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Native Unionoida Surveys, Distribution, and Metapopulation Dynamics in the Jordan River-Utah Lake Drainage, UT

Report To:
Wasatch Front Water Quality Council
Salt Lake City, UT

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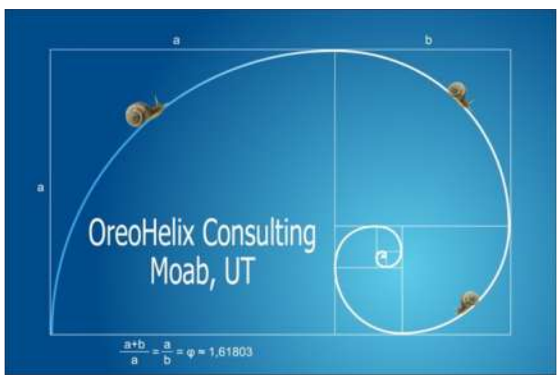


May 26, 2017

One of the few remaining live adult Anodonta found lying on the surface of what was mostly comprised of thousands of invasive Asian clams, Corbicula, in Currant Creek, a former tributary to Utah Lake, August 2016.

Summary

North America supports the richest diversity of freshwater mollusks on the planet. Although the western USA is relatively mollusk depauperate, the one exception is the historically rich molluskan fauna of the Bonneville Basin area, including waters that enter terminal Great Salt Lake and in particular those waters in the Jordan River-Utah Lake drainage. These mollusk taxa serve vital ecosystem functions and are truly a Utah natural heritage. Unfortunately, freshwater mollusks are also the most imperiled animal groups in the world, including those found in UT. The distribution, status, and ecologies of Utah's freshwater mussels are poorly known, despite this unique and irreplaceable natural heritage and their protection under the Clean Water Act. Very few mussel specific surveys have been conducted in UT which requires specialized training, survey methods, and identification. We conducted the most extensive and intensive survey of native mussels in the Jordan River-Utah Lake drainage to date from 2014 to 2016 using a combination of reconnaissance and qualitative mussel survey methods. We also developed probability of detection estimates to illustrate how critically low Anodonta densities are in the drainage and determined that even if our search efficiencies were theoretically atrocious, our methods were more than adequate to meet 90% probability of detections. Our findings are very disappointing. Out of the dozens of stream and shoreline kilometers surveyed, only two very small, highly-fragmented, and isolated populations of only one mussel species, *Anodonta* sp. were encountered. Reasons for the demise of native mussel in the drainage are numerous and entirely due to human activities including: sedimentation; intensive and extensive urbanization; industrialization; agriculture impacts (including dewatering and channelization); water quality impairment; invasive species particularly Asian clams, New Zealand mudsnails, and carp; loss of and extremely low densities of native fish hosts for glochidia larvae attachment; loss and fragmentation of suitable and occupied habitat; metapopulation and isolated population dynamics (demographic and environmental stochasticity); and absence of a monitoring program. These combined

impacts have reduced or completely eliminated dispersal between populations and have negatively affected population abundance and viability, which resulted in loss of genetic diversity, and subsequently have multiplicatively resulted in extremely high extinction risk in the drainage. We do not expect native mussels in the Jordan River-Utah Lake drainage to persist into the near future without adequate protection, improved habitat, and a comprehensive reintroduction program.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

Introduction

Native Freshwater Mollusks

North America supports the richest diversity of freshwater mollusks (clams, mussels, and snails) on the planet with over 700 species of snails and 300 species of freshwater mussels described so far (Johnson et al. 2013a, FMCS 2015). Freshwater mollusks serve vital functions in freshwater ecosystems, are excellent indicators of water quality, and are increasingly recognized as important ecosystem providers (Johnson et al. 2013a, Mock et al 2004). Mussels are water filterers (Huryn et al. 1995) and significantly influence algal primary productivity (e.g., Brown and Lydeard 2010). They play a pivotal role in aquatic food webs and nutrient cycling (Covich et al. 1999). Because mussels are filter feeders, they contribute greatly to water quality by removing suspended particles of sediment and detritus including harmful algae and bacteria (e.g. *E. coli*)(http://molluskconservation.org). An average-sized mussel can filter over eight gallons of water during a 4-hour period (Allen 1914, FMCS 2015). In high-density mussel beds, the filtering effect of thousands of mussels can be ecologically significant. Unfortunately, freshwater mollusks are one of the most disproportionally imperiled species groups on earth. Of the 297 freshwater North American mussel taxa, 213 (72%) are considered endangered, threatened or are species of concern (NatureServe 2014). This alarming decline is almost entirely due to human activities (Williams et al. 1993). The greatest diversity of North America's freshwater mussels, occurs in the southeast USA, whereas in the western half of N.A. the mussel fauna is relatively depauperate. However, the area consisting of Great Basin, Snake River Basin and Bonneville Basins, including the Great Salt Lake and Jordan River-Utah Lake drainages, is a freshwater molluscan hotspot. There are at least seventy mollusk taxa reported from UT (Oliver and Bosworth 1999), many of which are freshwater endemics to the Bonneville Basin. The evolution and distribution of the Bonneville Basin's and Utah's unique freshwater mollusks are strongly linked with the geological and geomorphic history of pluvial Lake Bonneville (Hershler and Sada 2002, Polhemus and Polhemus 2002, Mock et al. 2004) (Figure 1).

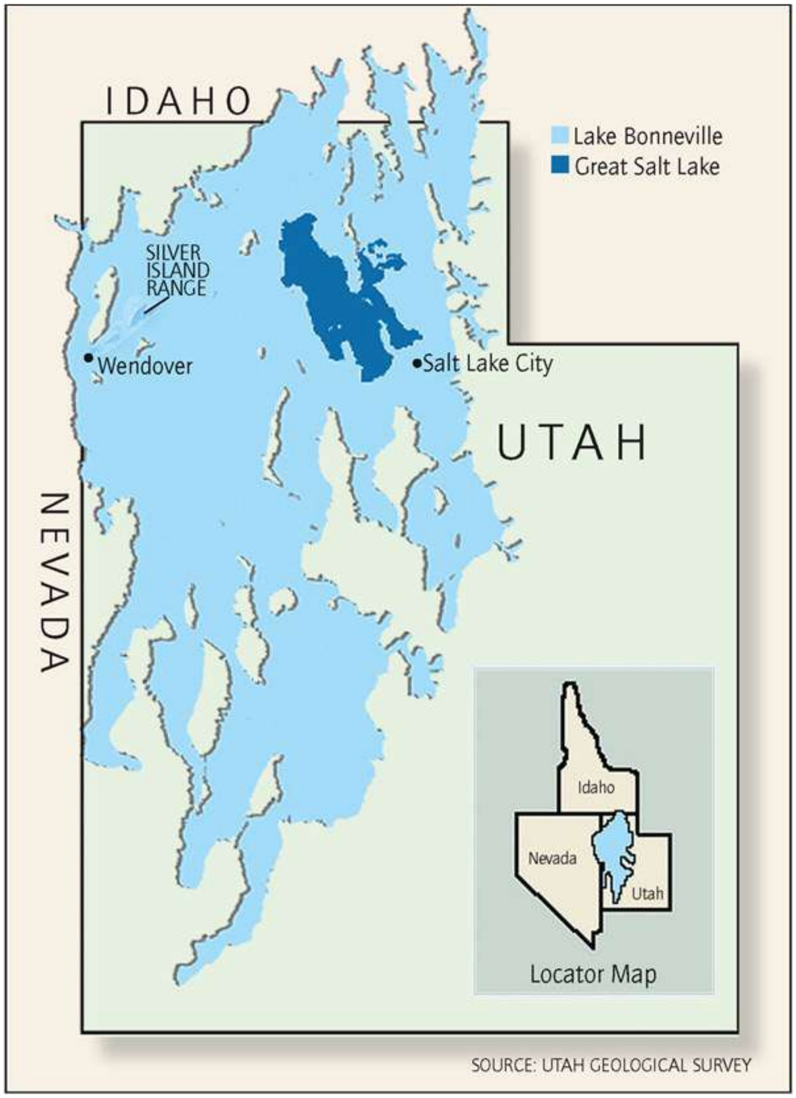


Figure 1. Location of Ancient Lake Bonneville at its maximum area (about 17,000 years ago) and what remains, Great Salt Lake (Utah Lake not shown).

Despite this unique and irreplaceable natural heritage, the taxonomy, distribution, status, and ecologies of Utah's freshwater mussels are poorly known. Very few mussel specific surveys have been conducted in UT. Most aquatic invertebrate surveys in Utah are related to water quality assessments (e.g. riffle habitat kick net, Surber, or Hess samplers with fixed subsample counts) and aren't specifically designed to collect mussels. Hovingh (2004) conducted the most recent comprehensive mollusk survey in UT and suggested that the rareness of mussels in the Bonneville Basin area requires a thorough survey of rivers, which he did not attempt. In addition, specialized training, survey methods, and identification of freshwater mollusks are required.

The focus of this report is on the order Unionoida mussels in the families Margaritiferidae and Unionidae surveyed from 2014 to 2016. The Jordan River watershed (drainage) encompasses an area of over 3,800 square miles (9842 km^2) with elevations ranging from 11,900 ft. (3627 meters) in the Wasatch Range to 4,200 ft. (1280 meters) at the confluence of the Jordan River into Farmington Bay, Great Salt Lake. This watershed includes Utah Lake, the fourth largest lake in the western U.S. The Jordan River watershed, until recently, had one of the most diverse freshwater mollusk assemblages in the western U.S. Native bivalves including the western Pearlshell mussel (*Margaritifera falcata*), the California floater mussel (*Anodonta californiensis/nuttalliana*), and fingernail clams (Familiy Sphaeriidae) were abundant. Well over a dozen species of freshwater snails also occurred in the drainage including many endemic springsnails (*Pyrgulopsis* spp.). However, waters in the Jordan River drainage have been heavily impacted by human economic activities in the last 150 years and the status of the area's native freshwater mollusks is unknown.

From 2014 to 2016, Richards and a team of researchers conducted the most intensive and extensive mollusk surveys in the Jordan River-Utah Lake drainage to date (Richards 2015a and 2015b). Surveys conducted in 2016 were more limited in scope than the 2014/2015 surveys but are an important follow up based on recommendations of the 2015 reports (Richards 2016).

Justification

The impetus of these surveys was EPA's updated 2013 freshwater ammonia aquatic life ambient water quality criteria based on recent ammonia toxicity data for mussel species in the Family Unionidae (Order Unionoida). EPA then recommended a single national acute and a single national chronic criterion be applied to all waters in the USA but because these mussel taxa may be absent at a site, EPA allowed for development of site specific ammonia criteria. In response to the proposed criteria and the need to potentially reevaluate ammonia criteria for wastewater treatment facilities' discharges into waters in the Jordan River-Utah Lake drainage; the Wasatch Front Water Quality Council (formerly Jordan River Farmington Bay Water Quality Council), Salt Lake City, UT contracted an experience malacologist, Dr. David C. Richards of OreoHelix Consulting, Vineyard UT (formerly Moab UT) to conduct an extensive mollusk survey in the drainage, with a focus on Unionoida mussels using EPA's recommended survey methods.

This report is a compilation of previous reports conducted by Richards for the WFWQC, supplemented with new pertinent information that provides background information on Utah's Unionoida mussels, survey locations and results of these surveys along with a discussion on metapopulation dynamics and reasons for their dramatic decline. The report also includes development of search efficiency, density, and probability of detection estimates and problems associated with these estimates when mussel densities are extremely low.

Figure 2. Jordan River flows north from the outlet of Utah Lake to its terminus at Great Salt Lake.

Unionid Mussels

Two Superfamily Unionidea mussel families have been reported in UT, Margaritiferidae and Unionidae. The single taxon in the family Margaritiferidae, *Margaritifera falcata* (Western Pearlshell mussel) and a Unionidae taxon, *Anodonta* (California floater) are considered critically imperiled and imperiled, respectively in UT (Table 1). Historical records of *Margaritifera falcata* have been reported from: Box Elder, Davis, Morgan, Rich, Salt Lake, and Summit counties. *Anodonta californiensis* has been reported historically in: Box Elder, Cache, Juab, Millard, Piute, Rich, Salt Lake, Tooele, and Utah counties. Three other Unionidae mussel taxa may possibly occur in UT (Table 1) but adequate surveys in UT have not been conducted and the taxonomic status of two is under revision.

Table 1. Unionidea mussel taxa that occur or may have occurred in UT (from NatureServe websites, Oliver and Bosworth UT DNR, Pacific Northwest Mussel Guide and Hoving 2004).

Species	UT Status		NatureServe Global Status	
Margaritifera falcata (Gould, 1850)	S1	Critically Imperiled	G4	Apparently Secure
Anodonta californiensis Lea, 1852	S2	Imperiled	G3	Vulnerable
Anodonta nuttalliana Lea, 1838	Unknown[1]	Unknown	G4	Apparently Secure
Anodonta oregonensis Lea 1838	Unknown[2]	Unknown	G5	Secure
Gonidea angulata (Lea, 1838)	Unknown[3]	Unknown	G3	Vulnerable

[1]From NatureServe: Preliminary analysis (K. Mock, Utah State University, pers. comm.) indicates Utah *Anodonta* are distinct from *Anodonta oregonensis* of the Pacific northwest and should tentatively be assigned to *Anodonta californiensis* pending future taxonomic work. From Pacific Northwest Mussel Guide: There were several historical records for Utah. Unfortunately, historical data are difficult to assess because people often included this species under other species names

[2] From NatureServe: Early reports of this species occurring eastward to Great Salt Lake and Weber and Jordan basins, Utah (see Oliver and Bosworth, 1999), are likely in error as this is likely a different species (K. Mock, pers. comm., 2006). Mock et al. (2004; 2005) found a lack of resolution (very little nuclear diversity) in phylogenetic reconstructions of *Anodonta* (*A. californiensis*, *A. oregonensis*, *A. wahlamatensis*) populations in the Bonneville Basin, Utah, but there was a tendency for the Bonneville Basin *Anodonta* (tentatively *A. californiensis*) to cluster with *A. oregonensis* from the adjacent Lahontan Basin in Nevada.

[3]From NatureServe: Despite early reports by Henderson (1924; 1929; 1936) for Utah and Montana, more recent surveys (Chamberlin and Jones, 1929; Jones, 1940; Oliver and Bosworth, 1999; Gangloff and Gustafson, 2000; Lippincott and Davis, 2000) of these states have failed to find any individuals

Native Mussel Taxa Historically Found in the Jordan River-Utah Lake Drainage

Two Unionoida taxa are known to have historically occurred in the Jordan River-Utah Lake drainage: *Anodonta* (Family Unionidae), common name California floater/Winged floater and *Margaritifera falcata* (Family Margaritiferidae), common name Western Pearlshell.

Anodonta californiensis Lea 1852/Anodonta nuttalliana (Lea, 1838)

<u>Common Name</u>: California floater/Winged floater

The range of Western *Anodonta* spp. extends from Alaska south to Mexico and as far east as Utah (Taylor 1966, 1981, 1985, Burch 1973, Clarke 1981, Warren and Harington 2000, Hovingh 2004)(Figure 4). Tertiary and Pleistocene records of *Anodonta* spp. are reported from the Bonneville Basin (Eardley and Gvosdetsky 1960, Currey et al. 1983, Oviatt et al. 1999) and Hovingh (2004) found live specimens and shells of *A. californiensis* in UT. Henderson (1931), citing Tanner's dredging efforts, noted that *A. californiensis* was the only remaining living mollusk in Utah Lake, although Call (1884) found many living mollusk taxa in Utah Lake fifty years earlier. Utah Lake was greatly reduced by drought in 1933, and by 1977 most fish in the lake were introduced species (Hovingh 2004). The BLM/USU BugLab database has no records of *Anodonta* spp. from the Salt Lake or Utah Counties area however they reported two *Anodonta* spp. locations in UT, the Bear River and East Fork Sevier River. Additionally, several researchers reported possible weathered *Anodonta* spp. empty shells along the shoreline of Utah Lake and Mill Pond in Utah County (Dr. Larry Gray, Utah Valley University, personal communication). More intensive and extensive native mussel surveys are clearly needed to document existing populations as well as continued compilation of recently reported locations (Figure 5). Richards and mussel surveyors in 2015 documented a very small population of Anodonta in Beer Creek and further documented occurrences in Salt Creek. In 2016, Richards verified an extant very small population in Currant Creek.

Recent genetic analyses have suggested that *A. californiensis* and *A. nuttalliana* are within the same clade and that Utah's remaining populations are genetically isolated (Mock et al. 2004). For this report all *Anodonta* spp. will be identified as either *Anodonta* or simply, Anodonta. *Anodonta californiensis* is ranked as "Critically Imperiled' in Utah (NatureServe 2014) but *A. nuttalliana* is not ranked in Utah. The State of Utah lists *A. californiensis* as a species of concern (Utah Department of Natural Resources 2007, http://www.xerces.org/wp-content/uploads/2010/12/xerces-status-review-Anodonta -californiensis-and-nuttalliana.pdf).

Unionoida mussels require fish hosts to complete their life cycle and many are considered host specific. Although the range of host species is speculative and unknown for *A. californiensis,* invasive carp do not appear to be a suitable host candidate (http://www.xerces.org/california-and-winged-floaters/, Lefevre and Curtis 1912). In addition, carp in Utah Lake have been present since the late 1880's and their numbers have reached in the millions and are estimated to comprise 90% of the biomass in Utah Lake (Horns 2005, Carter 2005). If no other factors were responsible for the demise of Anodonta in Utah Lake other than the absence or low abundance of suitable fish hosts (e.g. over fishing of cutthroat trout and June suckers), then carp are obviously not a suitable host. Further studies are needed to determine which fish species in the Utah Lake, if any, are suitable hosts. Dr. Richards' opinion, based on his review of historical reports, is that the most likely native fish hosts for Anodonta in the Jordan River/Utah Lake drainage were Bonneville cutthroat trout (*Oncorhynchus clarki utah*), June suckers (*Chasmistes liorus*), which are planktonic feeders and would have been actively filter feeding Anodonta glochidia through their modified gills, and Utah suckers (*Catostomus ardens*). Other native fishes could also have been hosts but they are either extinct or close to extinction (e.g. Utah chub). The BLM/USU BugLab database has no records of *Anodonta* spp. from the Salt Lake or Utah Counties area however they reported two *Anodonta* spp. locations in UT, the Bear River and East Fork Sevier River

Additionally, several researchers reported possible empty shells of *Anodonta* spp. along the shoreline of Utah Lake and Mill Pond in Utah County. Richards and mussel surveyors in 2015 documented a very small population of Anodonta in Beer Creek and further documented occurrences in Salt Creek, in northern UT (Figure 3). Recent genetic analyses have suggested that *A. californiensis* and *A. nuttalliana* are within the same clade and Utah's remaining populations are genetically isolated (Mock et al. 2004)(Appendix 10) with a loss of genetic diversity.

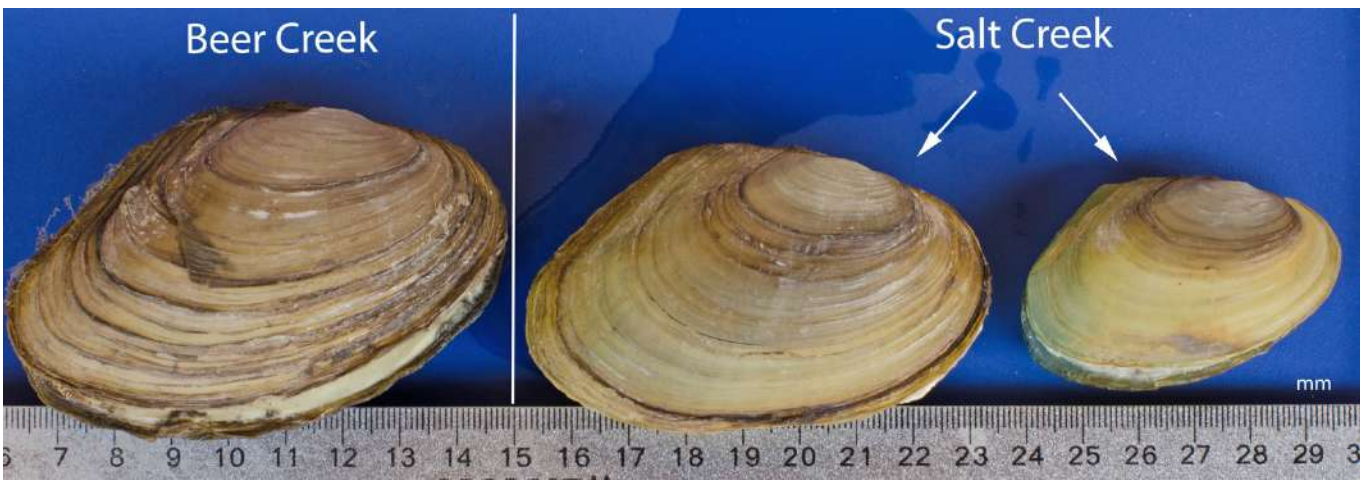


Figure 3. *Anodonta* (California floater/Winged Floater) collected from Beer Creek and Salt Creek, UT, 2015. The Beer Creek population is estimated at only 8 remaining older individuals with no apparent successful reproduction. The Salt Creek population appears to have many individuals of different size classes suggesting reproductive success, however they are outnumbered by over 1000 to 1 by invasive Corbicula. DNA samples have been collected from both Anodonta populations to help determine isolation and population dynamics and potential use in eDNA sampling (Appendix 10).

The IUCN Redlist website (http://www.iucnredlist.org/details/91149898/0) states that Anodonta "Populations in Nevada were once abundant (Call, 1884), and though the species still persists, it now appears absent in the Lahontan and Humboldt basins in part of northwestern Nevada and scarce in other historic locations (reviewed in Jepsen, et al., 2012; Hovingh, 2004; Smith, unpublished data, 2009). Recent surveys in Wyoming also suggest that the species may be more imperiled than previously recognized. In a survey of 23 sites, only 13 total Anodonta were found, comprised of only larger, older individuals (Mathias & Edwards, 2014). Indeed, recent surveys by Howard, et al. (2015) found that the species has been extirpated from all resurveyed historical southern California sites (n = 14; though the species was observed in the Bishop Creek Canal in Inyo County). Populations of Anodonta in northern California also appear to be declining in total population size and in number of populations (Howard, et al., 2015)," and that, "Given observations of population declines and extirpations and the reduction in extent of occurrence and watershed area over the last 25 years, a decline in population equal to or greater than 30% over the past three generations (with generation length being estimated at 8 years) is inferred."

Utah Department of Natural Resources, Division of Wildlife Resources reported the following concerning Anodonta in Appendix A of their "Utah Sensitive Species List" 2015:

> **"Species status statement.** Seven extant populations of this freshwater mussel are known in Utah, all within the Bonneville Basin. Population losses are evident, but the magnitude of the decline is difficult to interpret. Several species of Anodonta have been reported in Utah historically, but the identification of populations thought to be Anodonta species other than A. californiensis cannot be confirmed because they have been extirpated. Considering only those populations identified as A. californiensis, at least six populations have been extirpated (see Henderson 1936, Clarke 1993, Mock and Brim-Box 2003). However, all reported populations of Anodonta in Utah potentially represent one morphologically variable species (see e.g., Clarke 1993, Mock and Brim-Box 2003). The inclusion of these additional extirpated populations (e.g., those in Henderson 1924, Chamberlin and Jones 1929, Jones 1940) would suggest a decline even more dramatic than a strict interpretation of the historical distribution of the California floater would indicate.
>
> Several of the extant populations appear to be at high risk of extirpation. Mock and Brim-Box (2003) found just one live individual and two empty shells at one locality, which would indicate that this population is very small. Two populations are probably not viable because genetic diversity within the population is critically low (Mock and Brim-Box 2003). The catastrophic loss of larger populations is probable as well. The population formerly occurring in Utah Lake was likely to be among the largest in Utah, yet it was the first population reported to have been extirpated. Similarly, Mock and Brim-Box (2003) found thousands of empty shells but no live individuals in one reservoir, suggesting the recent and catastrophic extirpation of a population that was once large.
>
> **Statement of habitat needs and threats for the species.** This freshwater mussel occurs in lake and pond habitats, including several reservoirs, and low-gradient streams at middle elevations in Utah. Extant populations are localized and are vulnerable to habitat loss or degradation. Water withdrawal is of importance to all populations, but particularly to the several populations occurring in reservoirs (see Clarke 1993). Water pollution from agricultural run-off is of concern and may be the cause of the extirpation of some populations (Clarke 1993).
> Larval floaters (i.e., glochidia) are obligate parasites of fish, and so require appropriate hosts to complete their life cycles. It is not known whether they can parasitize nonnative fish species. Introduced fish species, habitat degradation, and other factors affecting host-fish populations would ultimately be a threat to populations of California floaters (Clarke 1993, Mock and Brim-Box 2003).

Reproductive depression arising from inbreeding is an immediate threat to two populations because critically low genetic diversity is evident in these populations. Hybridization is a threat as well; Mock and Brim-Box (2003) detected evidence of genetic introgression in one population. Limited genetic divergence among Utah populations of this mussel decreases the species' ability to adapt to environmental changes.

Anticipated costs and savings. Stable habitats are required for the long-term population viability of this species. Control of nonnative fish species may be required. Cooperative, proactive measures to stabilize habitats where the California floater occurs can help secure populations and decrease the need for governmental-imposed restrictions on development and agriculture. Locating, documenting, and protecting populations is needed to decrease the likelihood that local communities will be negatively impacted by development restrictions in the future.

