfowl species will utilize mussels as a food source (Madenjian et al. 2010). After mussels established in the Great Lakes, migratory patterns of greater scaup (*Aythya affinis*), lesser scaup (*A. marila*), and buffleheads (*Bucephala albeola*) changed to take advantage of the new food source (Vanderploeg et al. 2002, Luukkonen et al. 2014). In some areas, mussel biomass was temporarily reduced by up to 90% (Hamilton et al. 1994, Werner et al 2005). Changes caused by mussels may also improve habitat for waterfowl. Submerged macrophytes become more abundant with improved water clarity, and canvasback ducks expand their foraging area to deeper water in response (Luukkonen et al. 2014). The biomass of other plants that prefer clear water, such as Vallisneria and Chara, also increases, supporting larger populations of dabbling ducks (Vanderploeg et al. 2002).

1.2 Impacts in the West

Most infested or threatened waterbodies in the western US are artificially created and have a subtropical climate, which could lead to impacts that differ from those in temperate eastern lakes. Reclamation reservoir water levels also fluctuate within and between years. Although mussels may be able to reproduce multiple times per year in warmer water, they may also be desiccated or forced to recolonize areas that become dry during periods of low water. Waterbodies in the western US may also see less dramatic expansions of macrophyte coverage because many reservoirs were created in steep-sided canyons, limiting how much of the benthos will receive additional light when water clarity improves.

Although quagga mussels have been in Lake Havasu and other portions of the Colorado River system since at least 2007, relatively few published studies have investigated the ecological impacts in these locations. Turkett (2016) analyzed water samples from three locations in Lake Mead that were collected prior to (2004-2006), and immediately after (2009-2011), the establishment of quagga mussels and reported phytoplankton biomass reductions of 17 to 68%, while zooplankton biomass increased. However, a longer study found no significant changes to temporal or spatial patterns of zooplankton and phytoplankton from 2000 to 2015 in Lake Mead (Beaver et al. 2018).

In other regions, non-mussel invertebrate populations have often increased following the establishment of mussels. After quagga mussels were found in the aqueduct of the Central Arizona Project, researchers observed an increase in species richness but an overall decline in benthic species abundance due to declines in the caddisfly *Smicridea fasciatella* (Nelson & Nibling 2013). Freshwater

sponges, which can secrete toxins that inhibit colonization by other organisms (Ricciardi et al. 1995), increased in abundance. An early assessment of benthic changes in Lake Mead noted a decrease in macroinvertebrate diversity where quagga mussels exceeded a density of 2500/m², when compared to survey data from 1986 (Wittmann et al. 2010). However, the authors acknowledged that the apparent differences may not be due to the presence of quagga mussels.

Many native mussels and clams have been negatively impacted by human activity and climate change. Freshwater mussel richness in many western watersheds has declined by 35% compared to historic levels (Blevins et al. 2017), but western species may avoid the worst biofouling effects of dreissenid mussels. Quagga mussels have a weaker ability to attach to other shells compared to zebra mussels, decreasing the potential impact on native species (Burlakova et al. 2014).

There are several economically important fish species in Lakes Mead and Powell, including: largemouth bass, striped bass, rainbow trout, channel catfish, bluegill, black crappie, green sunfish, and walleye. Because the establishment of quagga mussels in the Lower Colorado Basin was relatively recent (2004-2007), fish populations are likely still adjusting and recent research into population dynamics is limited. Based on data acquired through 2008 in Lake Mead, the abundance of larval threadfin shad, an important prey fish, was apparently unaffected by the presence of quagga mussels (Loomis et al. 2011). However, gizzard shad were also found in Lake Mead in 2007. Because the larvae of gizzard and threadfin shad are indistinguishable, it is likely that reported abundances were inflated by the presence of a second species (Ianniello et al. 2015). Gizzard shad also consume benthic organisms as a large percentage of their diet (Judge 1973). As dreissenid mussels transfer energy to the benthos, gizzard shad may gain a competitive advantage over threadfin shad.