Rationale for designation. The California floater is dependent on limited water sources, often in remote locations, and so is vulnerable to habitat alteration and loss. Its limited genetic diversity increases its vulnerability to future environmental changes. A large fraction of the North American mussel fauna has been lost in the last 200 years, suggesting that this species could also be lost. Utah designates this unique animal a Species of Concern to highlight the need to protect California floater from additional habitat and population losses."

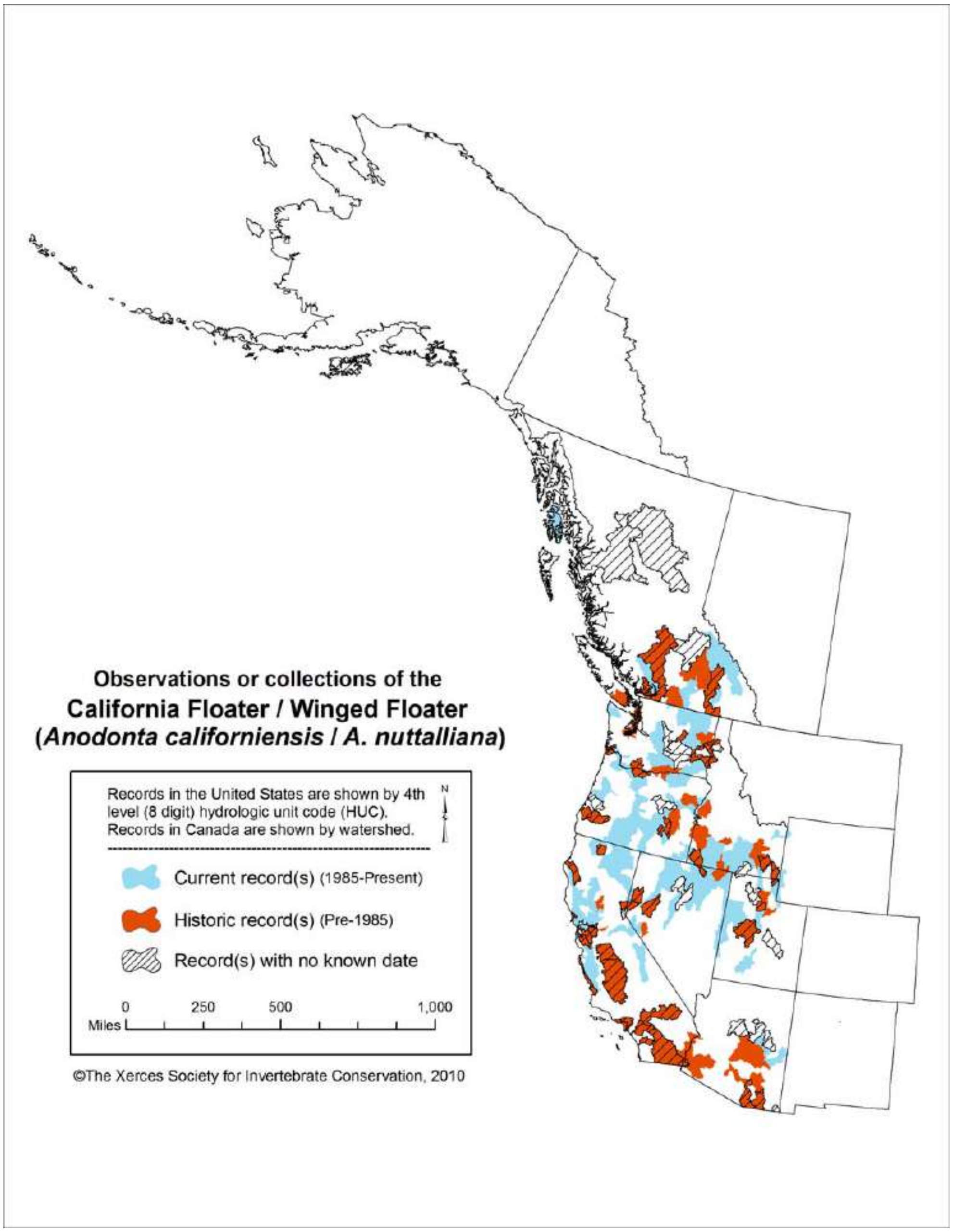


Figure 4. Map of *Anodonta californiensis/A. nuttalliana* observations and collections in western USA (http://www.xerces.org).

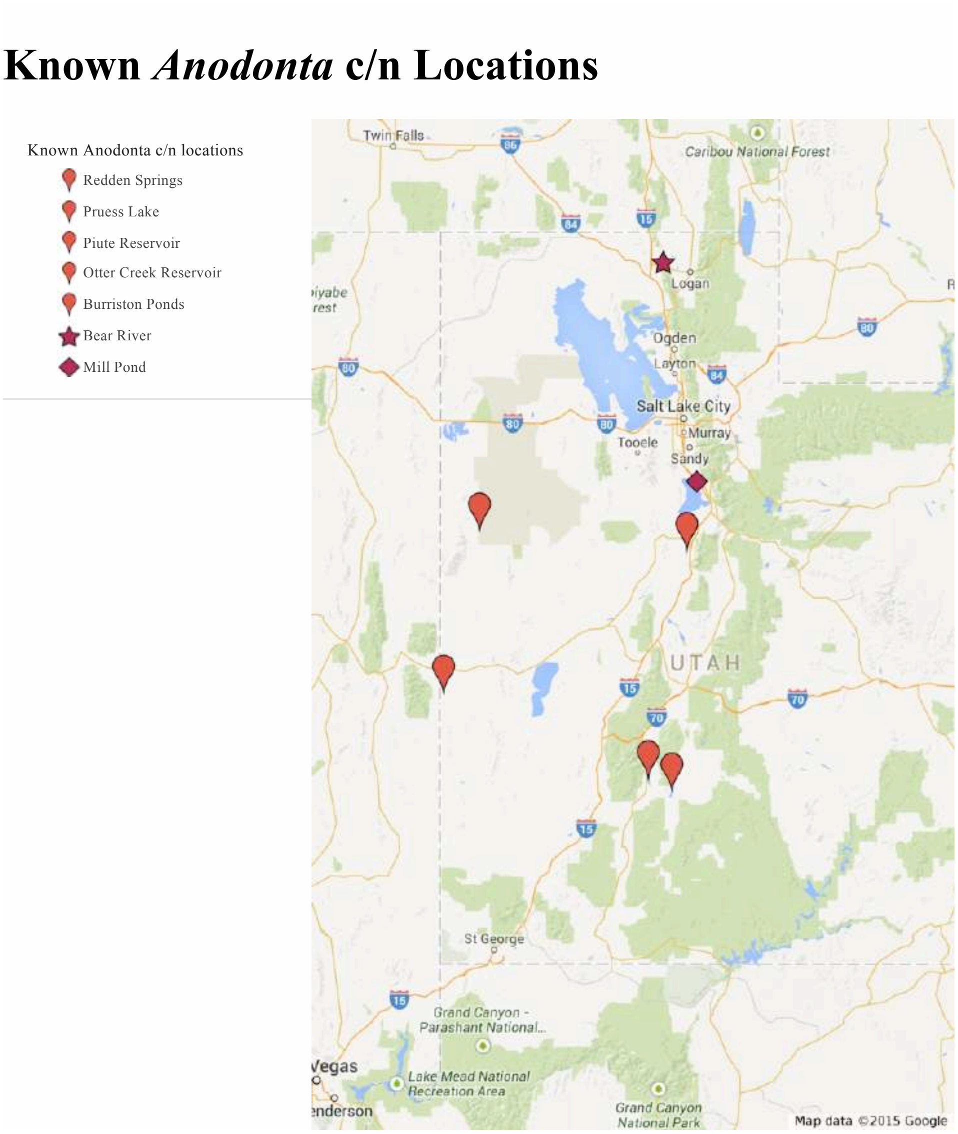


Figure 5. Several known locations of Anodonta in UT from Xerces Society web site, literature, and this survey. Red teardrops are geo-referenced locations; red star is location only reported as Bear River, and red diamond is location where only shells were found, no live individuals. Several additional populations not shown on this map have been reported including a Salt Creek population north of Great Salt Lake and a Beer Creek population, southern intermittent tributary to Utah Lake.

Margaritifera falcata Gould 1850

Common Name: western pearl shell mussel

Margaritifera falcata have historically been found in the Jordan, Weber, and Bear River drainages. Specimens collected between 1880 and 1890 near Salt Lake City are considered to be native (Hovingh 2004) and were once common in this area (Call 1884); however, Hovingh

(2004) did not find specimens at 155 sites in Utah, Nevada, and eastern California. According to Hovingh (2004):

> "In Utah's Jordan River drainage, populations could have been extirpated in 1948 by the destruction of Hot Springs Lake, a 3.5-km^2 lake that may once have contained populations of cutthroat trout that bred in the streams around Salt Lake City. Cutthroat trout native to Utah Lake were extirpated by 1936 (Radant and Sakaguchi 1980) by overfishing and spawning habitat destruction, which terminated spawning migrations up the Provo River (Heckmann et al. 1981)".

Other factors are likely contributing to the decline of *M. falcata* including; dredging, channelization, water diversion and flood control, dams, the use of river corridors as highway corridors, declining water quality, reservoirs, urbanization, and agricultural practices (e.g. cattle grazing, irrigation return flows)(Hovingh 2004) and severely reduced population numbers of secondary host fish. The BLM/USU BugLab database has no records of *M. falcata* from UT. More recent surveys have documented populations of *M. falcata* in the Weber River and Bear River drainage (http://www.xerces.org/western-pearlshell/, and others). Richards and mussel surveyors have documented a slight range extension for the Beaver Creek population in 2015. It is possible but unlikely that additional other small isolated colonies may be found using mussel specific surveys and that more intensive and extensive native mussel surveys are clearly needed to monitor existing populations and determine if other isolated populations exist.

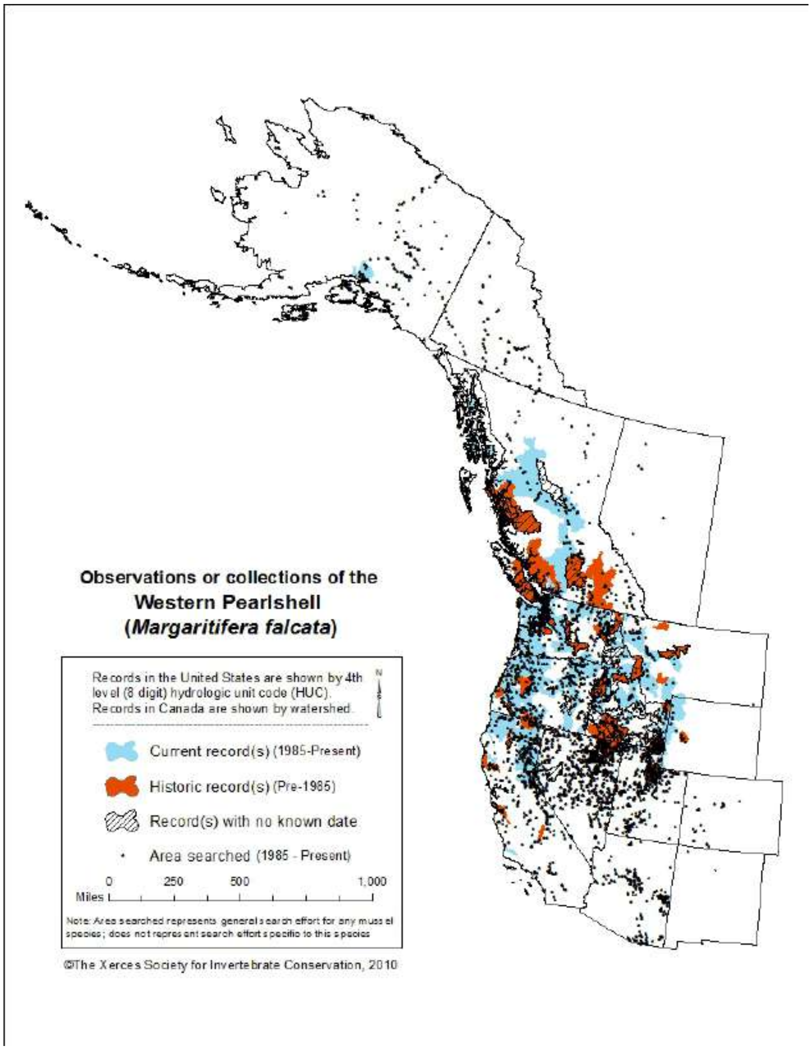


Figure 6. Map of *M. falcata* observations and collections in western USA (http://www.xerces.org/western-pearlshell/).

Figure 7. Snap shot of video of three *M. falcata* filter feeding (note black line of mantle outlining these individuals). This snap shot was from video taken of the last known remaining M. falcata population (< 20 individuals observed) in Utah in Beaver Creek, a tributary of the Weber River.

Figure 8. *Margaritifera falcata* from Big Cottonwood Creek, Salt Lake County, UT, circa 1880. These specimens are housed in the Natural History Museum of Utah, Salt Lake City, collected by Dr. Orson Howard, Professor Biology at University of Utah, in the late 1880's and were apparently fairly common (Richards personal examination of museum specimens) however, the exact location of collection in Big Cottonwood Creek was not documented. These historical specimens were identified by Dr. Howard as *Margaritana margaritifera*, which was later revised to *M. falcata*.

Utah Department of Natural Resources, Division of Wildlife Resources reported the following concerning *M. falcata* in Appendix A of their "Utah Sensitive Species List" 2015:

> **"Species status statement.** Formerly about nine populations of this freshwater mussel were known in Utah, all in the northern third of the state (Call 1884, Henderson 1924, Chamberlin and Jones 1929, Woolstenhulme 1942a, 1942b). Clarke (1993) expressed the opinion that all populations in Utah have been extirpated, but there is the possibility that small populations yet persist; evidence is not yet sufficient to assume that all populations have been extirpated because individuals of this species can be quite long-lived. Populations could exist at low levels for many years. The size and extent of historical populations were not reported. No populations have been found at historical localities in recent times (Clarke 1993).
>
> **Statement of habitat needs and threats for the species.** This freshwater mussel has been found in streams, primarily in areas with fast-moving waters. Larval pearlshells (i.e., glochidia) are parasites of fish and require the presence of an appropriate host species for successful reproduction. Changes in fish abundance, diversity, and species composition may have historically affected reproductive success and may continue to do so in extant populations. Because this is an aquatic organism occupying high-quality aquatic habitat, water withdrawals, changes to flow regimes and patterns of sediment deposition, and degradation of aquatic habitat would be threats to populations. Therefore, dams could affect population viability.
>
> **Anticipated costs and savings.** The western pearlshell requires high quality water. If proactive efforts can be implemented to protect such water sources and intermediate fish host species, the potential for restrictions to local communities, developers, and agriculture can be reduced. If habitats are degraded without regard for this species, state and/or federal government restrictions could be imposed.
>
> **Rationale for designation.** Previous actions by humans have reduced this species dramatically, to the point that it may no longer persist in the state. If live specimens are located, they will be of great value to Utah's biodiversity. Because it is a unique species that is vulnerable to reduced habitat quantity and quality and host population changes, it is considered a Species of Concern."

Utterbackia imbecillis (Say, 1829)

Common Name: paper pondshell

Recently *Utterbackia imbecillis*, a widespread, prolific, eastern USA Unionoida species was found to be infesting Cutler Reservoir, Bear River, UT (Cynthia Tait, USFS, Ogden, UT, personal communication, http://www.iucnredlist.org/details/189156/0). Dr. Karen Mock at USU, Logan, UT conducted DNA analyses and confirmed that indeed these specimens were *U. imbecillis*. This species can easily be confused with *Anodonta* and prior to 2007 was synonymous with several Anodonta species (Graf and Cummings 2006, http://www.itis.gov). *Utterbackia imbecillis* has yet to be reported in the Utah Lake/Jordan River drainage.

“*Utterbackia imbecillis* has been assessed as Least Concern due to its wide distribution and populations which are stable or increasing throughout its range. It also demonstrates tolerance to a wide range of habitat conditions and is currently not affected by any major threats” (http://www.iucnredlist.org/details/189156/0). This IUCN assessment suggests that *U. imbecillis* could invade waters in Utah that previously supported *Anodonta* (and possibly *M. falcata*) and there should be some concern that it could outcompete and eliminate these already stressed remaining populations.

Figure 9. *Utterbackia imbecillis*, (Say, 1829) Paper Pondshell, a recent invader to Utah waters (photo from http://www.jaxshells.org/1113xr.htm).

Jordan River-Utah Lake Drainage

The Jordan River drainage is in north central Utah and drains an area of over 9842 square km (Figure 1). Elevations range from 3637 m in the Wasatch Range, to 1280 m where the Jordan River enters the Great Salt Lake. Average precipitation ranges from 31 cm yr^{-1} in the lower valleys to over 127 cm yr^{-1} in the higher elevations. Much of the precipitation occurs as snow, which contributes to the rivers as snowmelt during spring and summer. The Jordan River flows north from Utah Lake for about 82 km through the most populous area of Utah including Salt Lake City before entering Great Salt Lake. The Jordan River was named after the River Jordan in the Middle East, which drains the Sea of Galilee (equated to Utah Lake) into the Dead Sea (equated to Great Salt Lake)(Bancroft 1889). After leaving the “Narrows Canyon” downstream of Utah Lake and before entering Great Salt Lake, the Jordan River historically was free to meander across its wide valley and did so regularly. Records show that during spring runoff the river could be several km wide. Historically, the Jordan River was a cold-water fishery with 13 native species, including Bonneville cutthroat trout (*Oncorhynchus clarki utah*) but is now mostly a warm water fishery dominated by common carp (*Cyprinus carpio*). The Jordan River was extremely polluted for many years and continues to be heavily regulated by pumps and diversions starting at the outlet of Utah Lake and continuing downstream. The remnant Jordan River is channelized and dredged and no longer allowed to follow its past meandering ways. Major tributaries to the Jordan River include; Big Cottonwood, Little Cottonwood, Red Butte, Mill, Parley's, and City Creeks. These Jordan River tributaries were immediately diverted and heavily modified starting on the second day of arrival of the Mormon settlers in the Salt Lake valley, mid 1800s (Bancroft 1889, Alexander 2002) and to date, these tributaries remain disconnected from the Jordan River for much of their length once they leave the Wasatch Mountains and enter the Salt Lake valley.

Directly upstream of the Jordan River is Utah Lake, the dominant body of water in the drainage. Utah Lake is a shallow, turbid, slightly saline, eutrophic, lake with an average depth of about 1.5 to 2.8 m, about 40 km long by 21 km wide, with a surface area of about 384 km^2. Thirteen fish were native to Utah Lake, including the Bonneville cutthroat trout. Only two species remain, the Utah sucker (*Catastomus ardens*) and the critically endangered June sucker (*Chasmistes liorus*) because of overfishing, introduction of common carp, pollution, and other human induced factors (Carter 2005, Heckmann et al. 1981). Evaporation accounts for 42% of its outflow because of its shallowness and arid climate. Although Utah Lake historically functioned as a natural shallow lake ecosystem, it has undergone what are known as ecological hysteresis (Nikanorov and Sukhorukov 2008, Beisner et al. 2003) and a catastrophic ecosystem shift (Scheffer et al. 2001, Beisner et al. 2003). These dramatic changes were primarily due to human impacts the most important of which were sedimentation, loss of submerged aquatic vegetation, introduction of benthic feeding carp, loss of native fish and invertebrates including filter feeding mussels, water diversion, increased nutrients and toxic metals, and man-made water- level fluctuations (Wakefield 1933, Petersen 1996, Crowl et al. 1998, Tan and Ozesmi 2006, Deseret News 1967, USFWS 2010, Carter 2005, Janetsi 1990, Coops et al. 2003). Utah Lake is no longer a natural lake but considered an operational water supply reservoir because of being dammed at its outlet into the Jordan River in 1872 (USFWS 2010). The Utah Lake ecosystem prior to Mormon settlement certainty was not at all what it is today. Utah Lake was arguably the most scenic and productive cold water fishery in the western USA prior to Mormon settlement (Janetski 1990, Carter 2005, Escalante 1776, Prat 1849, Bean 1854). In fact, Mormon settlers likely would not have survived their first winters in Utah if not for the tremendous native fishery in Utah Lake, particularly the Bonneville cutthroat trout fishery (Carter 2005, Heckmann et al. 1981). The following are a few excerpts from Janetski (1990) and Carter (2005) regarding Utah Lake prior to settlement:

> "... the valley and the borders of the lake of the Timpanogos (Utah Lake)... is the most pleasant, beautiful and fertile in all of New Spain . . . . The lake and the rivers which empty into the lake abound in many kinds of choice fish; there are to be seen there very large white geese, many varieties of duck, and other kinds of beautiful birds never seen elsewhere;

> beavers, otters, seals, and other animals which seem to be ermines by the softness and the whiteness of their fur.” (Escalante 1776).
>
> “I was at Utah Lake last week and of all the fisheries I ever saw, that exceeds all. I saw thousands caught by hand, both by Indians and whites. I could buy a hundred, which each weigh a pound, for a piece of tobacco as large as my finger. They simply put their hand into the stream, and throw them out as fast as they can pick them up . . . . Five thousand barrels of fish might be secured there annually . . . “(Prat 1849).
>
> “Indeed, so great was the number of suckers and mullets passing continuously upstream that often the river would be full from bank to bank as thick as they could swim for hours and sometimes days together.”— George Washington Bean, 1854.

Two mussel taxa native to Utah Lake, *Anodonta* spp. (presumably *A. californiensis/A. nuttalliana*) and *Margaritifera margaritifera* (now *M. falcata*) were abundant and large enough sized to be important food items to the natives and settlers alike, although *M. falcata* was usually not eaten (Chamberlain and Jones 1929, Janetski 1990). Utah Department of Natural Resources (2007) reported that Utah Lake likely had the largest population of *A. californiensis/A. nuttalliana* in the entire state but have now been extirpated from the lake. One likely reason for their disappearance from Utah Lake was predation by the apex predator, the introduced European carp (*Cyprinus carpio*), which occurs in the lake by the tens of millions.

Major tributaries of Utah Lake are; American Fork River, Provo River, Mill Race Creek, Hobble Creek, Spanish Fork River, Currant Creek, and several irrigation returns. Water uses in the area include agriculture, irrigation, municipal and industrial uses, and recreation. Most of the water in Utah Lake tributaries is also usurped for human consumption and diverted from a multitude of large scale diversion canals and tunnels originating from other drainages outside of the Jordan River drainage. The American Fork River and Currant Creek are entirely diverted for much of the year as are many of the other tributaries that once flowed perennially into Utah Lake. (http://www.greatsaltlakeinfo.org). A few other major water quality issues include metals, total dissolved solids, *E. coli*, high water temperatures, high levels of ammonia, and low dissolved oxygen. Major pollutant sources include: failing septic systems, industrial discharges, illegal dumping, equipment cleaning, agriculture, and stormwater runoff, to name a few (http://www.utahcleanwater.org/jordan-river-watershed.html).

Water from the Weber River drainage enters highly saline Great Salt Lake about 30 km to the north of the Jordan River-Utah Lake drainage, so there is no possibility of freshwater mussel natural recruitment from the north, including *M. falcata* from Beaver Creek. To the west of the Jordan River drainage is the Western Desert. To the south is more irrigated farmland desert dependent on diverted stream and river water, mostly from the Sevier River that once fed now dry Sevier Lake, another artifact of Lake Bonneville.

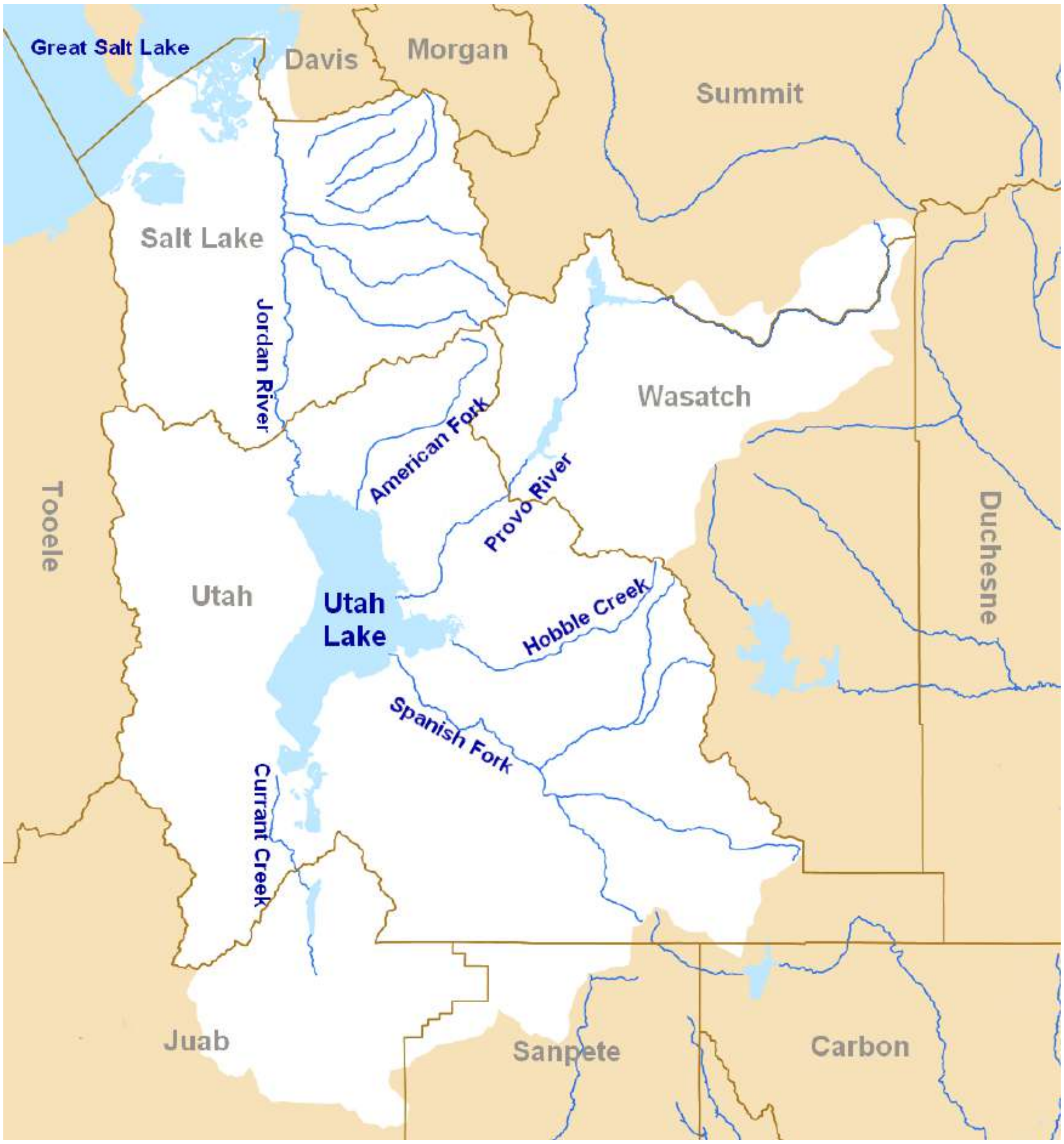


Figure 10. Jordan River drainage, UT with a few major tributaries highlighted (used with permission from: https://commons.wikimedia.org/wiki/File:Jordan_River_Basin.png)

Native Mussel Surveys 2014-2015

Survey methods

A combination of reconnaissance and qualitative mollusk surveys was conducted following EPA survey protocols (USEPA 2013) and methods that Dr. Richards has used in the past (see qualifications in Appendix 3). Reconnaissance surveys were cursory visual searches in the most promising habitats and gave us a preliminary understanding of native mussel presence or absence in the sites and along Utah Lake shoreline. Reconnaissance surveys were conducted to help determine if additional more comprehensive qualitative surveys were warranted. There was no evidence of native unionid mussel presence during reconnaissance surveys, however numerous weathered fragments were found, therefore, intensive qualitative surveys were conducted.

Richards trained surveyors for approximately eight hours on Mill Pond and Spring Creek, Utah County, in April 2014 and eight hours in late May 2015. This location is an area where Anodonta shells were previously reported. Several *Anodonta* shells were recovered during this training session by trainees. Surveyors working alongside Dr. Richards became experienced enough throughout the season that they could locate previously unreported individuals of *M. falcata* downstream of the relatively unknown Beaver Creek colony (see Closest Known Extant Population of *Margaritifera falcata* to) and locate numerous weathered native mussel shell fragments throughout the surveys.

Three to four experienced mussel surveyors using aquascopes (Figure 11), kick nets, clam rakes, snorkeling, and shoreline examination surveyed entire sections of Utah Lake shorelines up to about 1.2 meter depths, sections in numerous tributaries, and entire reaches within the designated sites (Appendix 7).

Figure 11. One of the commercial aquascope types used in the mussel survey.

Figure 12. Clam rake similar to the one pictured was modified with ¼ in. mesh chicken wire attached to cover the entire inside of the rake bucket. Rake was pulled through sand, silt, gravel, and small cobble substrates to approximately 10 cm.

Figure 13. Kick net with 1 mm mesh used to dig through silt, sand, gravel substrates to depths of approximately 5 cm

Probability of Detections, Search Efficiencies as Related to Density Estimates

Estimating search efficiencies given known or assumed densities with probability of detection (POD) estimates is very problematic when mussel population densities are at critically low levels or when mussels are expected to be absent based on historical data and literature. However, UDWQ recommends using methods such as those proposed by Smith (2006) for estimating these values. UDWQ recommends surveying enough area with 100% search efficiency at $0.1/m^2$ to obtain a 90% POD based on formulas presented by Smith (2006). We used the Smith (2006) formula:

$$0.90 = 1-e^{-\beta\alpha\mu},$$

where 0.90 is 90% probability of detecting at least on individual mussel; β=search efficiency, α=search area; and μ= density/m^2 to illustrate the relationship between search efficiencies and densities at 90% PODs for many of our survey results. We also discuss the problems associated with the use of these methods when mussel population densities are at critically low levels or when mussels are expected to be absent.

Jordan River

Methods and Results

We conducted mussel surveys at nine sites and approximately 12.0 km of Jordan River for an estimated minimum survey area of 58,000 in 2014 (Figure 14 to Figure 19; Appendix 7). We did not find any live native mussels or unweathered shells (Richards 2014). However, we did find one small < 3 mm long x 0.5 mm wide, highly weathered Anodonta shell, supportive evidence that native mussels historically occurred in the Jordan River drainage.

Figure 14. Sample location in "The Narrows" section of Jordan River. Sampling occurred between the blue pins on the map.

Figure 15. Site 2. Sampling occurred between the blue pins on the map.

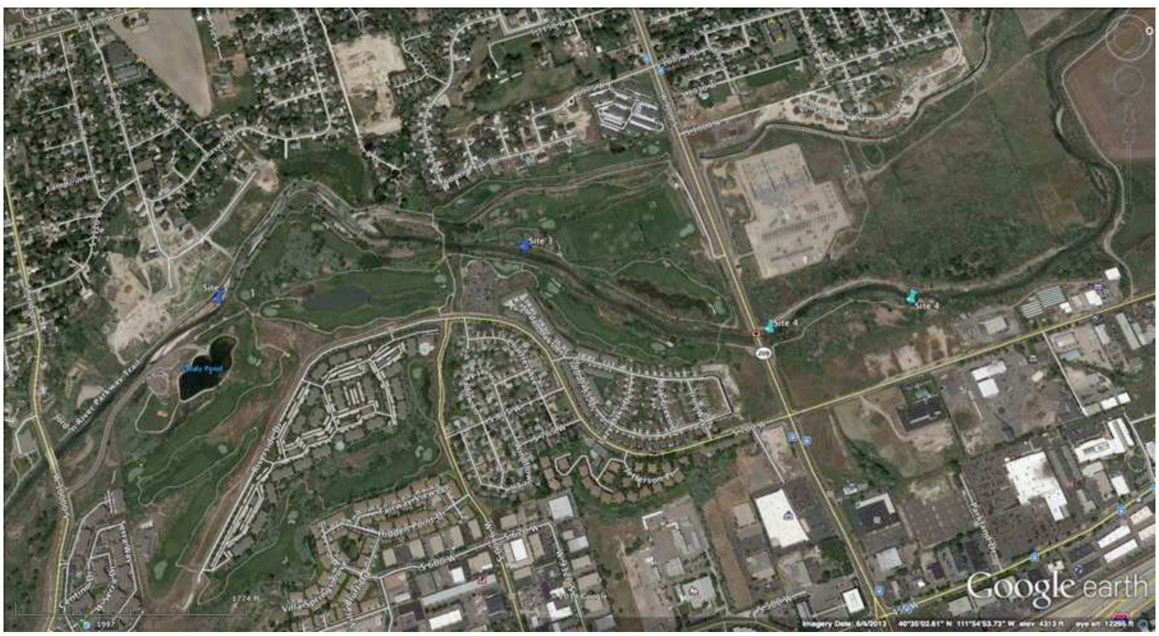


Figure 16. Mussel survey sites 3 and 4. Sampling occurred between the blue pins on the map.

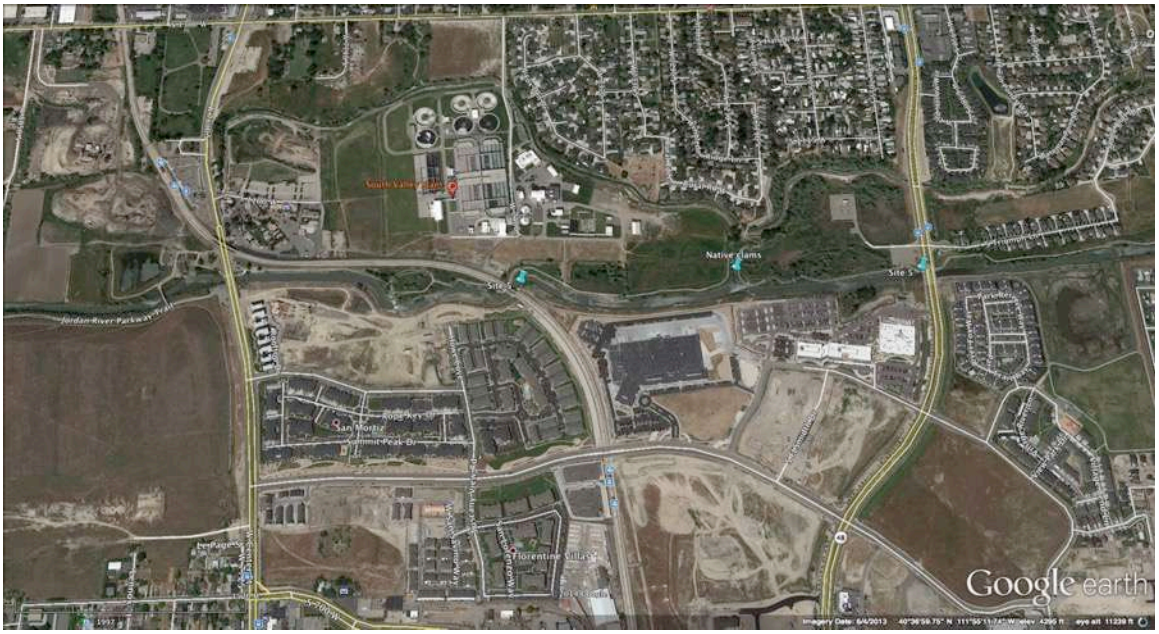


Figure 17. Mussel survey site 5 with tributary marked where native clams were common. Sampling occurred between the blue pins on the map.

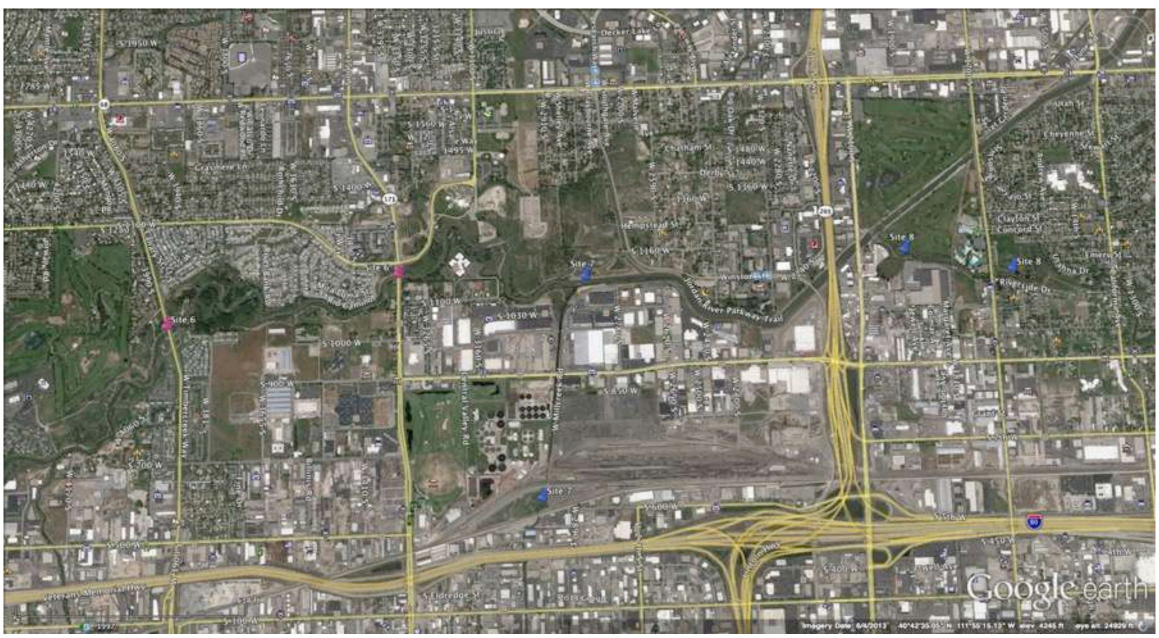


Figure 18. Mussel survey sites 6, 7, and 8. Site 7 was Mill Creek and small portion of Jordan River. Sampling occurred between the blue pins on the map.

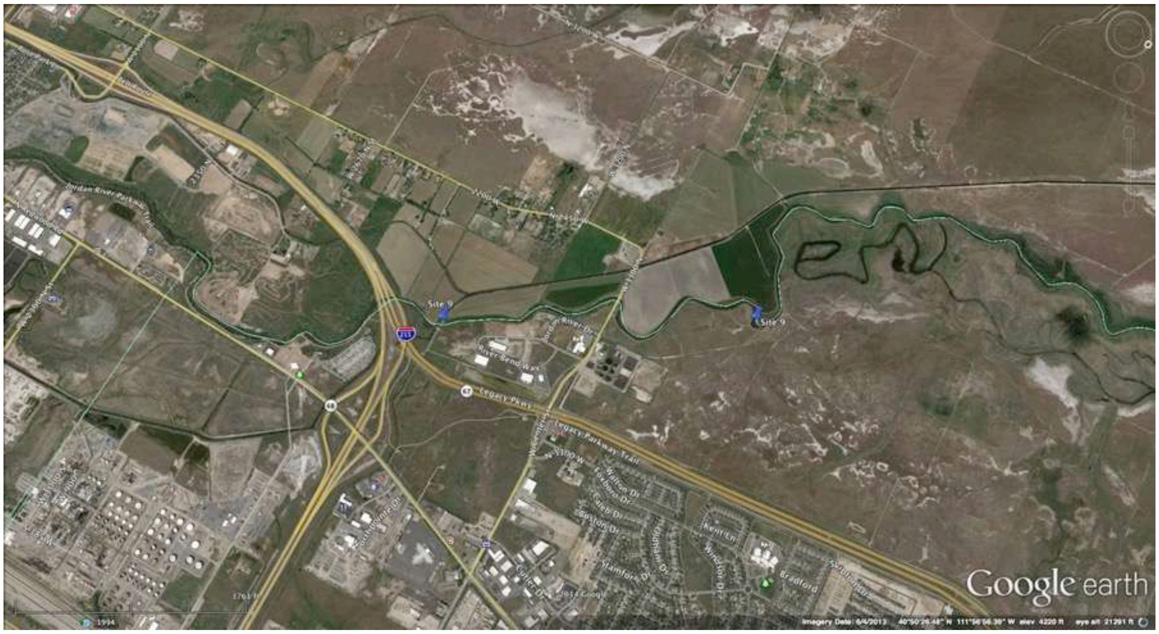


Figure 19. Mussel survey site 9. Legacy Nature Preserve. Sampling occurred between the blue pins on the map.

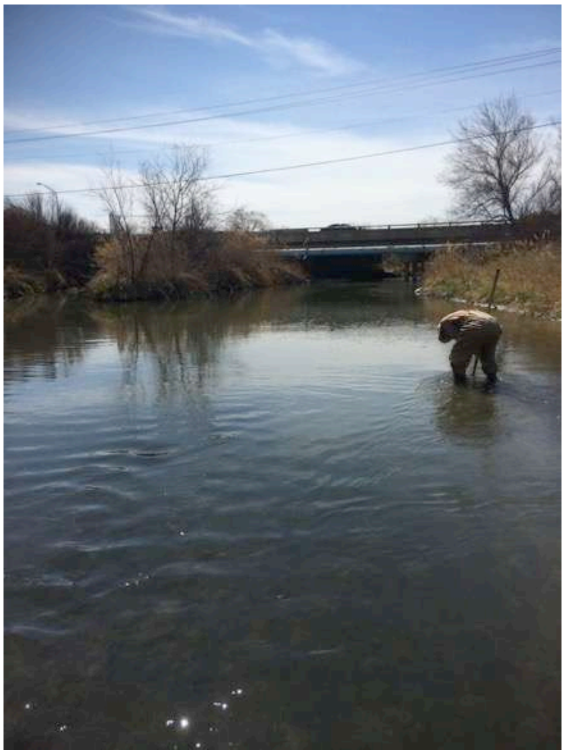
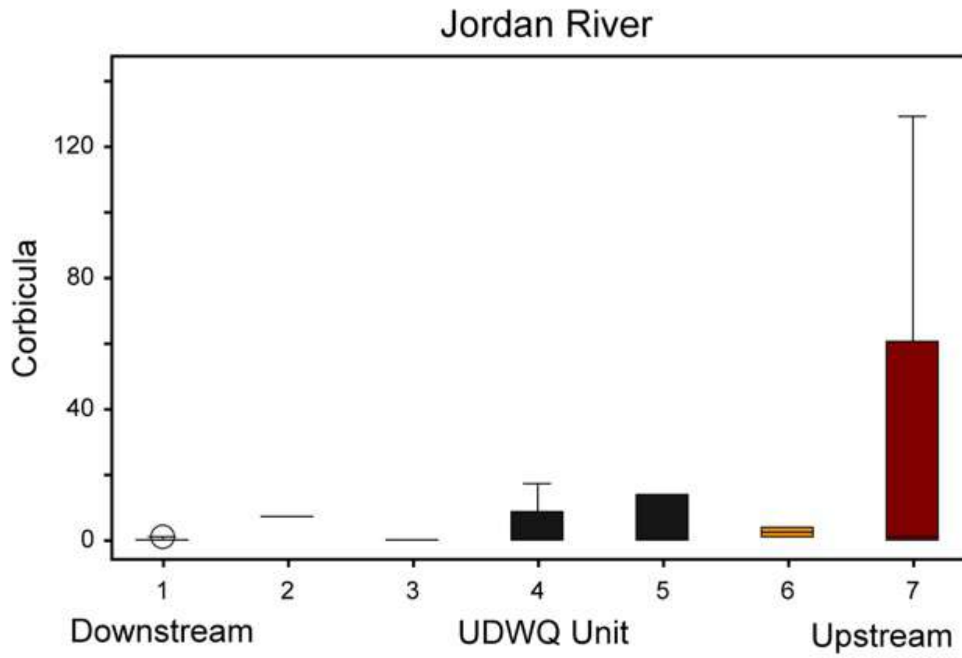


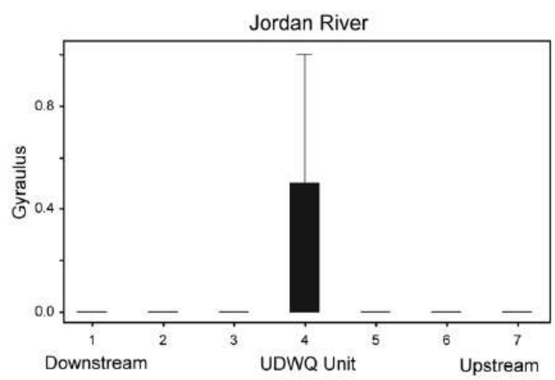
Figure 20. Mollusk surveyor in Jordan River using kick net

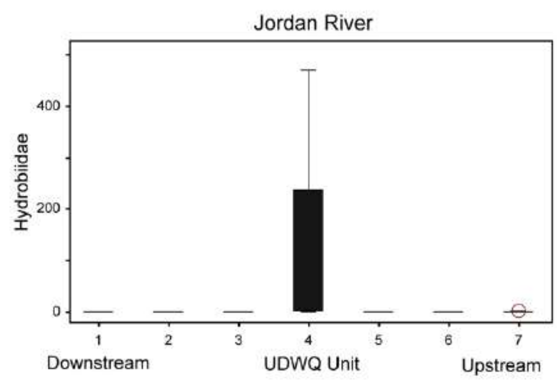
Figure 21. Mollusk surveyor searching shoreline and gravel bar, Jordan River.

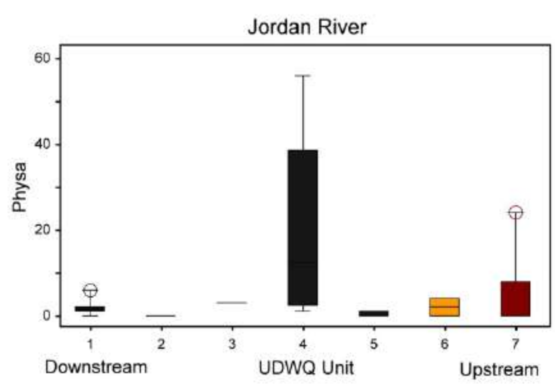
Other mollusk taxa as indicators of suitable native mussel habitat in the Jordan River

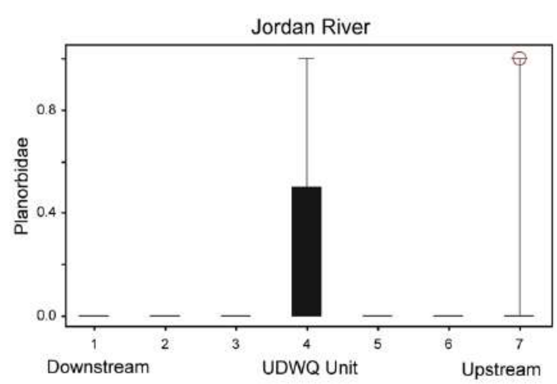
Because freshwater mollusk taxa often have similar habitat and water quality requirements, we examined distribution densities of several mollusk taxa throughout the Jordan River as potential indicators of native mussel extant population locations. We used twenty-five records collected in the Jordan River by UDWQ, which we retrieved from the USU/USGS BugLab Mapit website: http://wmc6.bluezone.usu.edu. Six mollusk taxa occurred in these samples: Corbicula, Physa, Potamopyrgus, Gyraulus, Planorbidae, and Hydrobiidae. Potamopyrgus was likely also reported as Hydrobiidae but is no longer a member of that family and Gyraulus is in the family Planorbidae so there maybe taxa overlap in some instances. Figure 22 suggests that mollusk assemblages are most likely to occur in the upstream sections of the Jordan River and there appeared to be an assemblage hotspot in UDWQ Unit 4 (Figure 22 and Figure 23) but Corbicula, the most taxonomically similar to native mussels in the Jordan River-Utah Lake drainage occurred at greatest abundances farthest upstream in Unit 7 and had scattered distributions downstream. These two molluskan ‘hotspots’ (DWQ management Unit 4 and Unit 7) may be useful for focusing future mollusk surveys and were adequately surveyed by us as reported in the previous section.


Jordan River
Corbicula
0
40
80
120
1
2
3
4
5
6
7
Downstream
UDWQ Unit
Upstream


Jordan River
Gyraulus
0.0
0.4
0.8
1
2
3
4
5
6
7
Downstream
UDWQ Unit
Upstream


Jordan River
Hydrobiidae
0
200
400
1
2
3
4
5
6
7
Downstream
UDWQ Unit
Upstream


Jordan River
Physa
0
20
40
60
1
2
3
4
5
6
7
Downstream
UDWQ Unit
Upstream


Jordan River
Planorbidae
0.0
0.4
0.8
1
2
3
4
5
6
7
Downstream
UDWQ Unit
Upstream

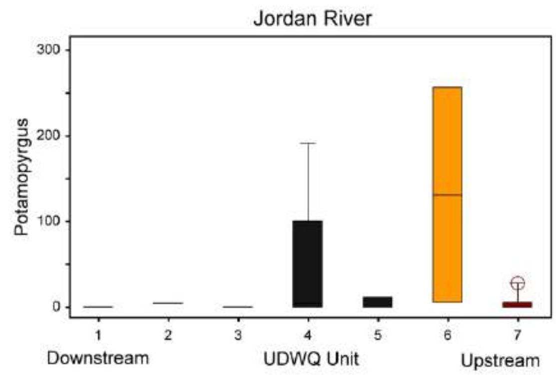
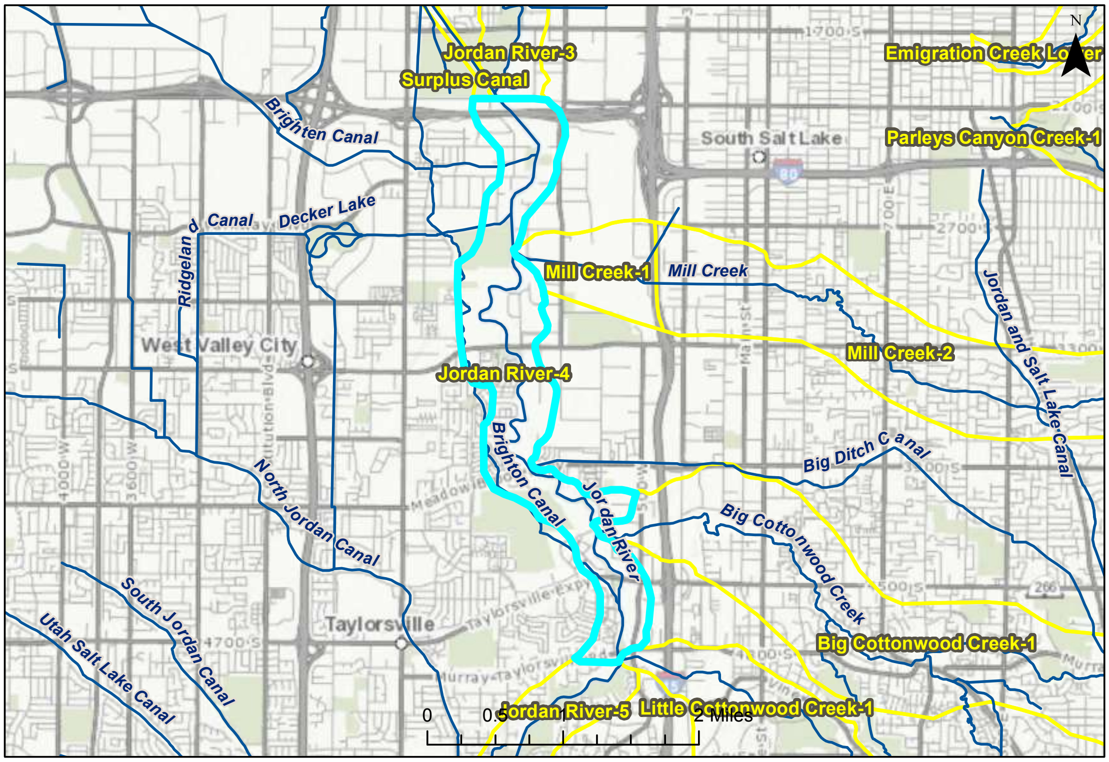


Figure 22. Potential mollusk taxa indicators of suitable native mussel habitat in the Jordan River.