The subtropical environment of Lakes Mead and Powell could also lead to different effects compared to the Great Lakes. Lake Powell littoral fish, such as largemouth bass, bluegill, and green sunfish, are likely to experience a positive effect, while pelagic fish, including striped bass and threadfin shad, will likely be negatively impacted (Verde 2017). The ecological impacts of mussels will likely not be homogenous throughout a lake like Powell. Lake Powell is a man-made reservoir in a deep canyon with continuous sediment inputs from the Colorado River. Because suspended sediment concentrations greater than 100 mg/l impede mussel filtering of water (Madon et al. 1998, Kennedy, 2007), the northern region of the lake may serve as refuge for fish species that struggle to adapt to changes caused by mussels (St. Andre 2020). Lake Powell fish population trophic positions and overall energy may diverge in the northern and southern portions of the lake (St. Andre 2020). Overall impacts on Lake Powell fisheries may be limited by changes in water levels that force mussels to recolonize several meters of depth each year (Mark Belk, BYU, pers. comm.)

The only native fish in Lake Mead, the razorback sucker (*Xyrauchen texamus*), relies on areas of high turbidity for successful recruitment (Holdren & Turner 2010), and habitat reductions could follow increased water clarity. The redear sunfish is a known molluscivore, and quagga mussels have been found inside individuals captured in Lake Havasu (Karp & Thomas 2014). In locations where it is present, the redear sunfish may act as a biological control to reduce mussel populations.

While *Microcystis* has been documented, there have not yet been harmful algal blooms comparable to those seen in the Great Lakes in the Colorado River system. However, if quagga mussels create more favorable conditions, blooms may become more common as the climate warms.

2. Methods

2.1 Data Collection

Data was collected from locations throughout Lake Havasu (Figure 1). Water quality data from the Arizona Department of Environmental Quality (AZDEQ), Mohave County Health Department (MCHD), Arizona Game and Fish Department (AZGFD), and US Geological Survey (USGS) was downloaded from the Water Quality Portal managed by the US Environmental Protection Agency (EPA) and USGS (www.waterqualitydata.us/). Data from the California Department of Fish and Wildlife (CalDFW) and California EPA (CalEPA) was downloaded from the California Environmental Data Exchange Network (CEDEN, ceden.org/index.shtml).

Plankton community data, invasive mussel population data, and water quality data was provided by the Resource Management Office in the LCB Region. Due to personnel turnover, ecological data from the Bureau of Land Management (BLM) was not received.



Figure 1. Locations monitored for water quality or plankton in Lake Havasu.

2.2 Analysis

The ecological data was organized and assessed to identify trends that deserve additional study. This effort was completed using visual comparison of Excel charts and trends. Gaps in the available water quality and ecological data were identified by comparing existing Lake Havasu data with previous research in the Great Lakes and other waterbodies. Published literature was reviewed to determine potential ecological impacts of invasive mussels.

3. Results

3.1 Zooplankton & Phytoplankton

Sampling for mussel veligers and zooplankton has been performed at Lake Havasu since 2009. Prior to the establishment of quagga mussels in 2007 data was not collected. As the population of adult quagga mussels in Lake Havasu grows, spawning events should increase in size, and the biomass of veligers has increased since 2009 (Figure AA-1).

Zooplankton samples collected at Lake Havasu are analyzed to determine the amount of each species present. There are five categories of zooplankton reported in samples collected since 2009: bivalves, cladocerans, copepods, ostracods, and rotifers. The bivalve division consists entirely of invasive quagga mussel veligers. Cladocerans, copepods, and ostracods are small crustaceans, while rotifers are soft-bodied pseudocoelomate animals. All of these zooplankton compete with quagga mussels for food in the form of floating organic material. Although multiple studies have concluded that zooplankton populations decline following a mussel invasion, other researchers have reported minimal changes in the presence of mussels. In Lake Havasu, a slight upward trend in total zooplankton biomass was found (Figure 2).



Figure 2. Total biomass of zooplankton in Lake Havasu from 2009 to 2018. Biomass has increased slightly.

The biomass of bivalves (quagga mussel veligers) and rotifers has generally increased since 2009, while cladoceran and copepod biomass has varied greatly (Figure 3). While the total biomass of zooplankton has slightly increased, the community composition has fluctuated. The largest trends appear to be a decline in cladocerans and an increase in rotifers (Figure 4).



Figure 3. Lake Havasu zooplankton biomass by division from 2009 to 2018. Rotifers and bivalves have generally increased in biomass, while cladocerans and copepods have fluctuated. Adapted from figure created by Jeff McPherson, LCB Region.