Beneficial Uses and Water Quality Assessment Map

utah automated geographic reference center

11/7/2014



undefined: 0
undefined: 0
undefined: 496
undefined: 496
undefined: 496
Assessment Unit Name: Jordan River-4
Unit ID: UT16020204-004
Unit Description: Jordan River from 2100 South to the confluence with Little Cottonwood Creek
Beneficial Uses: Use Class 2B = Infrequent primary contact recreation (e.g. wading, fishing); Use Class 3B = Warm water fishery/aquatic life; Use Class 4 = Agricultural uses (crop irrigation and stock watering)
undefined: 6.287
Watershed Management Unit: Jordan River
undefined:
undefined:
2010 Assessment: Assessment Category 5 = Impaired: TMDL required (303d list)
Beneficial Use: Cause of Impairment: Use Class 3B: Benthic-Macroinvertebrate Bioassessments; Use Class 4: Total Dissolved Solids
TMDL Required: 303d Cause of Impairment: poor Benthic Macro-invertebrate Community, Total Dissolved Solids
TMDL Approved: Cause of Impairment: n/a
Aquatic Habitat Impairment: n/a
undefined: 5
undefined:
undefined: 2
undefined:

Figure 23. Beneficial use and water quality assessment map: UDWQ management unit, Jordan-4 which appears to be a mollusk hotspot based on twenty-five records collected in the Jordan River by UDWQ and others, which we retrieved from the USU/USGS BugLab Mapit website: http://wmc6.bluezone.usu.edu. See Figure 22 for mollusk taxa distributions.

Jordan River search efficiency and density relationships at 90% probability of detection using the Smith (2006) formula suggested by UDWQ are in Figure 24. Search efficiency at 0.1/m^2 and 90% POD (UDWQ recommended criterion) was 0.00038, indicating that our surveys were more than adequate to conclude that native mussels are likely absent in the Jordan River or at such very low densities as to be not viable, ecologically irrelevant, or near extinction.

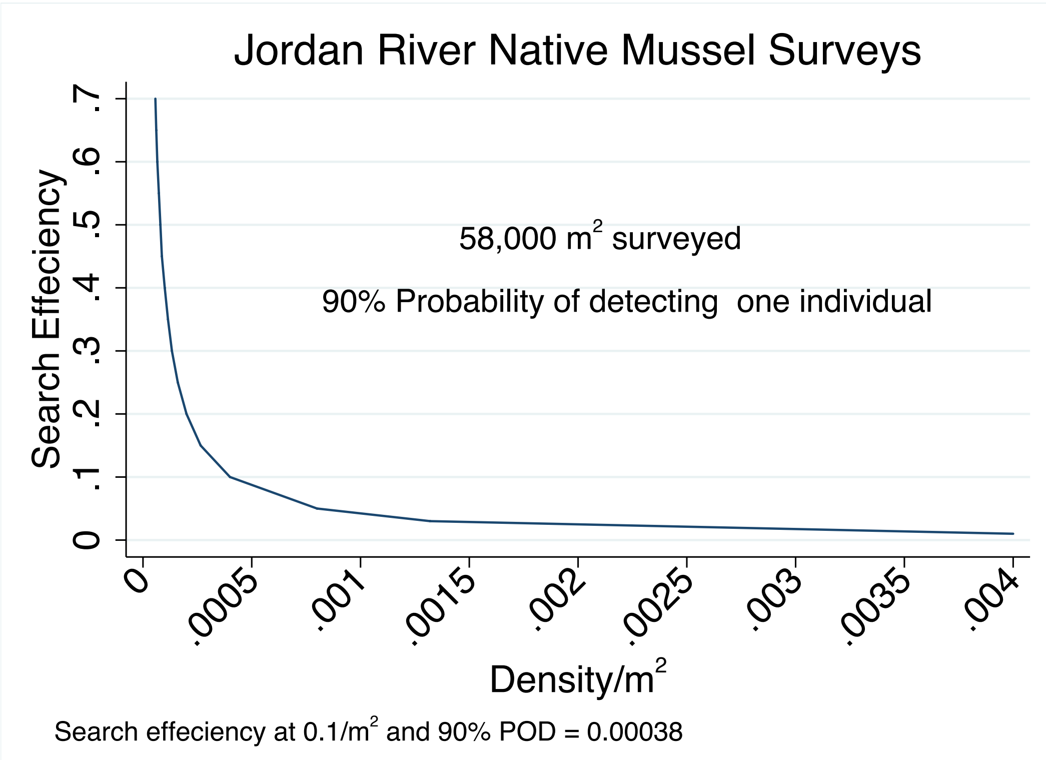


Figure 24. 90% probabilities of detecting at least one individual native mussel (*Anodonta* sp.) in the Jordan River at various search efficiencies and corresponding densities given we sampled 58,000 m² (our low estimate) of river. As an example, there was a 90% probability of detecting at least one individual if densities were 0.0005/m² and a search efficiency of approximately 0.078. That is, if our efficiency was only about 8%. Estimates were based on random mussel distributions from Smith (2006). Formula for graph: $0.90 = 1\text{-}e^{-\beta\alpha\mu}$**, where 0.90 is 90% probability of detecting at least on individual mussel; β=search efficiency, α=search area = 58,000 m²; and μ= density/m².**

Mill Creek

We conducted intensive mussel surveys in Mill Creek in 2015 and 2016 primarily because the Central Valley Wastewater Treatment Facility operations and upgrades are dependent on determining whether native mussels are present or absent in the area. Mill Creek originates in the Wasatch mountains and then flows through the City of Salt Lake where it joins the Jordan River (Figures 1-5), which then empties into Farmington Bay of the Great Salt Lake. After leaving the Wasatch Mountains and USFS lands, where it is relatively unimpaired, most of Mill Creek waters are captured for culinary purposes for use by the citizens of Salt Lake City. Remaining waters in Mill Creek are then supplemented and often dominated by waters transported directly from highly eutrophic Utah Lake via the Jordan and Salt Lake Canal. After the water quality in Mill Creek has been compromised by waters from Utah Lake, it then flows through a heavily urbanized, residential, and industrial landscape before entering the Jordan River. This heavily impacted downstream section of Mill Creek:

1) has been channelized and often dewatered for extended periods of time,
3) its natural ability to create meanders and floodplains has been eliminated,
4) habitats have been altered,
5) has numerous industrial point source discharges,
6) experiences large urban and industrial runoff events,
7) is dominated by highly invasive taxa including Eurasian Common carp (*Cyprinus carpio*), Asian clams (*Corbicula fluminea*) and New Zealand mudsnails (*Potamopyrgus antipodarum*).
8) has substrates that are predominately embedded with fine organic matter/silt/clay often > 50 cm thick (see Appendix 1),
9) has trash that often comprises a significant portion of the substrate (see Appendix 1), and
10) is designated by UDWQ as water quality impaired.

By all standards, the section of Mill Creek that flows through Salt Lake City is in poor condition, is poorly managed, and its integrity has been compromised.

Mill Creek Methods

The surveyor team continued gaining experience surveying for native mussels throughout the 2014 and 2015 seasons prior to conducting a formal survey in Mill Creek and Jordan River downstream in late August 2015. Surveyors became experienced enough throughout the two season that they could locate previously unreported individuals of *M. falcata* downstream of the relatively unknown Beaver Creek colony (see Closest Known Extant Population of *Margaritifera falcata* to Jordan River-Utah Lake drainage). Three to four experienced mussel surveyors using aquascopes, kick nets, clam rakes, and shoreline examination surveyed entire sections of Mill Creek and shorelines up to about 1.2 meter depths of the Jordan River downstream of Mill Creek from August 29 to 31, 2015 for a total of about 72 surveyor hours. In addition, survey results from Richards 2014 mollusk surveys in Mill Creek and lower Jordan River were synthesized into this report. Visibility during the 2015 survey was typically between 0.9 to 1.2 meters. Surveyors using aquascopes could view depths to about 1.5 meters therefore, habitats with depths > 1.5 meters were not closely examined. Habitats with silt/clay sediments approximately > 0.6 to 0.9 meters thick were also not examined because of inability of surveyors to move through the soft/gummy sediment. Although native mussels, in particular, Anodonta can be found in fine sediments, these sediments need to be supported by larger substrates underneath (Strayer 2013, see Substrate Habitat section of this report). Therefore, an estimated 90% of the Mill Creek substrate in the 2767 meters was viewed for an estimated total of 21,417 m^2 (approximate linear distance = 2767 m, average width = 8.6 m). Approximately 1684 linear meters were also surveyed along the Jordan River shoreline upstream and downstream of Mill Creek confluence. Surveyors using aquascopes traversed Mill Creek from side to side and then moved several meters upstream looking for mussel shell fragments or whole live or dead mussels. Habitats examined included: riffles, runs, pools, back eddies, undercut banks, and vegetation with substrate ranging from large cobbles to fine silt and clay. Empty invasive Asian clams, *Corbicula fluminea* shells and live, active, *Corbicula* were clearly visible using aquascopes, therefore native mussels were also assumed to be detectable on the benthic substrate surface using the aquascopes. In addition, highly invasive New Zealand mudsnails (*Potamopyrgus antipodarum*) were easily observed in upstream sections of Mill Creek in this survey as were other snail taxa, which further justifies the use of aquascopes for mussel surveys in Mill Creek and verified the ability of the surveyors to detect mollusks using scopes when visibility is good. However, as a precaution, kick net and clam rake samples were also collected in promising habitat (behind boulders, gravel, sand, pools, upstream of riffles, etc.) to help determine if mussels were buried under the sediment and not visible to aquascope surveys. Kick net and clam rake sampling allowed surveyors to collect sediments and mollusks to depths of up to about 10 cm. Shorelines were carefully examined for empty shells on sandbars, muskrat middens, and other areas of the shoreline. A large dredge pile (approximately 35 m x 7 m) along the western shore of Jordan River was also closely examined in 2014 and 2015 (Figure 25). Dredging is a superior but highly destructive method for surveying native mussels (USEPA 2013b). The dredge pile contained substrate from the section where Mill Creek empties into the Jordan River and native Unionoida shells that occurred in that area dredged would have been visible.

Mill Creek Survey Locations

Figure 25- Figure 27 show areas that were surveyed in Mill Creek in 2014 and 2015.

Figure 25. Native Unionoida survey area of lower Mill Creek and Jordan River. Surveyed areas are white lines. Approximately 1,122 meters of Mill Creek from confluence with Jordan River to Union Pacific rail yard were completely surveyed in 2014 and 2015. Shoreline of Jordan River up to about 1.3-meter depth were surveyed in 2014 and 2015. Approximately 1684 linear meters sampled along Jordan River shoreline. Dredge pile along western shore of Jordan River was examined for Unionoida shells in 2014 and reexamined 2015. CVWTF = Central Valley Waste Water Reclamation Facility.

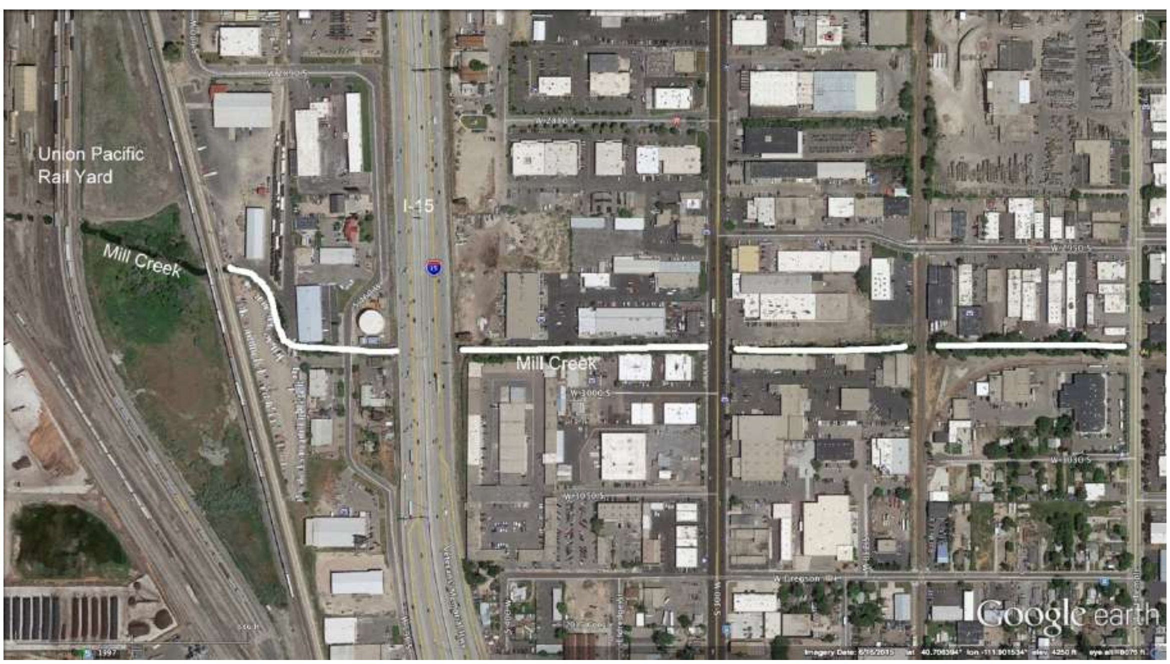


Figure 26. Unionoida survey area of Mill Creek from Union Pacific rail yard upstream to South West Temple St. Surveyed areas are white lines. Approximately 828 meters of Mill Creek in this area were completely surveyed in 2015.

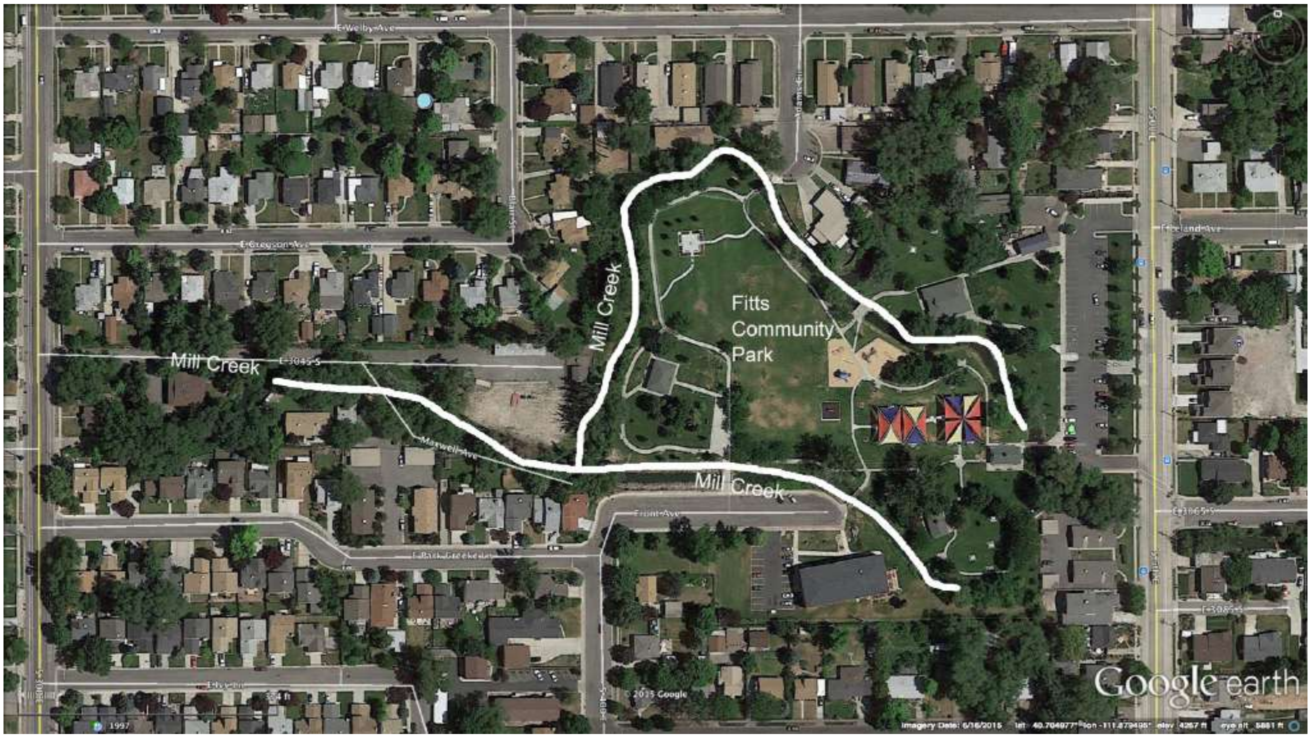


Figure 27. Unionoida survey area of Mill Creek at Fitts Community Park, South Salt Lake City, UT. Surveyed areas are white lines. Approximately 627 meters of Mill Creek in this area were completely surveyed in 2015.

Mill Creek Results

No live native unionid mussels or their empty unweathered shells were found in the 2014 and 2015 surveys of Mill Creek/Jordan River (and adjacent dredge pile). These findings are very disappointing and indicative of the likely fate of native Unionoida in the Jordan River/Utah Lake drainage and throughout UT. The absence of any mussel shells in the dredge pile at the confluence with Mill Creek and Jordan River is further direct evidence that native mussels are not resident in the sections that were too deep to visually survey or where soft sediments precluded wading by surveyors, in part because large sections of the Jordan River (and Mill Creek) in this area are routinely dredge for flood control. The large abundance of Corbicula shells and snail shells in the dredge pile supported our conclusion that close visual examination of the dredge pile was sufficient to decide that native mussels were absent in the study site.

Several very small Unionoida fragments, likely Anodonta, approximately 2-3 mm length were found embedded in the banks of Mill Creek about half way between CVWRF outfall and its confluence with the Jordan River (Figure 28). These fragments were extremely fragile and disintegrated upon extraction. Many remain and were left undisturbed. The age of these fragments was undetermined. The Unionoida fragments in the banks of Mill Creek were embedded somewhat in between soil layers where Fluminicola (pebble snail) shells were observed and Physidae and Lymnaeidae shells were observed. Fluminicola are cold, well-oxygenated water taxa, while Physidae and Lymnaeidae are more warm water or even wetland taxa. These shell layers are ideal for verifying past conditions of Mill Creek and the Jordan River and determining how old Unionoida shells can potentially be before disintegrating. We crudely estimated the bottom layers at greater than 100 years, however an experienced soil scientist familiar with the area and history of the north-south lateral migration of Mill Creek and the east-west lateral migration of the Jordan River will be consulted. No weathered native mussel shell fragments were found upstream of CVWRF outfall, either embedded in the stream banks or on the stream sediments.

Figure 28. Soil profile of Mill Creek between CVWWTF and confluence with the Jordan River. Several easily observable soil layers can be seen. Physidae and Lymnaeidae shells typically were found in the darker layers suggesting warm water, wetland habitat conditions, whereas Fluminicola were found in slightly coarser sediment layers suggesting cold-water conditions. Potential Anodonta fragments were found somewhat in between these layers.

Mill Creek search efficiency and density relationships at 90% probability of detection using the Smith (2006) formula suggested by UDWQ are in Figure 29. Search efficiency at $0.1/m^2$ and 90% POD (UDWQ recommended criterion) was 0.00107 indicating that our surveys were more than adequate to conclude that native mussels are absent in the Mill Creek survey area. However, because an absent determination is critical to CVWRF operations, we will conduct intrusive surveys in lower Mill Creek and adjacent sections of the Jordan River in 2017 to help substantiate our conclusion of absence.

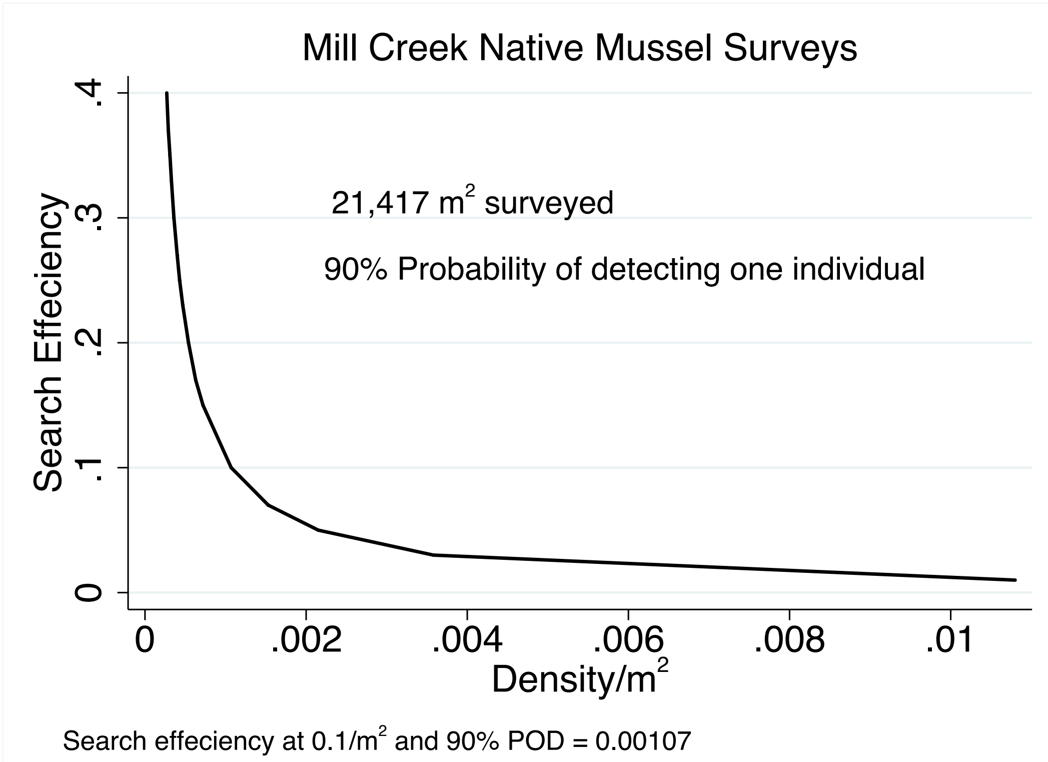


Figure 29. 90% probabilities of detecting at least one individual native mussel (*Anodonta* sp.) during the Mill Creek survey at various search efficiencies and corresponding densities given we sampled 21,417 m². As an example, we had a 90% probability of detecting at least one individual if densities were 0.001/m² with a search efficiency of approximately 0.07. That is, if our efficiency was only about 7%. Estimates based on random mussel distributions and the formula provided from Smith (2006). Formula used for graph: $0.90 = 1\text{-}e^{-\beta\alpha\mu}$**, where 0.90 is 90% probability of detecting at least on individual mussel; β=search efficiency, α=search area = 21,417 m²; and μ= density/m².**

Closest Known Extant Population of *Margaritifera falcata* to Jordan River-Utah Lake drainage

The closest known extant population of *M. falcata* to the Jordan River-Utah Lake drainage occurs in Beaver Creek (Richards 2015a, Utah Natural Heritage Program, UDNR a tributary of the Weber River, which empties into Great Salt Lake. This small isolated population contains approximately 20 or so known individuals and may also no longer be viable or sustainable and there appears to be no possibility of natural recolonization to the Jordan River-Utah Lake drainage (Richards 2015a).

Status of Native Unionids in Other Tributaries to the Jordan River

Mill Creek Upstream of Surveys

Water from Utah Lake is pumped into the Jordan and Salt Lake Canal in the Jordan Narrows (near the northern end of Utah Lake), which is then transported through the canal and overflows into Mill Creek at 1440 Murphy's Lane (http://hiddenwater.org). This diversion occurs throughout much of the irrigation season and water from Utah Lake can contribute to almost all of Mill Creek's flows. In addition, much of the water in Mill Creek upstream of the canal is diverted for culinary uses (http://hiddenwater.org). Water quality downstream of the canal outflow into Mill Creek is obviously affected and determined by Utah Lake water quality for a large portion of Unionoida activity season. In the unlikely event that any undetected native mollusk individuals occur in Mill Creek downstream of the Jordan and Salt Lake Canal, they have been and continue to be subject to these water quality and flow conditions.

Mill Creek Upstream of USFS Boundary

We did not survey Mill Creek upstream of the USFS boundary. Mill Creek upstream of the Jordan and Salt Lake Canal likely supported *M. falcata* populations prior to Mormon settlement, however as far as is known, no extant populations have been reported. The Utah Department of Wildlife Resources and U.S. Fish and Wildlife Service are conducting a Bonneville Cutthroat trout (BCT) and habitat restoration project on Mill Creek on USFS lands upstream. They have applied rotenone poison to several sections of upper Mill Creek for a total of about 9 miles of this cold-water fishery to remove nonnative fish and to repopulate BCT in 2015 (Mike Slater, UDWR personal communication). Rotenone is also a strong poison to gilled macroinvertebrates, including native Unionoida taxa (i.e. *M. falcata* and Anodonta). UDWR conducted limited macroinvertebrate surveys in 2012 and 2013 prior to rotenone application and did not find any native mussels (Mike Slater, UDWR personal communication). There is also almost zero probability that *M. falcata* can recolonize the upstream sections of Mill Creek because of no dispersal or connectivity to other populations.

M. falcata Extirpated from Big Cottonwood Creek

Big Cottonwood Creek is a large perennial stream just south of Mill Creek (approximately 3.4 km linear distance between where they both enter the Jordan River). The status of Big Cottonwood Creek's molluskan fauna therefore has important implications for potential natural dispersal and recolonization of native mussels to the Jordan River. We conducted extensive native mussel surveys of Big Cottonwood Creek within USFS boundaries during the summer of 2015. We visually surveyed approximately 27,750 m^2 using aquascopes. No live mollusks were observed in Big Cottonwood Creek, including no native snails or even the all too common invasive taxa, Corbicula and Potamopyrgus that are found throughout many waters of the Jordan River drainage. The apparent absence of any mollusks in Big Cottonwood Creek is disturbing (but not unexpected given the disregard for native mollusks in UT) because there are documented historical specimens of *M. falcata* from Big Cottonwood Creek housed in the Natural History Museum of Utah, Salt Lake City. These well-preserved specimens were collected by Dr. Orson Howard, Professor Biology at University of Utah, in the late 1880's and were apparently fairly common (Richards personal examination of museum specimens) however, the exact location of collection in Big Cottonwood Creek was not documented by Dr. Howard. These historical specimens were identified by Howard as *Margaritana margaritifera*, which was later revised to *M. falcata* (Figure 8). The reasons for the extirpation of native mussels from Big Cottonwood Creek are numerous (see section: Unionoida Biology, Ecology, Metapopulation

Viability in the Jordan River-Utah Lake Drainage) and the apparent absence of other mollusks may possibly be due to historic mining activities and their effects on water quality. Alternatively, the specimens documented by Dr. Howard in the 1880's may have been collected in the lower, downstream sections of Big Cottonwood Creek when its physical, chemical, and biological integrity was intact and conditions were much different than what they are today. It is plausible that the lower section, prior to Mormon settlement, or shortly thereafter, was a thriving cold water fishery. It is well known that Margaritifera individuals can live upwards to 200 years and at that time when Howard reported them there may no longer have been a large population of cold water secondary fish hosts or the potential fish host populations were in rapid decline. Any remaining *M. falcata* quietly lived out their last, unviable, senior years going unnoticed.

Big Cottonwood Creek mussel survey search efficiency and density relationships at 90% probability of detection using the Smith (2006) formula suggested by UDWQ are in Figure 30. Search efficiency at 0.1/m^2 and 90% POD (UDWQ recommended criterion) was 0.00083 indicating that our surveys were more than adequate to conclude that *M. falcata* is very likely absent in the creek or at such low densities so as to not be viable, ecological irrelevant, and near extinction.

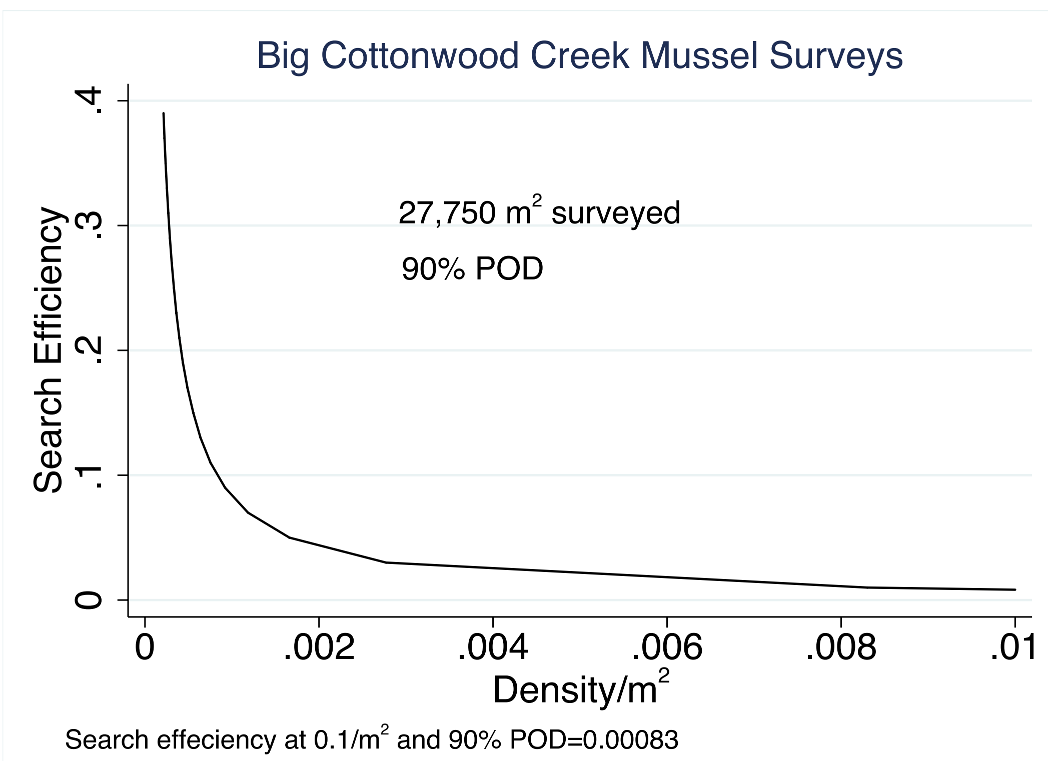


Figure 30. 90% probabilities of detecting at least one individual native mussel (*M. falcata*) during the Big Cottonwood Creek survey at various search efficiencies and corresponding densities given we sampled 27,750 m^2. Estimates were based on random mussel distributions and the formula provided from Smith (2006). Formula

used for graph: 0.90 = 1-e$^{-\beta\alpha\mu}$, where 0.90 is 90% probability of detecting at least on individual mussel; β=search efficiency, α=search area = 27,750 m^2; and μ= density/m^2.

City Creek

Richards surveyed approximately 1km section of City Creek upstream of the City Creek Center Mall, Salt Lake City. No live native mussels or shells were found. It is possible that a *M. falcata* population survives further upstream in City Creek as the watershed is protected as a drinking water source. However, this unsurveyed section of City Creek is completely isolated from the Jordan River due to dams, diversions, dewatering, pavement, artificial fountains, City Creek Center Mall, and Salt Lake City water use. The remnant of City Creek enters the Jordan River near North Temple Street and 1000 West from an underground culvert. Yet because of the vast water control structures, lack of habitat and lack of secondary fish hosts, there is no possibility that any remaining, unreported *M. falcata* individuals can naturally disperse from City Creek.

Red Butte Creek

We did not survey Red Butte Creek, which flows from the Wasatch Range through University of Utah campus and then is diverted. No records of extant mussel populations have been found by us and Red Butte Creek is a well-studied water body and existence of a native mussel population likely would have been reported. However, literature reviews and communications with experts are continuing to be conducted. As with all Wasatch Front tributaries to the Jordan River, Red Butte Creek is diverted, dammed, flows entirely underground through heavily urbanized areas after it joins Parleys and Emigration Creek. Much of its waters now consist of Utah Lake origin via the Jordan and Salt Lake Canal. Any remaining *M. falcata* population, if it exists in the upstream sections of Red Butte Creek is completely isolated from the Jordan River and there is no possibility of mussel recruitment to them.

Bingham Creek

Bingham Creek is a spring fed tributary to the Jordan River from the west and was surveyed in 2014 (Richards 2014). No live native mussels or shells were found. It is heavily infested with New Zealand mudsnails and Corbicula but still has surviving populations of native gilled snails in the less disturbed sections. This spring fed creek could have possibly been a refuge for native mussels. Unfortunately, Bingham Creek is in the middle of extreme housing and urbanization development and is fed by irrigation returns.

Utah Lake and Tributaries

We have conducted native mussel surveys on large sections of Utah Lake's shoreline and in many of its tributaries (see following sections) from 2014 to 2016. No live native mussels were found except for Beer Creek and Currant Creek (see following sections). Weathered Anodonta shells have been found at almost all the sites along Utah Lake supporting other research findings that native mussels were abundant in the past. However, given all the human caused restrictions on dispersal and connectivity discussed throughout this report, loss of secondary fish host species and now due to the mostly uncontrolled human population growth in this area, there is almost no possibility that an unknown native mussel population in Utah Lake can provide natural recruitment to any other tributaries.

Figure 31. Utah Lake shoreline and tributary Unionoida survey locations 2014-2015: 1) Outlet Jordan River, 2)Spring Creek Utah Lake to Walmart, Mill Pond shoreline, 3) Utah Lake shoreline from American Fork Marina to Linden Marina, include American River, 4) Utah Lake shoreline from Powell Slough Wildlife Refuge, entire Powell Slough, 5) Utah Lake shoreline to Utah Lake Marina, Provo River, 6) tributaries to Provo Bay, Hobble Creek, Mill Race, 7) Utah Lake shoreline from Provo Bay to Lincoln Park including Salmon Fork River, Beer Creek, Benjamin Slough, 8) need name of site, and 9) Utah Lake shoreline from Saratoga Springs Marina to south of Pelican Point.

Beer Creek

Figure 32 and Figure 34 show survey locations in Beer Creek (sections also known as Benjamin Slough). A total of 29,450 m^2 was surveyed. Maps showing irrigation dams/barriers on Beer Creek are being made but are not included in this report. There are at least five barriers on Beer Creek and many downstream sections become intermittent during irrigation season which dramatically reduces mussel population viability. Unfortunately, it appears that the section of Beer Creek where the last known Anodonta population exists had a major green algal bloom in July 2016 (Figure 33). Although Anodonta is one of the most pollution tolerant of the unionid mussels, this amount of total dissolved and suspended solids is likely detrimental (see following sections on viability, dissolved solids, and water quality).

Search efficiency and density relationships at 90% probability of detection using Smith (2006) formula suggested by UDWQ are in Figure 35. Search efficiency at $0.1/m^2$ and 90% POD (UDWQ recommended criterion) was 0.00078.

Figure 32. Extant Anodonta population found at section 2 which looks to be the largest, most intact block of agricultural land in this area.

Figure 33. Satellite image of green algae bloom (light green color) at last known remaining Anodonta population location in Beer Creek (image dated: 7/8/2016).

Figure 34. Survey locations. Beer Creek often does not connect with Utah Lake due to agricultural withdrawal (Section labeled Benjamin Slough is interchangeable called Beer Creek).

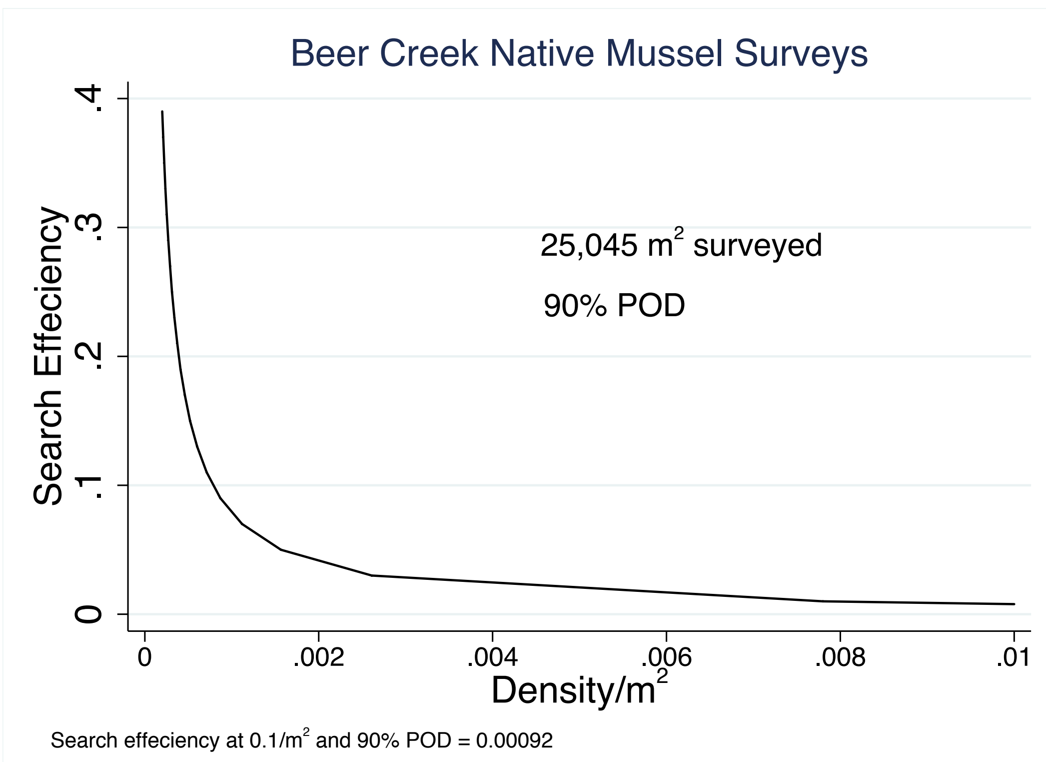


Figure 35. 90% probabilities of detecting at least one individual native mussel (*Anodonta sp.)* during the Beer Creek surveys (2015) at various search efficiencies and corresponding densities given we sampled 25,045 m². **Estimates were based on random mussel distributions and the formula provided from Smith (2006). Formula used for graph:** $0.90 = 1-e^{-\beta\alpha\mu}$**, where 0.90 is 90% probability of detecting at least on individual mussel; β=search efficiency, α=search area = 25,045 m²; and μ= density/m².**

Southern Utah Lake Shoreline and Spanish Fork River

We visually surveyed approximately 7.6 kilometers of southern Utah Lake shoreline and bottom substrate in the Spanish Fork River (Figure 36). No live native or recently dead mussels were found. We did not develop POD distribution models because results would have been similar to those reported for Utah Lake at Vineyard in 2016 (see Native Mussel Surveys 2016 Results), i.e. more than adequate PODs and zero density.

Figure 36. Mussel survey locations along Utah Lake southern shoreline between Lincoln Marina and Sandy Beach and in Spanish Fork River.

Hobble Creek

We surveyed several sections of Hobble Creek near the town of Springville, UT (Figure 37). We also surveyed a 1km section of Hobble Creek directly downstream of I-15 at the June Sucker stream restoration site for a total of approximately 21,650 m^2 surveyed. No live native or recently dead mussels were found.

Search efficiency and density relationships at 90% probability of detection using Smith (2006) formula suggested by UDWQ are in Figure 38. Search efficiency at $0.1/m^2$ and 90% POD (UDWQ recommended criterion) was 0.00107.

Figure 37. Survey locations on Hobble Creek.

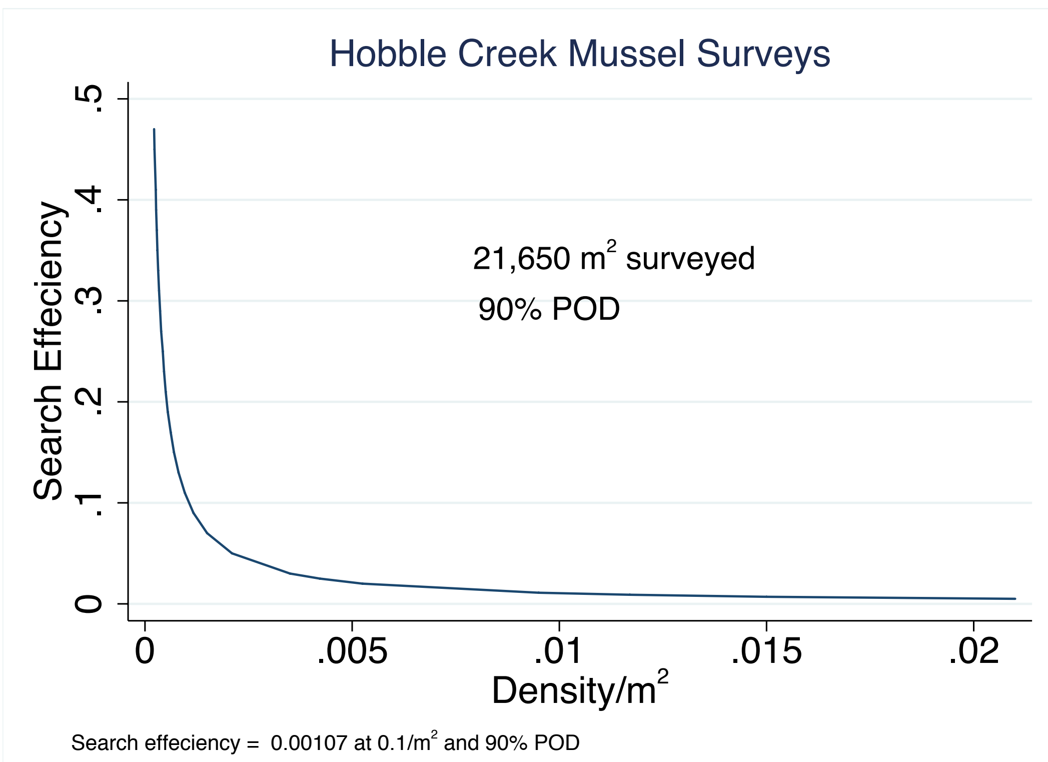


Figure 38. 90% probabilities of detecting at least one individual native mussel (*M. falcata*) during the Hobble Creek survey at various search efficiencies and corresponding densities. Estimates were based on random mussel distributions and the formula provided from Smith (2006). Formula used for graph: $0.90 = 1\text{-}e^{-\beta\alpha\mu}$, where 0.90 is 90% probability of detecting at least on individual mussel; β=search efficiency, α=search area = 21,650 m^2; and μ= density/m^2.

Mill Race Creek

We surveyed several locations on Mill Race Creek including ponds at East Bay golf course (Figure 39 and Figure 40) with a total of approximately 23,250 m^2 of Mill Race Creek surveyed (Appendix 7). No live native or recently dead mussels were found although highly-weathered fragments were common. We suggest re-snorkel surveying these ponds in the future.

Search efficiency and density relationships at 90% probability of detection using Smith (2006) formula suggested by UDWQ are in Figure 41. Search efficiency at $0.1/m^2$ and 90% POD (UDWQ recommended criterion) was 0.001.

Figure 39. Survey locations on Mill Race Creek and East Bay Golf Course, City of Provo, UT.

Figure 40. Survey locations on Mill Race Creek upstream of golf course, City of Provo, UT.

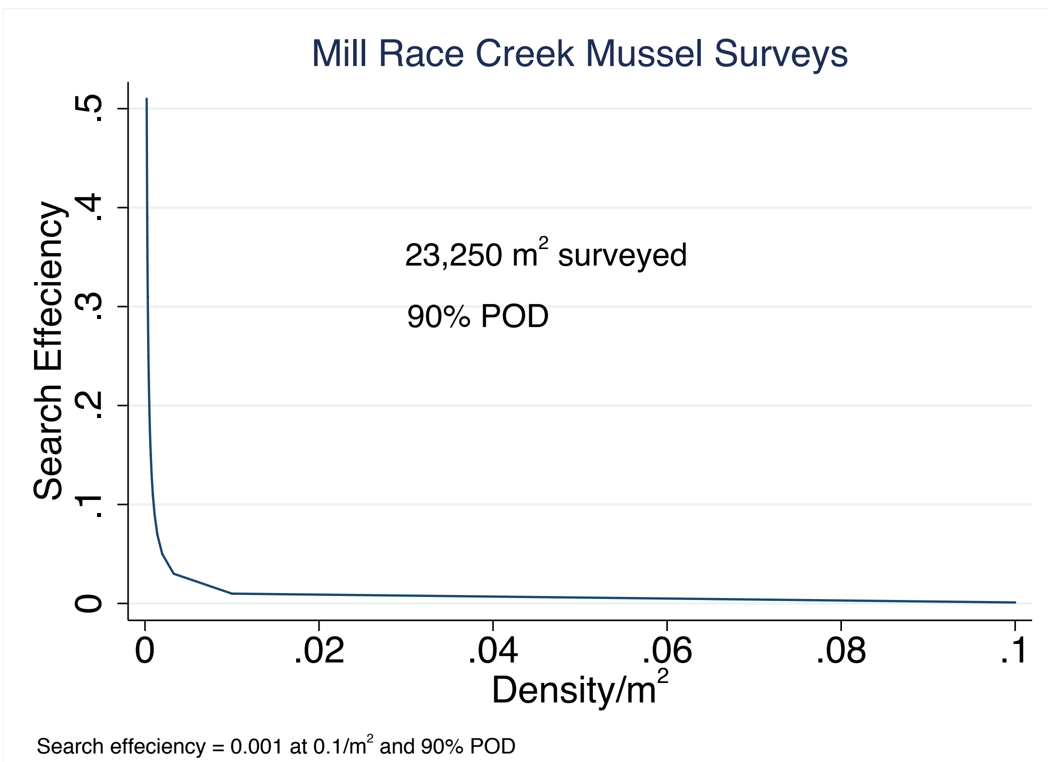


Figure 41. 90% probabilities of detecting at least one individual native mussel during the Mill Race Creek survey at various search efficiencies and corresponding densities. Estimates were based on random mussel distributions and the formula provided from Smith (2006). Formula used for graph: $0.90 = 1\text{-}e^{-\beta\alpha\mu}$, where 0.90 is 90%

probability of detecting at least on individual mussel; β=search efficiency, α=search area = 23,250 m^2; and μ= density/m^2

Spring Creek

We surveyed sections of Spring Creek and Mill Pond near Lehi, UT on several occasions (Figure 42-46). No live native mussels were found, however intact Anodonta shells were found in one section of Spring Creek. These findings suggest that one of the most promising sites for finding extant populations of native mussels was Spring Creek. This was the only waterbody that we surveyed in 2014 where we found large fragments of half shells of *Anodonta californiensis/ nuttalliana*. Consequently, we spent many surveyor hours (> 40 hours) and an estimated surveyor are of 2242 m^2 in 2015 surveying Spring Creek in hopes of finding at least one live individual *A. californiensis/A. nuttalliana*. We surveyed the entire length of Spring Creek from bank to bank from its apparent source in the Walmart parking lot downstream to its confluence with Utah Lake. We found numerous weathered *A. californiensis/A. nuttalliana* shells in the middle sections of Spring Creek mostly buried under hundreds of live and empty Corbicula shells in 2015. These finding are consistent with others who found empty *A. californiensis/A. nuttalliana* shells (Dr. Larry Gray, Utah Valley University, personal communication) along the shores of Mill Pond. We surveyed the entire shoreline of Mill Pond up to 1 m water depth and only found two or three weathered empty *A. californiensis/A. nuttalliana* shell fragments. *Corbicula* sp. shells were quite numerous both in the pond and along the shoreline. Dr. Richards spend 3 hours snorkel surveying Mill Pond on May 21, 2015 but did not find any native mussels. A more through SCUBA survey of Mill Pond is recommended. However, Mill Pond occurs on private property and it appears that the outflow of Spring Creek was diverted from its prior channel sometime during summer 2015 and the future of the pond is dependent on the owners.

Spring Creek is a yet another classic example of the conditions that prevent native mussels from reestablishing in the Jordan River-Utah Lake drainage and the fate of spring creeks in the drainage. The headwater springs of this important spring creek are now under pavement within a heavily urbanized landscape. The springs themselves flow crystal clear from underground sources but are immediately polluted by human refuse and garbage including shopping carts, undergarments, trash bags, dumpsters, etc. These springs are also now home to millions of New Zealand mudsnails, *Potamopyrgus antipodarum* (Gray 1843). Once the creek leaves the Walmart parking lot it enters an impounded pond filled with sediment and abundant muskrats and raccoons as witnessed by the numerous traps set along its shoreline and clearly visible tracks. Spring Creek then passes under Interstate -15 through a culvert before entering Mill Pond. After it leaves Mill Pond it is diverted into a channel that runs alongside many subdivisions and agriculture lands. It is dammed by an irrigation farmer and several other smaller impoundments before terminating above ground for several hundred meter and then resurfacing and entering Utah Lake. The upstream sections of Spring Creek appear to be excellent habitat for *Margaritifera falcata* and for Anodonta throughout its entire length, except for the fact that urbanization, irrigation, fertilized and pesticide applied agricultural and subdivision runoff, impermeable surface runoff, dispersal limiting dams, low densities of potential host fish species, and invasive species predominate. All of which alone are detrimental to native mussel viability, but in combination, seem insurmountable for hopes of continued viability.