Figure 4. Changes in zooplankton community composition at Lake Havasu from 2009 to 2018. Rotifers have become a larger percentage of the community since 2009, while cladocerans have declined. Adapted from figure created by Jeff McPherson, LCB Region.

Phytoplankton and cyanobacteria biovolume data was only available for 2013 to 2016 (Figure 5). Without data prior to the establishment of quagga mussels, it is difficult to assess changes to the phytoplankton of Lake Havasu. During the period of 2013 to 2016, the total phytoplankton biovolume trended upward, and cyanobacteria volume remained low, except for one spike in 2015.



Figure 5. Changes in phytoplankton and cyanobacteria biovolume from 2013 to 2016. Adapted from figure created by Jeff McPherson, LCB Region.

3.2 Water Quality

Water quality data including temperature (Temp), dissolved oxygen (DO), pH, and specific conductance (SpCond), collected at Lake Havasu since 1992 is publicly available through the EPA Water Quality Portal. Data has not been collected on a set schedule, and data does not exist for several entire years. From 1995 – 2019, data exists for 21 out of 25 years when limited to dates between May 14 – July 14. For many of these years, multiple collections occurred between the date limits. Since the Temp, DO, pH, and SpCond were collected as part of a profile from the surface to 11.6 meters deep, data was relatively equally divided into four depth bins labeled A-D: (A) 0 – 1.8 meters, (B) 1.8 - 4.5 m, (C) 4.5 - 7.1 m, and (D) 7.1 - 11.6 m. Prior to the discovery of quagga mussels in 2007, the water temperature appeared to be increasing, but that trend seems to have reversed post-invasion (Figure 6). The pH and dissolved oxygen of Lake Havasu may have increased slightly (Figure AA-2, Figure AA-3), while specific conductance has decreased (Figure AA-4).



Figure 6. Water temperature changes in Lake Havasu before quagga mussels (QM) were present (1995 - 2006) and after discovery (2007 - 2019). Depth bins are as follows: Bin A = 0 - 1.8 m, Bin B = 1.8 - 4.5 m, Bin C = 4.5 - 7.1 m, Bin D = 7.1 - 11.6 m.

Additional water quality data has been collected at Lake Havasu since 1990, but there is little consistency in the timing of sampling or parameters analyzed. Several parameters are highlighted here. For all analyses, the data was divided into before and after quagga mussels were found, indicated by the dashed red line in the figures.

Previous studies identified the transfer of phosphorus from offshore to nearshore areas as a change caused by invasive mussels. For this study, sampling data for phosphorus was divided into pelagic (offshore) points and benthic (nearshore) points. Phosphorus in both benthic and pelagic areas was slightly declining prior to the establishment of mussels (Figure 7). After mussels were discovered, phosphorus in pelagic locations began to increase, while benthic phosphorus stayed flat. This is somewhat unexpected, but the change is minimal and overall phosphorus in Lake Havasu has remained relatively consistent.



Figure 7. Phosphorus concentration at Lake Havasu before and after quagga mussel invasion. Phosphorus appears to be shifting slightly to offshore areas.

Chlorophyll a concentration in Lake Havasu has increased since the discovery of mussels in 2007 (Figure 8). The amount of chlorophyll in the lake seems to have increased immediately following the establishment of quagga mussels.



Figure 8. Chlorophyll a concentration in Lake Havasu before and after quagga mussel establishment. Chlorophyll a concentration increased.

Previous studies have identified increases in nitrate-nitrogen (inorganic) and chloride as ecological impacts caused by dreissenid mussels. The inorganic nitrogen concentration does appear to have increased following the discovery of quagga mussels in Lake Havasu (Figure 9). Chloride had not significantly changed since 1992 (Figure AA-5).

Oxidation Reduction Potential (ORP) is a measure of how quickly a waterbody can breakdown dead matter. A high ORP means more oxygen is in the water and bacteria can more efficiently breakdown detritus. Low ORP, below 300 mV, can be an indication of an unhealthy waterbody. The ORP in Lake Havasu was declining slightly prior to the establishment of mussels, and a large gap in the data exists from 2003 to 2014. However, the ORP measurements recorded after discovery of quagga mussels are all at or below the 300 mV threshold (Figure 10).



Figure 9. Nitrate-nitrogen concentration at Lake Havasu before and after quagga mussel establishment.



Figure 10. Oxidation reduction potential in Lake Havasu before and after quagga mussel invasion. ORP has decreased since the start of data collection.