Search efficiency and density relationships at 90% probability of detection using Smith (2006) formula suggested formula suggested by UDWQ are in

Figure 46. Search efficiency at $0.1/m^2$ and 90% POD (UDWQ recommended criterion) was 0.01026.

Figure 42. Survey locations on Spring Creek near the city of Lehi, UT.

Figure 43. Upper sections of Spring Creek no longer connect to Utah Lake.

Figure 44. Upper sections of Spring Creek no longer connect to Utah Lake (enlarged view from Figure 35).

Figure 45. Well preserved empty Anodonta shell from Spring Creek (see Appendix 9 for more details).

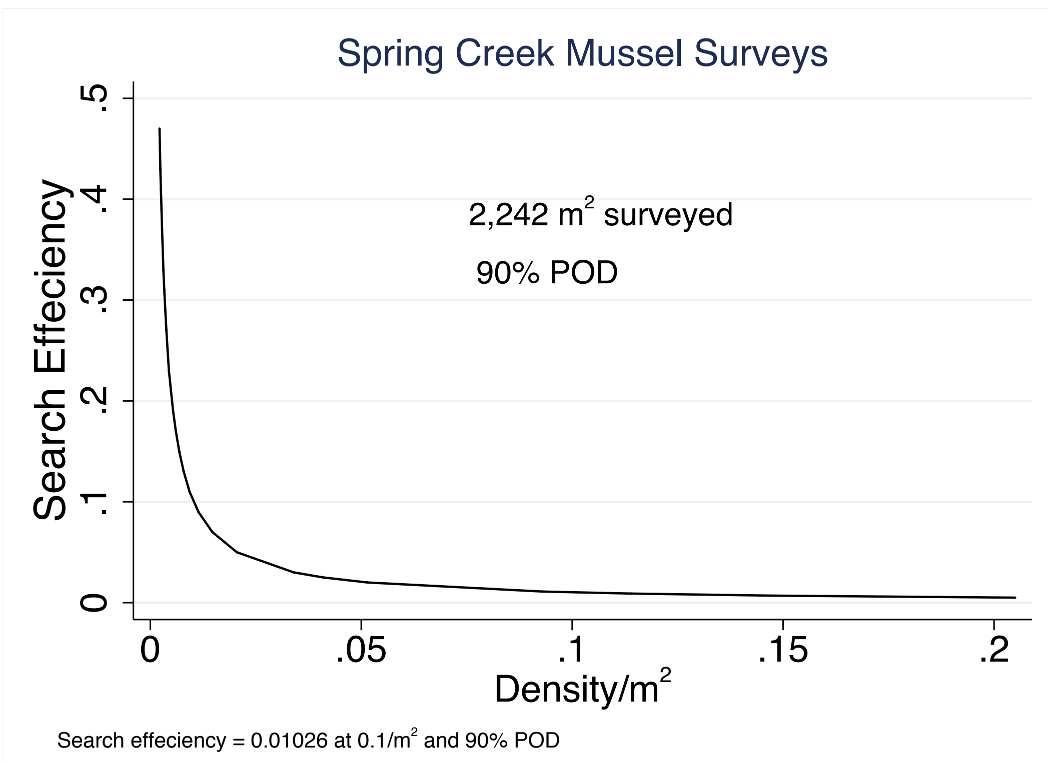


Figure 46. 90% probabilities of detecting at least one individual native mussel during the Mill Race Creek survey at various search efficiencies and corresponding densities. Estimates were based on random mussel distributions and the formula provided from Smith (2006). Formula used for graph: $0.90 = 1\text{-}e^{-\beta\alpha\mu}$, where 0.90 is 90% probability of detecting at least on individual mussel; β=search efficiency, α=search area = 2,242 m^2; and μ= density/m^2.

American Fork River

Remnants of the American Fork River were also surveyed from the mouth at Utah Lake upstream approximately 1km (Figure 47). Aquascopes, clam rakes and kick nets were used in May 2015 when water was flowing; no survey equipment was necessary when river water was diverted for agriculture and the river bed was dry during the August 2015 survey. American Fork River is diverted for irrigation in most summers resulting in a dry river bed for long durations of time. Of course, native mussels cannot survive in intermittent water bodies.

Figure 47. Survey sections of American Fork River.

Burraston Ponds and Currant Creek

Anodonta subpopulations have been reported from Burraston ponds and Currant Creek, near Mona, UT (Mock et al. 2004, 2010) (see section: Currant Creek downstream, Mona Reservoir, and Goshen Canyon). Currant Creek no longer reaches Utah Lake but it is possible it could reach Utah Lake during extremely wet, flood years. Richards and three surveyors snorkel surveyed areas of Burraston Ponds in 2015 but did not find any native mussel shells or live mussels. Visibility was good but the substrate in most sections surveyed were covered with dense vegetation and Anodonta may still exist in the ponds hidden under the vegetation. However, invasive carp, crayfish, and Corbicula were abundant in the ponds. The surveyors also visually censused about 300 m of Currant Creek from the outlet of Burraston Ponds downstream. No live native mussels or empty shells were found. The substrate of this section of Currant Creek and all available mussel habitat were completely covered by invasive Corbicula. However, we did find several Anodonta individuals in Currant Creek in 2016 (see Currant Creek 2016 section). Currant Creek no longer enters Utah Lake. Irrigation diversions prevent Currant Creek from entering Utah Lake for at least 3 to 4 km upstream of the lake. There are also at least three dams, including Mona Reservoir dam on Currant Creek that block secondary fish host migration from Burraston Ponds to Utah Lake. Dams and low secondary fish host densities are a primary factor limiting mussel dispersal (Strayer 2013). If Anodonta subpopulations continue to persist in Burraston Ponds as they do in at least one section of Currant Creek (and in a spring complex of Currant Creek near Burraston Ponds), downstream dispersal into Utah Lake and other tributaries seems impossible and their continued viability is severely compromised. UDNR: DWR (2015) states in Appendix A, page 100: "Locating, documenting, and protecting (Anodonta) populations is needed to decrease the likelihood that local communities will be negatively impacted by development restrictions in the future." Documentation by us and others supports the call by Utah Department of Wildlife Resources to protect these populations and suggest that more intensive surveys and metapopulation viability analyses should begin immediately.

Figure 48. Survey locations in Burraston Ponds and Currant Creek.

Provo River

Several locations of the Provo River were surveyed from the mouth at Utah Lake upstream to Deer Creek Reservoir. Approximately 20% of 72,800 m^2 of the Prove River survey area was closely examined. No live native or recently dead mussels were found. The Provo River appears to be excellent *M. falcata* habitat and the most likely reason for their apparent absence was low densities of secondary fish hosts.

Search efficiency and density relationships at 90% probability of detection using Smith (2006) formula suggested by UDWQ are in Figure 49. Search efficiency at $0.1/m^2$ and 90% POD (UDWQ recommended criterion) was 0.0016.

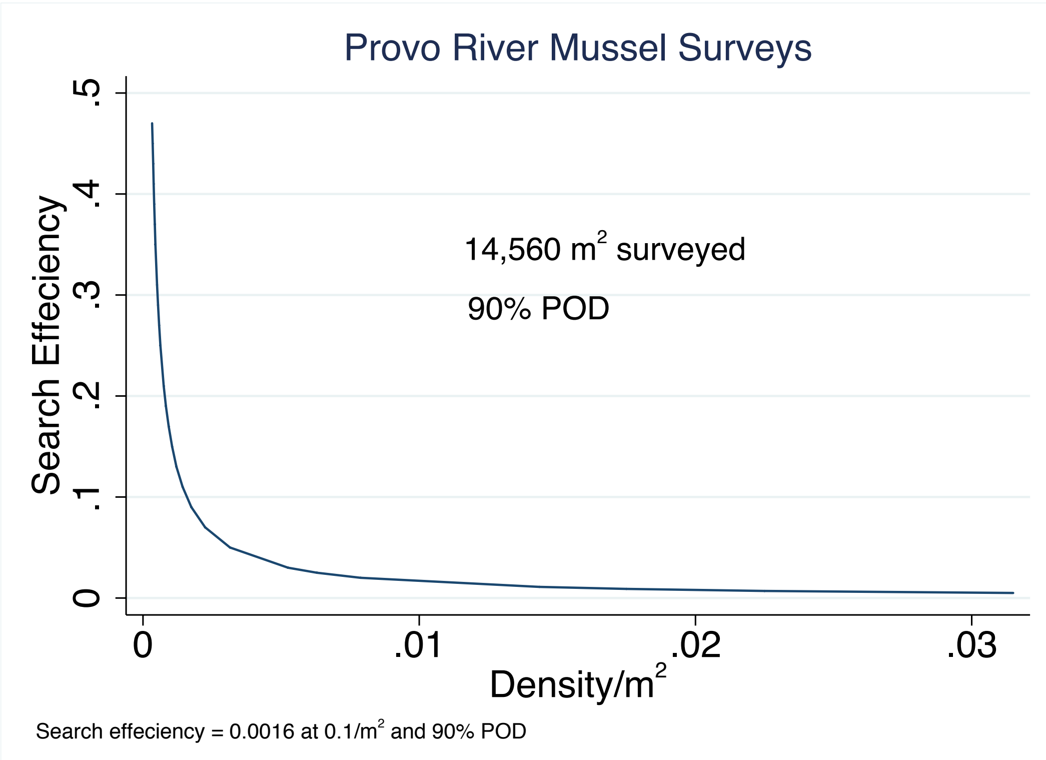


Figure 49. 90% probabilities of detecting at least one individual native mussel during the Provo River survey at various search efficiencies and corresponding densities. Estimates were based on random mussel distributions and the formula provided from Smith (2006). Formula used for graph: $0.90 = 1\text{-}e^{-\beta\alpha\mu}$, where 0.90 is 90% probability of detecting at least on individual mussel; β=search efficiency, α=search area = 14,560 m^2; and μ= density/m^2.

Powell Slough

Surveys were conducted the length of Powell Slough from Orem water treatment facility discharge to its confluence with Utah Lake and then the shoreline to Utah Lake State Park marina including surveying approximately 100 upstream in two irrigation returns for a total of approximately 21,850 m^2 of Powell Slough proper. No live native or recently dead mussels were found.

Search efficiency and density relationships at 90% probability of detection using Smith (2006) formula suggested by UDWQ are in Figure 50. Search efficiency at $0.1/m^2$ and 90% POD (UDWQ recommended criterion) was 0.00105.

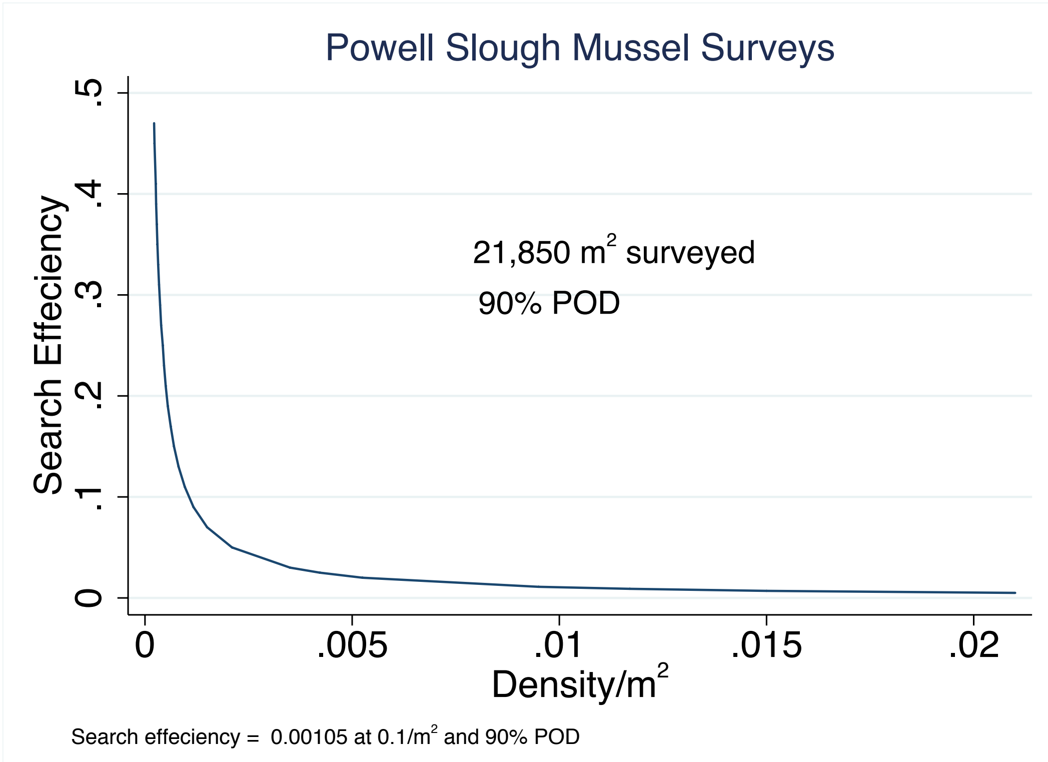


Figure 50. 90% probabilities of detecting at least one individual native mussel during the Powell Slough survey at various search efficiencies and corresponding densities. Estimates were based on random mussel distributions and the formula provided from Smith (2006). Formula used for graph: $0.90 = 1\text{-}e^{-\beta\alpha\mu}$**, where 0.90 is 90% probability of detecting at least on individual mussel; β=search efficiency, α=search area = 21,850 m²; and μ= density/m².**

Native Mussel Surveys 2016

Figure 51. Shoreline and shallow water mollusk survey of Utah Lake at Sandy Beach. View is looking west.

Vineyard Springs Area

Utah Lake shoreline sampling occurred near Vineyard, UT (Figure 52 to Figure 57) on the east side of the lake on numerous occasions from late August through October. Approximately 834,000 m^2 (4.17 km x 200 m) was surveyed by Dr. Richards for live, recently dead, or weathered mollusks and their shells for a total of about forty hours of surveying.

Figure 52. Location of mollusk survey along the shores of Utah Lake, 2016 near Vineyard, UT. Length of shoreline was approximately 4.2 km where many freshwater springs occurred. This type of spring influenced habitat is likely one of the best types for finding any remnant native mussel populations.

Utah Lake's low water levels this summer, 2016, resulted in exposed dewatered habitat up to at least 200 meters away from the normal meander line near Vineyard, UT and created ideal conditions to survey mollusks, particularly bivalves. In the extremely unlikely event that live Anodonta sp. still existed in the survey area or in Utah Lake, they would most certainly not have been able to anticipate or escape the rapidly receding water levels during 2016 drought conditions and most likely would have buried themselves into the damp/wetted sediments to avoid desiccation. Upon further drying and heating of the sediments, Anodonta would then have attempted to leave their burrows and thus become exposed to predators and surveyors. This response was all too evident with Corbicula in the survey area where these invasives exposed themselves to desiccation as they attempted to move to favorable conditions and then became fodder for predators (Figure 60 and Figure 63). Predators are experts at locating and exposing bivalves hidden in the sediments as substantiated by the hundreds of empty Corbicula shells scattered along the shoreline.

Figure 53. Aerial view of northern springs of the Vineyard spring complex, between Lindon Marina and Powell Slough, Utah Lake. September 2016. These springs may have historically been a creek/river but are now inundated and covered by Geneva Steel Co. lands and recent subdivisions and presently only surface flow occurs at this location for a short distance before entering Utah Lake. Utah Lake is the green body of water in the foreground. Numerous subdivision developments are occurring up to the normal meander line of the lake.

Figure 54. Aerial view of southern spring complex, spring pools, and Utah Lake at Vineyard, UT. Photo altitude = 100 m, original resolution = 3 cm/pixel. Utah Lake is the green area on the left. The area within the arrows is the exposed substrate up to the normal meander line towards the right that was surveyed and was due to low water levels from Utah Lake. The green connected oblongs in the exposed areas of Utah Lake's substrate are waters from springs that have algae and are mixed in a mosaic of gray colored dry areas. Springs and pools flow from the right of the image and empty to Utah Lake on the left. Far right is new subdivision with paved path.

Perennial spring tributaries and pools covered about 20 to 30% of the survey area and provided refuge for any surviving bivalves from desiccation as lake levels lowered. However, these survivors would have been visible to both predators and researchers alike in these shallow < 2 cm deep pools. These same spring waters likely provide substantially better habitat for native mussels than the lake itself during times of high lake waters. Indeed, spring influenced areas of

Utah Lake were likely the sole remaining habitat during the 1930's drought when all of Utah Lake's tributaries were diverted for irrigation and Utah Lake almost completely dried up. The springs also may have been the last sanctuary for any surviving mollusks in winter during the 1930's drought when the lakebed froze solid, likely to several meters' depth. Spring fed waters are also prime habitat for spawning fish including carp, which could potentially be secondary hosts for Anodonta glochidia and are areas where young mussels would likely abandon their hosts and take up residence.

Figure 55. View of Utah Lake near Vineyard, UT looking SW. The lake is in the far distance with several pelicans observable on its shoreline. Water in foreground out to the Utah Lake shoreline is pools from the many springs in the area.

Figure 56. Flowing spring water and algae and aquatic vegetation at the most northerly spring in the survey near Vineyard, UT, September 5, 2016.

Figure 57. Researcher taking notes at one of the flowing springs along the eastern shores of Utah Lake, September 2016.

Results

No live or recently dead Anodonta were encountered. Very few highly fragmented Anodonta shells were found scattered across the survey site (Figure 58 and Figure 59).

Figure 58. Weathered mollusk shells and fragments in the main channel of the most northerly spring surveyed. Shells are mostly fingernail clams (Family Sphaeriidae) with one large Anodonta sp. fragment visible in the center of the photo.


Figure 59. A highly weathered Anodonta shell fragment found in the most northerly spring.

There were many (N > 1000) widely scattered Corbicula popping out of the sediments near spring influenced substrate. Some Corbicula were still alive, while most were recently killed by predators (Figure 60 to Figure 63). Shorebirds (mostly gulls) and raccoons pulled many of the Corbicula out of substrate, waited until the clams became dehydrated and exhausted and then were eaten. Even though there were hundreds of Corbicula, they were more dispersed and at lower densities than anticipated most likely because they are preyed upon by the super abundant carp population in the lake. Corbicula tends to occur in habitats and conditions where Anodonta likely occurred in the past (Richards 2015 and personal observations). It is probable that Anodonta biomass (densities) was at least as much as what now occurs with Corbicula in Utah Lake and in the entire Jordan River drainage.

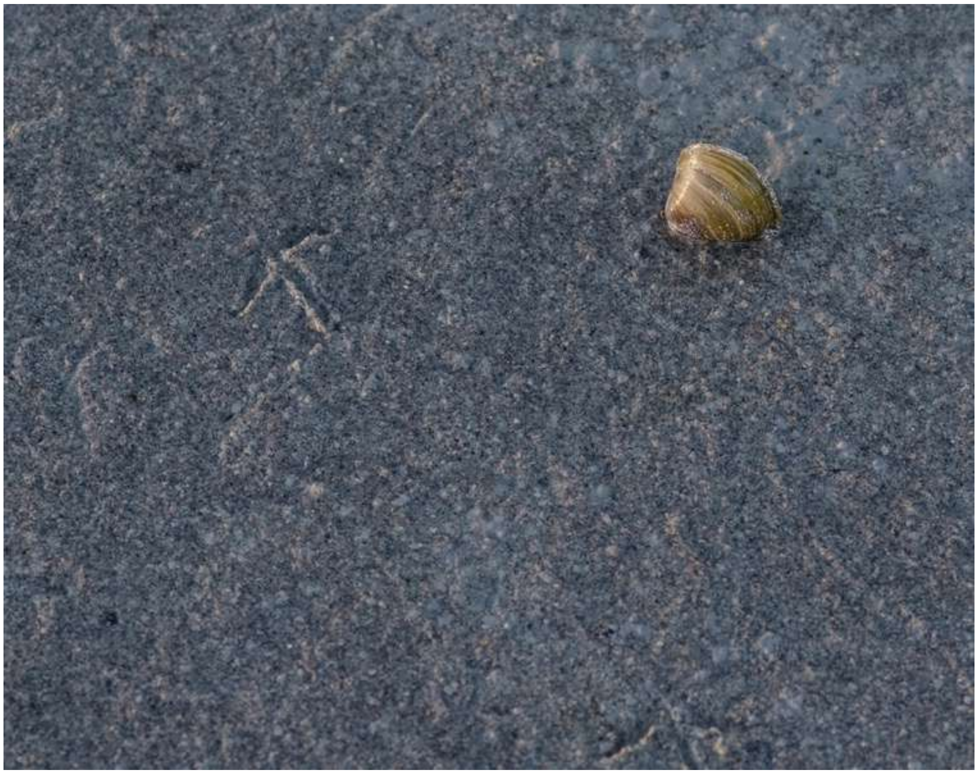


Figure 60. A live Corbicula exposed due to receding Utah Lake waters. Tracks of potential bird predators are also visible.

Figure 61. Another Corbicula exposed to predators during receding Utah Lake shoreline, September 2016.

Figure 62. Corbicula debating whether to leave receding Utah Lake waters and imminent desication or becoming exposed to predators near Vineyard, UT. Run little clam, run!

Figure 63. Corbicula that took a gamble and was eaten by predators, Vineyard, UT, September 2016.

Thousands and thousands of highly weathered fingernail clam shells (Family Sphaeriidae) were found along the normal meander line of the lake and there were very high densities of shells in the spring flows (Figure 64).

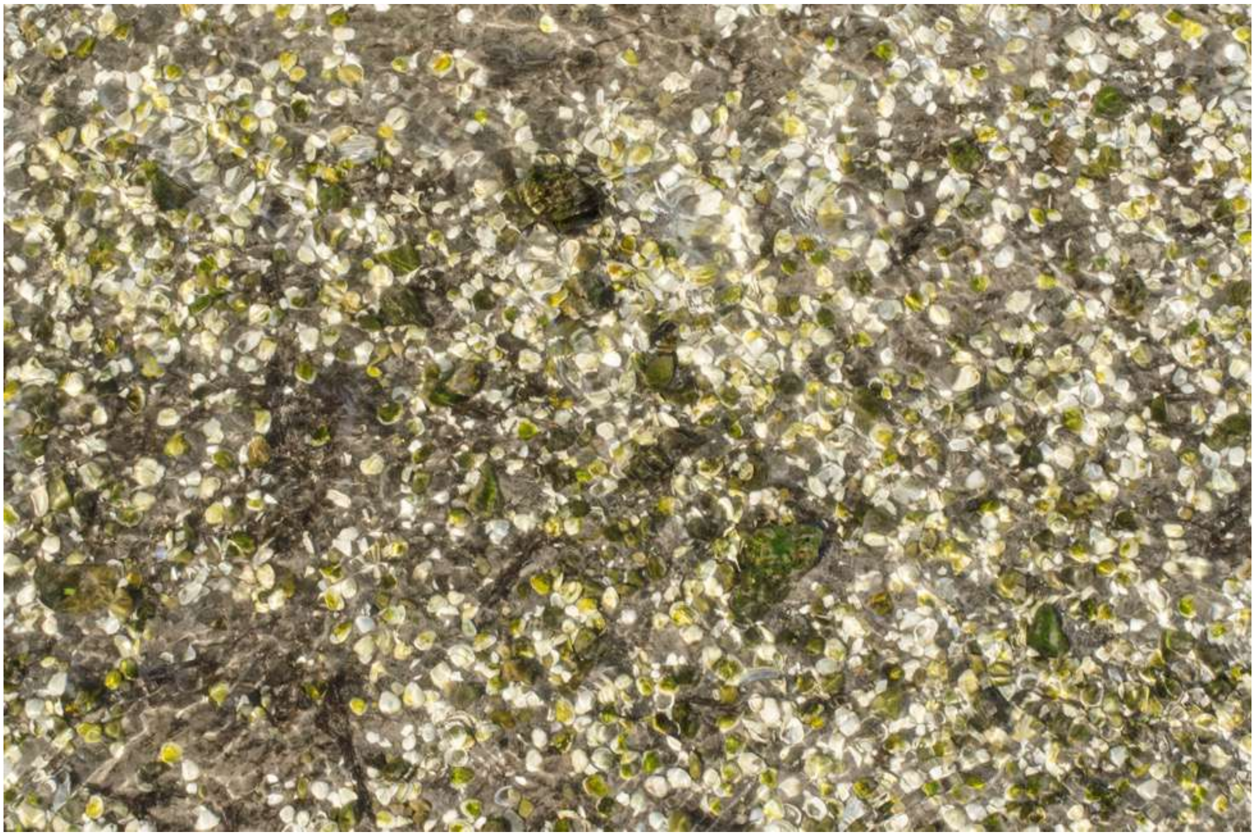


Figure 64. Weathered mollusk shells, primarily native fingernail clams (Family Sphaeriidae) in one of the spring tributaries to Utah Lake near Vineyard, UT. This is typical of the number and densities of shells found covering the substrates in these spring tributaries.

The high densities of weathered mollusk shells in the springs and exposed areas of Utah Lake shoreline is typical of the entire lake and almost all its tributaries. In every instance of surveying for the last several years and during benthic sampling in the lake, there was often a thick layer of sediment covering thousands of weathered mollusk shells including Anodonta, Sphaeriidae, Hydrobiidae, Valvatidae, Lymnaeidae, and Physidae. This is direct evidence of past favorable conditions in Utah Lake for a rich and diverse molluskan assemblage. We can only speculate as to what caused rapid sedimentation, often greater than several centimeters thick, which likely was an important contributor to the demise of Utah Lakes native mollusks. The only live mollusks other than Corbicula that were found in the survey were Physa snails which were abundant in many of the spring pools (Figure 65).

Figure 65. The only living gastropods found in the springs were physa snails. Snails are all the dark spots in the photo.

Our definition of search method for Utah Lake shoreline surveys in 2016 was visible live or recently dead mussels approximately > 2 cm shell length. This was the approximate size of Corbicula that we found on the surface trying to avoid desiccation. Search efficiency and density relationships at 90% probability of detection using Smith (2006) formula suggested by UDWQ are in Figure 66. Search efficiency at $0.1/m^2$ and 90% POD (UDWQ recommended criterion) was 0.0000275. This suggests that if our search efficiency of finding whole exposed Anodonta was for example 30% (a reasonable but underestimated value (EPA 2013)), then shoreline densities would have been about $0.000009/m^2$ at 90% POD. Shoreline exposed Anodonta obviously were a function of individuals in Utah Lake wetted habitat (i.e. the lake itself), but we don't know what this relationship is. However, we are also conducting benthic surveys in Utah Lake and find Corbicula regularly in our samples. Corbicula densities appear to be somewhere between 1 and 2 times greater in the lake than what we have found exposed along the shoreline (unpublished data). If the same relationship between exposed Anodonta along the shoreline and within the lake is the same as it is for Corbicula, then a crude estimate of Anodonta densities in Utah Lake would be $< 0.000018/m^2$ or most likely as other have suggested, extinct in Utah Lake. Of course, there could be very remote chance of an as -of -yet undetected small population remaining in some obscure location in the lake; however, the lake-wide distributed, super abundant apex molluscivoruos carp virtually guarantees that not happening (see Carp, Predation section).

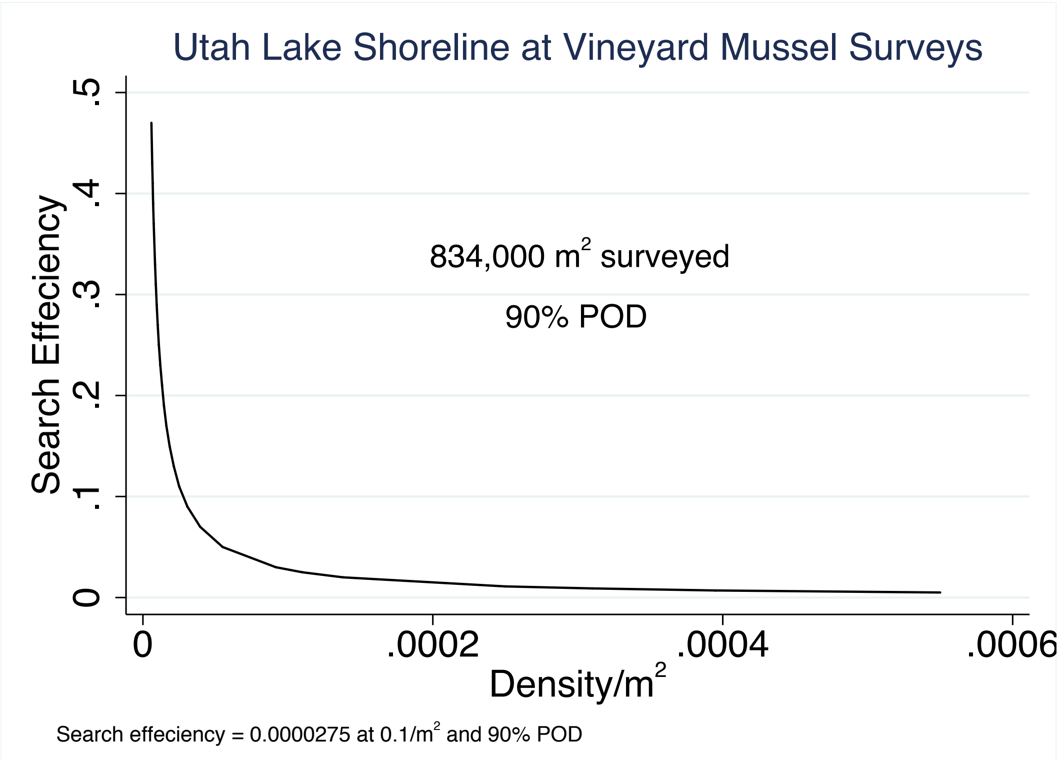


Figure 66. 90% probabilities of detecting at least one individual native mussel during the Utah Lake at Vineyard surveys at various search efficiencies and corresponding densities. Estimates were based on random mussel distributions and the formula provided from Smith (2006). Formula used for graph: $0.90 = 1\text{-}e^{-\beta\alpha\mu}$**, where 0.90 is 90% probability of detecting at least on individual mussel; β=search efficiency, α=search area =834,000 m²; and μ= density/m².**

Goshen Bay shoreline at Goose Point North

Three surveyors examined the shoreline and wetted area up to 1 m depth for 2 hours using clam rakes at Goose Point North, Goshen Bay (Figure 67)(from Longitude 111°51'48.17"W to 111°52'5.38"W).

Figure 67. Goshen Bay survey site.

Results

No live or recently dead native mussels were encountered. A few highly weathered Anodonta fragments were found. There were wave washed piles of weathered pulmonates and prosobranch snail shells as well as fingernail clams. Several live Corbicula were also found. Again, the wave washed piles of highly weathered shells is typical of Utah Lake's shoreline indicating a once thriving native mollusk assemblage unique to the western USA.

Shoreline SW of Provo Airport

A total of approximately 2 km length and 150 m width of the shoreline of Utah Lake up to 10 cm wetted depth near the SW corner of Provo City Airport (Figure 68 to Figure 71) was visually surveyed by Richards on several occasions throughout the summer/autumn of 2016.

Figure 68. Locations of mollusk survey site near SW corner of Provo City Airport.

Figure 69. Shoreline of Utah Lake near SW corner of Provo City Airport looking south on August 17, 2016. Receding Utah Lake waters although indicative of the severe drought conditions the area is experiencing, were ideal for surveying exposed mollusks.

Figure 70. Shoreline of Utah Lake near SW corner of Provo City Airport looking southwest on August 17, 2016. Area in foreground is where weathered mollusk shells started to become more abundant and increased in abundance up to the lakes meander line (see next photo).

Figure 71. Area near normal meander line of Utah Lake shoreline near SW corner of Provo City Airport. Note weathered Anodonta shell in foreground right, near bulrush. Thousands of weathered shells including Anodonta and an occasional Utah valvata can be found all along this area for several kilometers. Utah Lake was a unique molluskan hotspot in the western U.S. in the not too distant past.

Results

No live or recently dead native mussels were encountered. Quite a few complete highly weathered Anodonta half- shells and shell fragments were encountered, mostly along the normal meander line along with piles of fingernail clams and a variety of snail shells including the heterobranch *Valvata utahensis* presumed to be extinct in Utah. This further confirms the mounting evidence that Utah Lake once supported vast numbers of mollusks and that this area of Utah Lake near the mouth of Provo Bay may have had large beds of Anodonta. These results further support ours and others conclusion of Anodonta extinction in Utah Lake (see Vineyard Springs Area).

Figure 72. Weathered Anodonta shell at normal meander line of Utah Lake near SW corner of Provo Airport, July 29, 2016.

Beer Creek

Beer Creek is home to one of two known remaining isolated small populations of Anodonta in the Jordan River watershed. Unfortunately, Beer Creek is heavily used for agricultural purposes and its downstream sections from W 6400 S to its confluence with Utah Lake is often without water for many consecutive days and weeks throughout the summer. Freshwater mollusks can survive limited desiccation in cool damp conditions, however summer temperatures and humidity levels typically bake these sections of Beer Creek's mud/clay sediments to the consistency of hardened cement. Three surveyors, including Dr. Richards, examined Beer Creek for approximately 300 meters upstream of its confluence with Utah Lake (Figure 73 to Figure 75) using clam rakes and visual examination of shoreline and exposed substrates on August 15, 2016.

Figure 73. Mollusk survey location on Beer Creek at confluence with Utah Lake. Survey was conducted on August 15, 2016.

Figure 74. Stagnant pool of Beer Creek water at Lincoln Beach Road bridge looking north, August 15, 2016

Figure 75. Stagnant pool of Beer Creek water at Lincoln Beach Road bridge looking north, August 24, 2016. This is the same location as the previous photo.

A recent examination of Beer Creek using Google Earth resulted in a somewhat surprising but very concerning event. Beer Creek at the last known extant Anodonta site appeared to be undergoing a large green algal bloom (Figure 76). This is cause for alarm because algal blooms of this magnitude can easily cause Anodonta to stop feeding or even worse cause mortality (see ***Inorganic Suspended Matter*** section).

Figure 76. A visible large green algal bloom (light green color) in Beer Creek at the last known extant Andodonta site circa July 2016.

Results

No live or recently dead native mussels were encountered. This was expected because this section of Beer Creek is often without water. Native mussels need water. Three highly weathered Anodonta shell fragments were found, further demonstrating that Beer Creek was once suitable habitat for Anodonta.

Spanish Fork River

The Spanish Fork River is one of the major tributaries to Utah Lake. However as with all of Utah Lake's tributaries; most Spanish Fork River flows are diverted for irrigation during irrigation season other than those waters that flow out of water treatment facilities. Flows in the section of Spanish Fork River downstream of W 4000 S to its confluence with Utah Lake often stop and become stagnant (Figure 77 to Figure 80). Only minuscule amounts of irrigation water in the area infiltrates into the groundwater and is then able to somewhat recharge the Spanish Fork River's flow into the lake during low flow years. Several estimates of flow in these sections of the Spanish Fork River were made in the summer and ranged between 0 and < 5 cfs (SDSD dataset).

Richards surveyed 1.4 km of the Spanish Fork River from its confluence with Utah Lake upstream (Figure 77) using aquascopes, clam rakes and visual surveys on August 16, 2016 for 10 hours. Flows were estimated between 0 and 1 cfs.

Search efficiency and density relationships at 90% probability of detection using Smith (2006) formula suggested by UDWQ are in Figure 81. Search efficiency at 0.1/m^2 and 90% POD (UDWQ recommended criterion) was 0.0165.

Figure 77. Mollusk survey site on Spanish Fork River at confluence with Utah Lake.

Figure 78. Spanish Fork River and algal bloom just upstream of a diversion dam and downstream of W 4000 S bridge on July 18, 2016. Flow was estimated to be << 1 cfs.

Figure 79. Green algal bloom on Spanish Fork River as it enters Utah Lake on July 18, 2016. Flows were estimated to be < 5 cfs and most of the water was pooling and stagnating before entering the lake.

Figure 80. Spanish Fork River between W 4000 S bridge and confluence with Utah Lake on July 18, 2016. Most of the river was diverted for irrigation and flows here were estimated at <3 cfs. Notice thick algal mats indicating nutrient overload.

Results

No live or recently dead mussels were encountered, although as was the case for most survey locations, several highly weathered Anodonta fragments were found indicating that the Spanish Fork River was also once prime habitat for native mussels.

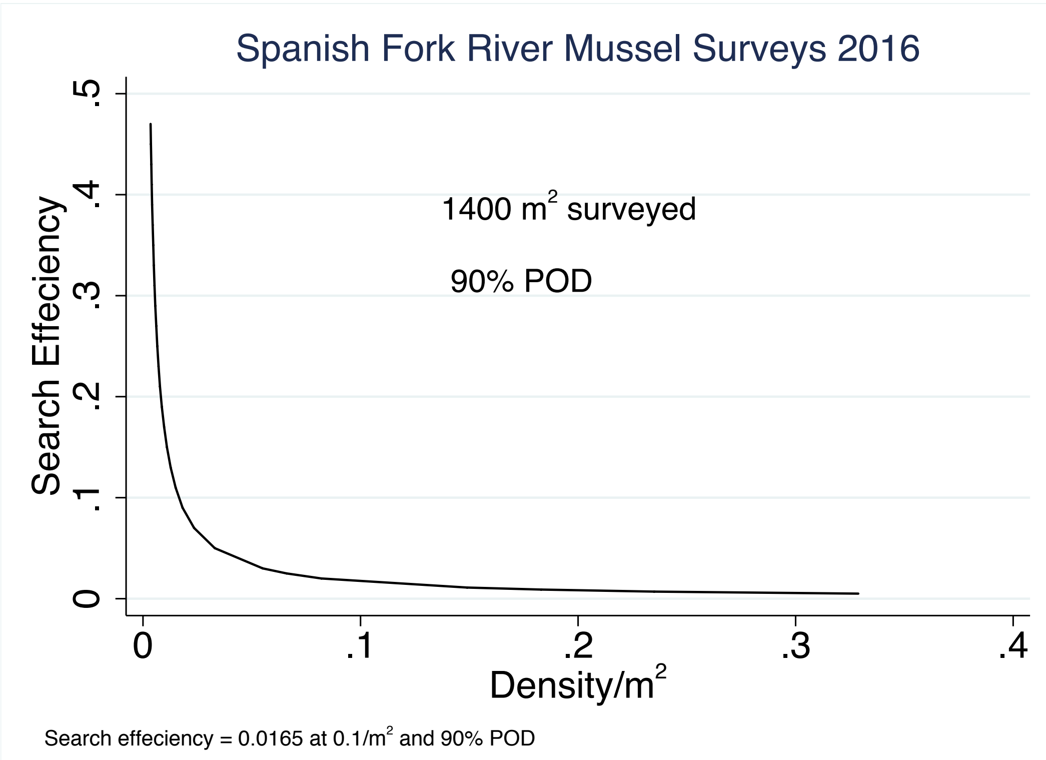


Figure 81. 90% probabilities of detecting at least one individual native mussel during the Spanish Fork River survey at various search efficiencies and corresponding densities. Estimates were based on random mussel distributions and the formula provided from Smith (2006). Formula used for graph: $0.90 = 1\text{-}e^{-\beta\alpha\mu}$**, where 0.90 is 90% probability of detecting at least on individual mussel; β=search efficiency, α=search area = 1400 m²; and μ= density/m².**

Burraston Ponds

Burraston Ponds have been reported to support an Anodonta population in the recent past (Hovingh year, Mock et al. year, and Richards 2015). However, none were found by Richards and three technicians snorkel surveying in 2015 (Richards 2015). Dr. Richards snorkel surveyed the largest of Burraston Ponds for 2 hours on August 22, 2016.

Results

No live or recently dead native mussels were encountered. As was the situation in 2015 aquatic vegetation severely limited the area that could be surveyed. SAV dominated the pond but was mostly decadent and visibility was limited to areas with no SAV. It is hopeful that an isolated

Anodonta population still survives in these ponds and that future more intensive surveys will verify.

Currant Creek: *Last Hope for Anodonta?*

Outlet Burraston Ponds

Unfortunately, Currant Creek at the outlet of Burraston Ponds was almost completely dry with several stagnant pools when surveyed on August 22, 2016 (Figure 82 to Figure 85).

Results

As was the case when surveyed in 2015, massive amounts of Corbicula covered the substrate for the entire 100 meters examined. However, in 2016 thousands of Corbicula were stranded and became desiccated due to the extreme low flows resulting in most of the substrate being exposed (Figure 82 to Figure 85). As in 2015, no native live, recent dead or weathered native mussels or their shells were found.

Figure 82. Stagnant pool in Currant Creek looking upstream from outlet of Burraston Ponds, August 2016. Low flows, increased exposed substrates, algal blooms, stagnant conditions, and Corbicula dominate the creek.

Figure 83. Currant Creek looking downstream of Burraston Ponds outlet, August 2016. Low flows, increased exposed substrates, algal blooms, stagnant conditions, and Corbicula dominate the creek.

Figure 84. Trashed out, stagnant section of Currant Creek at outlet of Burraston Ponds, August 2016. Note all of the exposed Corbicula shells becoming exposed due to low flows.

Figure 85. Corbicula left high and dry. This was normally wetted substrate in Currant Creek at Burraston Ponds. Photo taken August 2016.

Currant Creek downstream, Mona Reservoir, and Goshen Canyon

There is an irrigation check dam at W 200 N bridge crossing in Mona, UT and Currant Creek appeared to have become dry downstream of the dam into Mona Reservoir. There may have been some seeps and flowing water in the channel between the bridge crossing and the dry Mona Reservoir but this section wasn’t closely examined. Of course, Mona Reservoir was completely dry during the summer of 2016 (Figure 86).

Figure 86. Mona Reservoir high and dry. August 2016.

Currant Creek was completely dry for about 2 km downstream of the Mona Reservoir dam, (Figure 87).

Figure 87. Currant Creek dry from Mona Reservoir (also dry) downstream to about 100 meters of this photo where springs recharge occurs.

Several springs again recharged Currant Creek creating limited flows starting at the beginning of Goshen Canyon. However, this section was heavily grazed by cattle (Figure 88 and Figure 89). Most of the creek and riparian vegetation was trampled and the little water that flowed was filled with cattle excrement and algae (Figure 88 and Figure 89).

Figure 88. Several cattle patrol one of the last remaining occupied Anodonta habitats in the Jordan River drainage at Currant Creek, near Goshen Canyon, August 2016. Currant Creek is recharged from springs about 10 meters upstream (right side of photo) but is immediately impaired from poorly managed cattle grazing practices.

Figure 89. Limited spring recharge in Currant Creek at beginning of Goshen Canyon becomes impaired by cattle.

Flows increased going downstream in Goshen Canyon from additional spring recharge and five live adult Anodonta were found just upstream of an irrigation check dam (Figure 90 to Figure 93).

Figure 90. Location of last reported Anodonta population in Currant Creek, Goshen Canyon, August 2016.

One recent dead and several relatively unweathered empty shells were also found at this site. The recently dead Anodonta was obviously killed and eaten by a raccoon by evidence of the tell-tale bite marks and shell breakage and tracks around it in the mud (Figure 93). Two of the live Anodonta were fully exposed from the sediments laying on their sides in the creek suggesting that they were moving from their current location for reasons unknown but presumable in search of better conditions (Figure 91 and cover photo). The entire substrate in this section was completely covered by Corbicula up to several centimeters depth making it difficult for any remaining Anodonta to burying themselves into the substrate (Figure 92).

Chemistry readings were collected at three locations in Goshen canyon (Table 1). Ammonia levels dropped by 38% and phosphate by 50% from the upstream cattle infested site to where Anodonta were found, about 1.2 km. Ammonia levels dropped by 72% from the upstream site at the start of the canyon to the mouth of Goshen Canyon and phosphate levels dropped by 70%, about 2.5 km. Nitrate levels (mg/l) were fairly constant but decreased from upstream (0.68) to down (0.60) (Table 2).

Table 2. Ammonia (NH_3), Nitrate (N), and Phosphate (P) readings at three locations in Currant Creek, Goshen Canyon, UT. Collected on September 2, 2016.

	Lat	Long	NH_3	N	P
Upstream at start of springs	39°53'18.28"	111°53'10.71”	1.65	0.68	0.1
Midstream (where live Anodonta were found)	39°53'47.03"	111°53'17.77"	1.03	0.66	0.05
Downstream (mouth of Goshen Canyon)	39°54'49.44"	111°54'3.44"	0.46	0.6	0.03

There is an urgent need to conduct more intensive research on Currant Creek in Goshen Canyon and to determine the viability of this remaining Anodonta population, which may number << 10 individuals.

Figure 91. "No Vacancy: Anodonta on the run", Currant Creek, Goshen Canyon. Exposed Anodonta apparently trying to escape surroundings including water quality problems or just too many Corbicula.

Figure 92. Corbicula are the substrate. Over several centimeters thick of live and empty Corbicula shells. Currant Creek, Goshen Canyon August 2016.

Figure 93. "Just not fast enough". Anodonta recently killed and fed on by raccoon. Notice some soft tissue remains.

Currant Creek continued to flow through the canyon but only cursory investigations were conducted. The water in the canyon was extremely turbid and the substrate at most locations was composed of large cobbles and boulders which made visual surveying using aquascopes and clam rakes unfeasible. Additional sampling needs to be conducted in the canyon.

Once Currant Creek leaves Goshen Canyon it is diverted for irrigation. At W 15200 S (Main St.) in the hamlet of Goshen just downstream of Goshen Reservoir, Currant Creek was dry (August 2016). Goshen Reservoir was also dry. It is assumed that Currant Creek remained dry downstream to its former confluence with Utah Lake.

Currant Creek was surveyed on May 26, 2016 from Goshen Bay, Utah Lake upstream for approximately 1 km. The creek was dry at that time also (Figure 94). Several highly weathered Anodonta shell fragments were encountered (Figure 95 and Figure 96). Most were slightly exposed in the muddy substrate substantiating the fact that Currant Creek historically was suitable habitat for Anodonta. Although Goshen Bay had water during the mollusk survey at this location on May 26, 2016, it later dried up for about 2 km north by the end of August 2016 (Figure 97).

Figure 94. Currant Creek streambed on May 26, 2016. This 1 km surveyed section of Currant Creek was dry. Only a few puddles from Utah Lake waters or rain events were present.


Figure 95. Anodonta weathered shell fragment in Currant Creek mud at mouth Utah Lake.

Figure 96. Several weathered Anodonta shells and large gastropod shells found in dry Currant Creek sediments near confluence with Utah Lake. Notice the large Lymnaeidae shell in whit jar top and the large Planorbidae shells.


Figure 97. Goshen Bay dry in late August 2016. View is looking south towards dry Currant Creek.

As with the last remaining Anodonta population in Beer Creek, the last isolated small populations in Currant Creek have been known by management agencies for many years. However, there appears to be no habitat protection for these few remaining individuals in Goshen Canyon, Currant Creek.

Mill Pond

Mill Pond near Lehi, UT cannot be completely ruled out for supporting a small population of Anodonta. Dr. Richards snorkel surveyed for Mill Pond for 2 hours on August 30, 2016. Visibility was up to 1 meter but most of the pond was covered in SAV which limited ability to survey completely. Additional sampling is suggested.

Results

No live, recently dead, or weathered Anodonta shells were encountered, although many Corbicula were found. Continued surveying of Mill Pond is recommended.

Spring Creek

Spring Creek was surveyed by five surveyors including Richards in 2016 for a total of 30 hours of searching. Most of Spring Creek is very shallow from the outlet of Mill Pond downstream for about 2 km but then becomes deeper and slower because of several irrigation dams and a recently constructed beaver dam that was not there in during our 2015 surveys (Figure 98).

However, Spring Creek no longer reaches or is connected to Utah Lake because of diversions (Figure 99). It is not likely but possible that Spring Creek could reconnect to Utah Lake during extreme high flow years.

Figure 98. Spring creek beaver dam and trash.

Figure 99. Disjunct flow of northern portion of Spring Creek at confluence with Utah Lake.

Results

No live Anodonta were found. Three complete somewhat weathered Anodonta half-shells were found at the upstream section just downstream of Saratoga Hwy crossing suggesting that Anodonta was present in the recent past. Unfortunately, most of the available habitat is now occupied by Corbicula. Unfortunately, Spring Creek no longer connects to Utah Lake and its ample flows from cold water springs just several kilometers upstream either are used for irrigation and/or disappear as groundwater and reappear about 1 km west or as groundwater springs in Utah Lake. Thus, there is no connection between the remaining degraded but potentially suitable Anodonta habitat upstream in Spring Creek and Utah Lake and therefore no potential for dispersal into other waterbodies in the drainage.

Provo River in Orem

Two surveyors including Dr. Richards searched for native mussels in the Provo River in Orem, UT for 8 surveyor hours from the bridge on Center St. upstream for 600 m. No live, recently dead, or weathered native mussel shell fragments were found. The most likely native mussel to have been encountered would have been Margaritifera as the habitat was mostly cobbles and cold water. Several live Corbicula were found and two hydrobiid snails, Fluminicola and Pyrgulopsis occurred at high abundances, as well as the invasive New Zealand mudsnail (Potamopyrgus) (Family Tateidae).

Jordan River

Reports of large numbers of 'clams' in the Jordan River by Salt Lake County biologists prompted Dr. Richards and Dr. Miller to conduct a brief one-hour clam rake at the location reported near the W 1700 S bridge crossing.

Results

Thousands of live and dead Corbicula were found in this section of the Jordan River. In one location, each rake of the clam rake produced hundreds of clams (Figure 100). No live, recently dead, or weathered Anodonta shell fragments were found. The Jordan River obviously was once very good habitat for native mussels. Their apparent disappearance is a tragic loss for this impaired ecosystem and for the citizens of Salt Lake City.

Figure 100. Dr. Theron Miller, Wasatch Front Water Quality Council, with a clam rake brimming with Corbicula. Densities were the highest yet found in the Jordan River and equaled or surpassed densities in other productive locations in the drainage.

Historical vs. Current Data; Resident vs. Non-Resident for Regulatory Purposes

Utah Department of Water Quality and U.S.E.P.A. require determinations of "historical" vs. "current" data and whether native mussels are "resident" or "non-resident" for setting ammonia criteria (USEPA 2013b). Discussion of these definitions, including our conclusions based on these definitions are in:

Appendix 8. Defining Native Mussel Historical and Current Data for Regulatory Purposes and

Appendix 9. Defining “resident” (“occur at the site”) and “not resident” (“do not occur at the site”) as it pertains to EPA and UDWQ ammonia criteria recalculation.

Unionoida Biology, Ecology, and Metapopulation Viability

A thorough knowledge of the biology, ecology, metapopulation dynamics, and dispersal limitations of Anodonta and *M. falcata* in the Jordan River-Utah Lake drainage is crucial to understanding their apparent absence from most waters in the Jordan River-Utah Lake drainage, and their (in)ability to recolonize these areas and extinction risk.