Because dreissenid mussels are prolific filter feeders, large populations could amass significant quantities of heavy metals or other contaminants in their tissue and reduce the concentrations in the waterbody. Since 1992, the concentration of copper, iron, lead, magnesium, selenium, and zinc have all declined (Figure AA-6). It is not clear that this is related to the presence of quagga mussels, pollution remediation efforts, or natural changes, or some combination of factors.

4. Discussion

The ecological impacts of invasive dreissenid mussels appear to vary significantly based on the initial conditions of the waterbody, local climatic conditions, and a variety of other factors. Initial trends identified in the Lake Havasu water quality and plankton data are both supported by, and contradict, published impacts from other locations.

4.1 Current Study

Zooplankton communities in Lake Havasu may be changing in response to the presence of quagga mussels. Relative rotifer abundance has increased slightly since 2009, even though mussels have been identified as predators of rotifers in other waterbodies. There are large fluctuations in zooplankton species biomass between sampling years. No plankton community data exist prior to the discovery of quagga mussels at Lake Havasu, so it is difficult to establish a non-mussel baseline and separate the impact of quagga mussels from other background factors.

Water quality is a complex concept that encompasses many different parameters and is impacted by many competing influences. An assessment of the conditions at Lake Havasu is further complicated by a lack of consistency in water sampling locations and timing. It appears that the concentration of chlorophyll *a* and nitrate-nitrogen did increase following the appearance of quagga mussels, although other parameters such as chloride appear unaffected. The spatial distribution and abundance of phosphorus in infested waterbodies has often shifted in favor of benthic regions. The Lake Havasu data contradicts this expectation, as phosphorus appears to be rising faster at pelagic sampling locations.

None of the literature reviewed for this study directly identified changes to oxidation reduction potential as a potential impact of a dreissenid mussel population. Reservoirs in steep canyons with poor turnover often have anoxic areas throughout the lake. Quagga mussels may be extending these areas and reducing the ability of bacteria to breakdown detritus in Lake Havasu.

4.2 Next Steps

Even though quagga mussels have been established for over a decade, the ecosystem is still likely adapting to their presence. Although this initial investigation of ecological impacts of invasive mussels at Lake Havasu did not uncover any obvious, significant changes, gaps exist that should still be explored. Data about fish population dynamics, aquatic plant coverage, and other organisms was either not acquired as part of this study or is not currently collected. Understanding the ultimate

impacts of quagga mussels in the Lake Havasu ecosystem will require additional data collection and extensive multivariate statistical analysis.

A long-term monitoring program, with consistent sampling locations and methods, could provide additional insights into any changes caused by the mussels. The LCB Region has been collecting plankton data since 2009 and water quality data since at least 2015. Their data includes: dissolved orthophosphate, nitrate/nitrite, ammonia, chlorophyll *a*, E. coli, pH, total dissolved solids, and various cations (Na, K, Ca, Mg) and anions (CO₃, HCO₃, CaCO₃, Cl, SO₄, SiO₂, Fl). Incorporating additional monitoring, for fish, plants, and other organisms, at the same locations as the plankton surveys, would help future researchers compare changes through time. Any future exploration of the Lake Havasu ecosystem could begin with a deeper investigation of the existing LCB Region data, including a thorough multivariate statistical analysis.

5. Data

Water quality data available at EPA Water Quality Portal (<u>https://www.waterqualitydata.us/</u>). LCB Region plankton data is posted to the Southern Nevada Water Authority database (<u>www.snwa.com</u>).

Project data is stored on the TSC shared drive at: Z:\DO\TSC\Jobs\DO_NonFeature\Science and Technology\2021-PRG-Mussel Impacts to Lake Havasu Ecosystem

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Appendix A – Additional Figures



Figure AA-1. Veliger biomass changes in Lake Havasu from 2009 to 2018.

Figure AA-2. Changes to pH in Lake Havasu from 1995 to 2019.



Figure AA-3. Dissolved oxygen concentration at Lake Havasu from 1995 to 2019.



Figure AA-4. Specific conductance changes at Lake Havasu from 1995 to 2019.



Figure AA-5. Chloride concentration at Lake Havasu from 1992 to 2018. Concentrations appear to fluctuate slightly both before and after quagga mussel establishment.



Figure AA-6. Concentration of select metallic elements in Lake Havasu. All metal concentrations have decreased since 1992.