Unionoida Life History

Unionoida are the principle bivalve fauna of North American rivers and lakes (McMahon 2002). They tend to inhabit only infrequently disturbed aquatic habitats and achieve densities approaching the carrying capacity of the environment (McMahon 2002). This can result in extensive intra- and inter-specific competition for limited resources (McMahon 2002). Native unionid life-history traits associated with stable habitats include: slow individual growth rates, delayed maturity (6 to 12 years), grow rapidly to maturity and, thereafter, grow slowly, have extremely low juvenile survivorship but high adult survivorship, long life spans (6 to >100 years), low fecundity, extensive iteroparity (multiple reproductive cycles over lifetime), large egg–offspring size (glochidia), and limited capacity for dispersal (Sibly and Calow 1986, McMahon 2002). Native unionids typically have one reproductive period per year, and tend to allocate high proportions of non-respired assimilated energy (85.2–97.5%) to growth and low proportions to reproduction (2.8–14.8%) (McMahon and Bogan 2001). Low juvenile survival and low adult growth rates lead to low population productivity, reflected in extended turnover times (i.e., time in days for population production to produce the equivalent of mean population standing crop biomass) of 1790–2849 days (McMahon 2002). High adult survival, long life spans, and low juvenile survival result in domination of unionoidean populations by adults relative to juveniles (Sibly and Calow 1986). Their slow population growth prevents rapid population recovery after extirpation or reduction by catastrophic environmental disturbance and there is likely strong selection pressure for unionid development of extensive resistance to environmental extremes (McMahon 2002).

Unionoideans deviate from the life-history traits expected of species adapted to stable habitats in that females produce every large numbers (200,000 – 17,000,000) of small young (size = 50–450 µ m) (McMahon 2002). Females retain eggs in marsupial chambers within the exhalant water channels of their outer gills where they are fertilized by sperm carried to the inhalant currents (McMahon 2002). After fertilization, eggs develop into a small, externally released, bivalved larva called a glochidium (plural = glochidia)(McMahon and Bogan 2001). The glochidium is parasitic on specific fish hosts, encysting in their fins or gills for periods of less than 200 days to more than 1000 days depending on species, allowing dispersal and growth to a more competitive size before excystment as a free-living juvenile (Bauer 1987, 1992). Thus, elevated fecundity and small offspring size in unionoideans are adaptations that ensure a sufficiently high probability of glochidial contact with appropriate fish hosts to maintain adequate juvenile recruitment (McMahon and Bogan 2001). Low success of glochidial host-fish contact, high levels of host-fish immune rejection of encysted glochidia, and host-fish mortality before excystment of the transformed juvenile allow only a tiny fraction of released glochidia to transform into relatively large well-developed juveniles (McMahon 2002). Thus, the effective fecundity of unionoidean species is quite low and leads to production of a few, large, well-developed offspring (i.e., excysted juveniles), a characteristic of K -selected species from stable habitats (Sibly and Calow 1986). Mussel fertility may increase with increasing food supply and usually increases with mussel size. Since young mussels grow asymptotically, fertility increases with age (Bauer 1998, Bauer and K. Wachtler 2001). Unionoid taxon specific glochidial host-fish species are often closely associated with their preferred adult habitat (McMahon and Bogan 2001), increasing chances for excystment of juveniles into habitats favorable for survival to maturity. However, utilization of fish hosts associated with habitat of the adult reduces chances for long-distance juvenile dispersal. Limited dispersal capacity is hypothesized to have resulted in high levels of diversity and endemism within the North American unionid fauna (McMahon and Bogan 2001). Extended life spans, delayed maturity, low effective fecundities, reduced powers of dispersal, high habitat selectivity, poor juvenile survival, and long turnover times make unionoidean populations highly susceptible to human perturbations (Strayer et al. 1999; McMahon and Bogan 2001, McMahon 2002). These unionoidean life-history traits (particularly long life spans and low effective fecundities) slow population recovery from human- or naturally mediated habitat disturbances (Strayer et al. 1999; McMahon and Bogan 2001, McMahon 2002).

O'Brien et al. (2013) found that *Anodonta californiensis* was gravid from early May to late July in the Middle Fork John Day River, Oregon. Mature glochidia were hooked, rust-colored, sub-triangulate, averaged 276 µm in length. *Margaritifera falcata* were gravid in early May and their glochidia were hookless, white, sub-round, and averaged 55 µm in length (O'Brien et al. 2013). They found *Anodonta californiensis* glochidia attached to six wild-caught fish species from early June to late July and in laboratory experiments, speckled dace (*Rhinichthys osculus*), longnose dace (*R. cataractae),* and margined sculpin (*Cottus marginatus*) were likely hosts. O'Brien et al. (2013) did not observe any *M. falcata* glochidia on fish in the river or in their experiments.

Flood events can also cause high mussel mortality and reduce population viability. Vannote and Minshall (1982) concluded that the long-term population dynamics of the long lived *Margaritifera falcata* is mainly caused by periodic floods, perhaps approaching 50 to 100-year flood events, which cause high mussel mortality due to bed scour (Bauer and Wachtler 2001). Alternatively, excessive sedimentation often leads to increased mortality of newly settled juveniles (Bauer 1991; Bogan 1993, Bauer and Wachtler 2001).

Population Ecology and Metapopulation Viability

The viability of native mussel populations is dependent on many factors including population dynamics, life histories, predation, and interspecific competition. Several of these factors are discussed in the following section.

Glochidial success, fish host abundance, and mortality rates

The rate of successfully attaching glochidia has been estimated at comparable secondary fish host densities of 4.5 per $10m^2$ and 5.3 per $10m^2$ for *M. margaritifera* and *A. grandis simpsoniana* (Bauer 1988, Jansen and Hanson 1991, and Jansen et al. 2001, Bauer and Wachtler 2001), which seems to be a reasonable estimate for *M. falcata* and *A. californiensis/nuttalliana*. Martel and Lauzon-Guay (2005) found that fishes such as sculpins and sticklebacks that co-occurred most often with *Anodonta kennerlyi* in lakes in British Columbia had the highest density of glochidia. These studies further support the obvious supposition that there is a strong relationship between abundances of secondary fish hosts and glochidial success. For example, based on the survival rate values estimated in Bauer and Wachtler (2001), approximately 960 to 1135 suitable fish hosts need to be residing in the sections of Mill Creek surveyed for this report, which seems unlikely because Mill Creek is poor fish habitat and mostly dominated by carp which aren't considered secondary hosts for native mussel glochidia and are efficient predators of Anodonta juveniles.

Unionoida mortality rates are so high because of the inefficient mode of host infection (Bauer and Wachtler 2001). Estimated survival of the glochidia in the Bauer 1988, Jansen and Hanson 1991, and Jansen et al. 2001 studies was about 7 per million for *M. margaritifera* and 70 per million for *A. grandis simpsoniana*. The reason *Anodonta* survival was an order of magnitude greater than *Margaritifera* was likely due to *Anodonta* 's ability to use more secondary host species than *Margaritifera* and their ability to perceive the presence of hosts (Bauer and Wachtler 2001). Mortality rates for juvenile *Margaritifera margaritifera* after releasing from fish hosts were estimated to be 95% per year just due to juveniles falling off secondary fish hosts into unfavorable habitats (and possibly predation). (Young and Williams 1984b, Bauer and Wachtler 2001)(Figure 101). It was estimated that out of every billion glochidia produced, only ten *M. margaritifera* survive to age 1 and up to 18,000 of out of every billion glochidia produced by *Pyganodon grandis* (formerly *Anodonta grandis*) can survive to age 2 years (Bauer and Wachtler 2001).

Maximum drift distances of glochidia in a typical *M. margaritifera* stream with an average current speed of 0.4 m/s are most likely limited to a few hundred meters (Bauer and Wachtler 2001). Wenz (1990) found that juvenile trout caught within a mussel bed were all infested with glochidia, whereas fish captured 500 m downstream of the bed were free of glochidia. In addition, glochidial survival times may only range from 2 to 14 days between release from the marsupia and until they come into contact with a suitable host (Mackie 1984, Bauer and Wachtler 2001). Therefore, it appears that not only is there a need for a large abundance of fish hosts present at the right time and distance but there needs to be an adequate number of mussel beds for Utah's native mussel populations to remain viable. Other than predation by molluscivorous fish and Corbicula and interspecific competition with Corbicula, this phenomenon is perhaps the most critical factor in the drastic loss of Anodonta and Margaritifera populations in the Jordan River-Utah Lake and needs to be fully understood and incorporated into any assessment population viability.

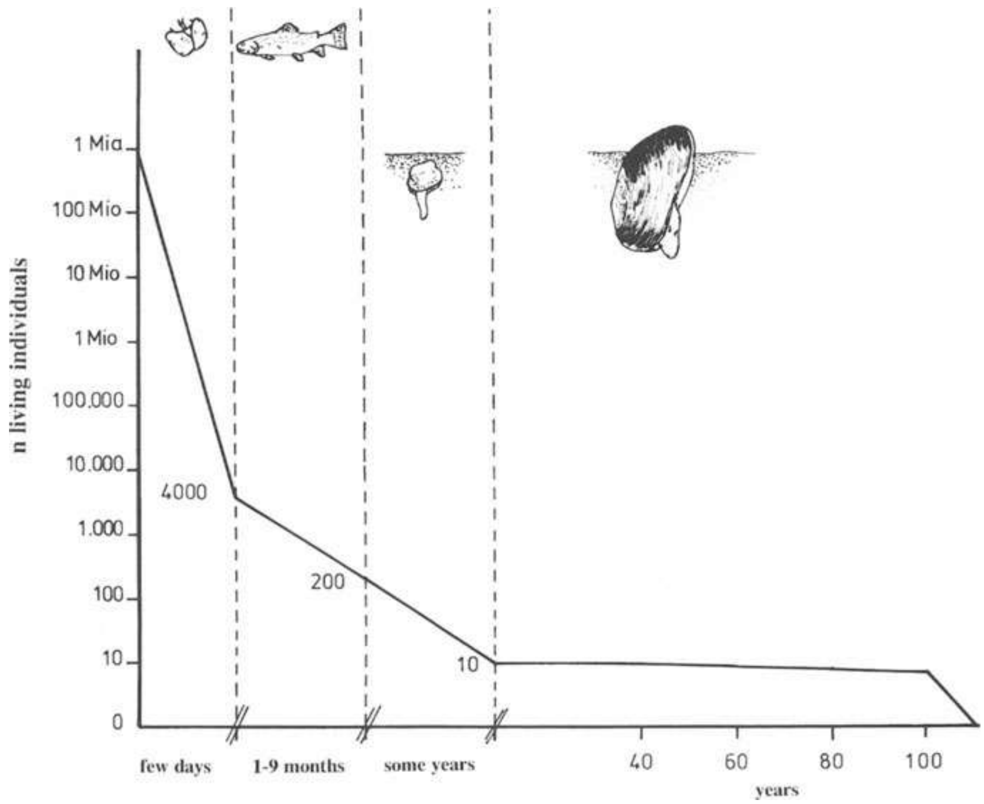


Figure 101. Approximate survivorship curve of the freshwater pearl mussel, M. margaritifera (from Bauer and Wachtler 2001). This is a typical survivorship curve for most unionids although Anodonta reaches maturity much faster and is shorter lived than *M. margaritifera*.

Predation

Carp

Invasive carp (*Cyprinus carpio*) are also known to be highly efficient apex predators on mollusks (Strayer 2008). Carp can have devastating population reduction effects on mollusks, including native mussels and can even prevent Corbicula from becoming established into a waterbody (Robinson and Wellborn 1988, Kelvin et al. 2014, Bowers et al. 2005, Tucker et al. 1996). Unfortunately, carp are one of the most abundant fish species in the Utah Lake/Jordan River drainage and fisheries biologists have estimated carp biomass in Utah Lake to exceed 20 million pounds. If nothing else, their sheer abundance in Utah Lake may be the primary cause of Anodonta extinction from Utah Lake and the also the reason that Corbicula occurs at such low abundances in the lake. Carp are notorious bottom feeders, rooting and consuming anything edible likely including any relatively soft shelled Anodonta juveniles (compared with hard shelled Corbicula) that are small enough to be consumed. Carp are also well established throughout most water bodies in the Jordan River-Utah Lake drainage and certainly prey on native mussels whenever the opportunity arises.

Muskrats

Muskrats are one of the primary natural predators of *Anodonta* and *M. falcata*. (Bauer and Wachtler 2001). Hanson et al. (1989) found that muskrats consumed 5.8% of the biomass and 31% of the annual production, and from 6 to 21% of the glochidia of *Anodonta grandis* in a lake in Alberta. Muskrats may be also be highly selective due to mussel taxon-specific shell thickness and differences in energetic value (meat weight)(Zahner-Meike and Hanson 2001, Bauer and Wachtler 2001). Therefore, *Anodonta* are more likely to be selectively preyed upon by muskrats than the invasive Asian clam, *Corbicula*, given their much greater energetic value (e.g. much larger size)(Hanson et al. 1989) and thinner shell. Foraging success of muskrats is expected to be greatest on mussel assemblages in small rivers (Bauer and Wachtler 2001). This does not bode well for the remaining known populations of *Anodonta* in small Beer Creek and *M. falcata* in small Beaver Creek because muskrats are common in both creeks, or for any other undiscovered mussel populations in the Jordan River-Utah Lake drainage. Muskrats as witnessed by their middens, are known to consume large numbers of bivalves, particularly Corbicula within the drainage (Figure 102- Figure 104).

Figure 102. Muskrat midden comprised entirely of Corbicula on the Jordan River @ 3300 South and within 1 km of Mill Creek. No native mussel shells were found in this midden (Photo courtesy of W.D. Robinson, Salt Lake City, UT, November 2015).

Figure 103. Close-up of muskrat midden consisting entirely of Corbicula on the Jordan River @ 3300 South and within 1 km of Mill Creek. No native mussel shells were found in this midden (Photo courtesy of W.D. Robinson, Salt Lake City, UT, November 2015).

Figure 104. Empty *Anodonta* shell broken by predator (likely muskrat or raccoon) from Beer Creek, UT August 2015

Other predators

Additional predation likely occurs from other species in the drainage including introduced and native molluscivorous fish and filter feeding of glochidia by Corbicula. Filter feeding on free-floating glochidia by Corbicula may account for high mortality rates to remaining native mussel populations when this invasive species is abundant and cause other problems (see Competition, Predation, and the Invasive Ecosystem Engineer, Corbicula section below). Fortunately, we did not find any Corbicula in Beer Creek at the *Anodonta* location or any in Beaver Creek near the *M. falcata* location. However, Corbicula is very abundant throughout the Jordan River-Utah Lake drainage and is extremely abundant in Currant Creek, a tributary to Utah Lake, and one of the few remaining reported Anodonta populations. Invasive crayfish are also known predators on unionids (Strayer 2008). Crayfish are not native to Utah Lake/Jordan River drainage but have recently invaded and are now frequently observed and likely will spread throughout the drainage. Invasive crayfish are now abundant in many sections of the Jordan River (D. C. Richards, personal observation). Tanypodinae midges and oligochaete worms are also potential predators of juvenile mussels in the sediments (Strayer 2008). Both invertebrates are highly abundant in the Utah Lake/Jordan River drainage and are usually the most dominant taxa in Mill Creek (Richards unpublished data).

Parasites and Diseases

There is limited data on parasites and diseases that may affect Utah's native mussel populations. However, digenetic trematodes may completely prevent mussel reproduction when their densities are high (Strayer 2013). Bacterial and viral disease outbreaks can eliminate mussel populations (Neves 1987, Strayer 2008). Given the poor condition of many waters in the drainage, parasites and diseases cannot be ruled out as not being detrimental to mussel survival.

Competition, Predation, and the Invasive Ecosystem Engineer, Corbicula

Regarding invasive species, Charles Elton in his seminal book, The Ecology of Invasions by Plants and Animals (1958) stated:

> "We must make no mistake: we are seeing one of the great historical convulsions in the world's fauna and flora."

Scientists studying invasive species have called this phenomenon, 'The Great Homogenocene' or the 'New Pangaea', where loss of native species and the preponderance of invasive species is resulting in a world with much fewer but globally wide- spread species. Overall, invasive species are considered to be the second greatest threat to imperiled species in the United States, after loss of habitat (Wilcove et al. 1998). There is a vast amount of scientific literature on invasive species driving local native species to extinction and it has been well documented that of all ecosystems, lakes and streams have been most affected (Mooney and Cleland 2001). One only has to look at the tremendous negative ecosystem effects that invasive carp are having on the waters in the

Jordan River-Utah Lake drainage to understand this threat. Contrarily, and almost without notice, is the major effects that invasive Asian clams, Corbicula are having on waters in the drainage. Corbicula are highly invasive, competitive, predacious on native mussel glochidia, and are dominant ecosystem engineers once they become fully established and they are well known to alter nutrient cycling and ecosystem function (see following sections).

Anodonta and Margaritifera in the Jordan River-Utah Lake drainage evolved without interspecific competition, except where populations of these two species overlapped and in habitats that were suitable for both. Of course, Anodonta and Margaritifera no longer have populations that overlap in the drainage (i.e. Margaritifera is presumed extinct in the drainage or possibly limited to small isolated populations in headwaters; whereas Anodonta is now limited to small isolated populations in lower elevation streams and ponds in the drainage). Anodonta and Margaritifera may be poorly adapted to compete with Corbicula for food resources and habitat via niche displacement and competitive exclusion, particularly Anodonta because it has a similar niche to Corbicula. Interspecific competition has long-been theorized to cause extinctions of small isolated populations, including metapopulations, since Darwin's 'On the Origin of Species', MacArthur and Wilson's 'Theory of Island Biogeography' published in 1967 and Moulton and Pimm (1986) and has unequivocally been shown to occur in field experiments (Bengtsson 1989).

It is unknown when Corbicula first invaded the Jordan River-Utah Lake drainage but it was first reported in Utah in Sevier Lake in 1978 (Counts 1985). It has only been recorded in Colorado since 1993 but is expected to have negative impacts on Colorado's native mussels once it becomes established (Cordeiro et al. 2007). The earliest records we have found for the Jordan River were from 2001, documented by the USU buglab MAPIT website, however their data was based on sampling methods that were not specifically designed for bivalve detection and we assume that based on their reported methods, Corbicula was likely well established by then.

Corbicula is a very rapid colonizer. Once established it can rapidly spread throughout a river drainage and become the dominant mollusk taxon. For example, it took only 5 years for Corbicula to invade and then to completely dominate the Potomac River and Chesapeake Bay (NEMESIS website accessed April 29, 2017). If Corbicula invaded the Jordan River-Utah Lake drainage circa mid to late 1990's or even a decade earlier, its negative effects on Anodonta still will not have been fully realized. It takes many generations to see an effect of an invasive species, particularly a complete extinction. Elton (1958) stated it would take 50 to 100 years to see the full effects of an invasion.

To fully understand the effects Corbicula on remaining native mussel populations in the Jordan River-Utah Lake drainage, a more complete understanding of theirs and native mussel life histories is required than what was presented in the previous sections: *Unionoida Life History* and *Glochidial success, fish host abundance, and mortality rates.*

The following literature review with interlaced comments was conducted in response to the high densities of the invasive Asian clam, *Corbicula* sp. that we found throughout the survey and its likely negative impacts on native mussels in the Jordan River-Utah Lake drainage. This review describes *Corbicula* sp. and native bivalve, biology, life history, ecology, and known and assumed impacts of *Corbicula* sp. on the native mussels.

Bivalve mollusks (clams and mussels) are dominant filter feeders that often make up most of the biomass and exert control over ecosystem structure and function of many streams (Dame, 1996; Strayer et al., 1999). Production by bivalves (range from 1 to 20 g dry mass m^2/ year) can equal that of all other macrobenthos in many stream systems (Strayer et al., 1994) and can rival other highly productive systems such as tropical rainforests and kelp beds (Leigh et al., 1987). Aggregations (beds) of bivalves can also alter light, temperature, sediment loading and deposition, and water circulation patterns (Dame, 1996; Seed, 1996; Wildish & Kristmanson, 1997). Bivalves remove particles from the water column, excrete nutrients, and biodeposit feces into the sediment layer. Filtration by bivalves has been shown to lead to a large decrease in phytoplankton and other particles in the water column (Kasprzak, 1986; Kryger and Riisgaerd,1988; Welker and Walz, 1998; Strayer et al., 1999) and has the greatest effects on ecological processes when their biomass is large (Strayer 1999). This is likely the case with *Corbicula* sp. in the Jordan River and other tributaries because their biomass can be quite large.

Welker and Walz (1998) and Vaughn et al. (unpublished data) have found that the volume of water filtered by unionid mussels within dense beds can equal or exceed daily stream discharge. Welker and Walz (1998) reported that filtration by unionids in the River Spree, Germany, caused `biological oligotrophication' by decreasing phytoplankton biomass and total phosphorus, thus increasing water clarity. *Corbicula* sp. also has the ability to influence phytoplankton abundances and water clarity (Cohen et al., 1984; Phelps, 1994). In fact, Strayer et al. (1999) and Dame (1996) have suggested that <u>any</u> assemblage of bivalves may significantly influence phytoplankton concentrations when filtration rates are large relative to food supply.

Bivalves can filter and consume interstitial bacteria (Mitropolskij, 1966; Lopez & Holopainen, 1987, Say, 1829). Some species of native clams have elongated inhalant siphons to vacuum detrital particles from the streambed surface (Way 1989). Pedal feeding is another form of deposit feeding and has been observed for juvenile unionids. For example, during the first 18 months or so, juvenile *Margaritifera margaritifera* (Unionidae) pedal feed by using cilia on their foot to move small particles into their mantel cavity. However, most adult unionids do not pedal feed. Pedal feeding unionid juveniles have been shown to grow faster when able to feed in sediment as compared with filter feeding alone (Hudson and Isom, 1984;Yeager et al. 1994; Gatenby et al. 1996). *Corbicula* can both pedal and filter feed as adults (Reid et al., 1992) and can decrease sediment organic matter concentrations when very little planktonic food is available (Cleland, 1988; Hakenkamp and Palmer, 1999). Even though bivalves can filter the daily discharge of a stream, deposit feeding may also provide a significant proportion of total food energy (Raikow and Hamilton 2000).

Unionids in Lake St Clair (Nalepa et al., 1991) and a Polish lake (Lewandowski& Stanczykowska, 1975) filtered large quantities of seston much of which was which in turn biodeposited to the sediments. *Corbicula* is associated with significant increases in nearby sediment organic matter concentrations (Hakenkamp and Palmer, 1999) and has been shown to increase sediment concentrations by as much as 25 to 30% (Prokopovich, 1969). It is unknown how much sediment concentrations the *Corbicula* sp. population deposits in the Jordan River-Utah Lake, but we propose that Corbicula are now driving the Jordan Rivers nutrient budget, nutrient spiraling, sediment organic matter concentrations, and are central to its ecosystem functioning.

Bivalves act as 'top-down' controls on phytoplankton and can reduce turbidity caused by phytoplankton (Newell 2004). Excreted nitrogen and phosphorus and regenerated from biodeposits can then be recycled back to the water column and support phytoplankton production (Newell 2004). Some of the original N and P that were excreted can become buried in the accumulating sediments. Coupled nitrification-denitrification can permanently remove N from the sediments as N_2 gas from the aerobic sediment layers that overlay deeper anaerobic sediments via microbial activity (Newell 2004). Bivalves can also reduce phytoplankton production by curbing anthropogenic N and P in eutrophied aquatic systems. However, biodeposition at very high bivalve densities may be so intense that resulting microbial respiration can reduce the oxygen content of the surrounding sediments and can inhibit coupled nitrification-denitrification (Newell 2004). This can cause P to become unbound and released to the water column, and result in a toxic buildup of H_2S (Newell 2004). We propose that all the nutrient dynamics in the Jordan River are either directly or indirectly governed or affected by Corbicula.

Corbicula is usually assumed to be a non-selective feeder (Lauritsen, 1986; Way et al.,1990) and can physiologically adjust its filter-feeding rate in response to food availability and a wide range of particle concentrations (Way et al., 1990). Contrarily, many unionids are more selective in terms of the size of particles consumed (Newell 2004). Therefore, *Corbicula* would be less impacted than other bivalves when any one type of resource becomes limiting (Newell 2004). Not all bivalve species have similar feeding mechanisms and behavior and may use different food sources in different habitats (Newell 2004).

Freshwater bivalves produce hypo-osmotic urine, primarily NH_3 (Burton 1983). Williams and McMahon (1989) showed a 20 to 40-fold increase in NH_3 excretions during *Corbicula* spawning activity. Extremely high densities of *Corbicula* sp. in sections of the Jordan River may thus be a significant ammonia source, particularly when they are most active, especially during spawning periods. *Corbicula* excretory products are also likely important and readily useable resources for phytoplankton by other organisms (James 1987, Lauritsen and Mozley 1989). In addition, Fisher & Matis (1985) found that bivalve burrowing activities can indirectly influence nutrient cycling by enhancing the rate of nitrate release in sediments. Phosphorus recycling by bivalves may be sufficient to shift the phytoplankton community structure towards nitrogen-limited cyanobacteria (Strayer 1999, Newell 2004).

Bivalves may serve as a nutrient source when their biomass is declining and when populations release more nutrients than they absorb (Strayer 1999, Newell 2004). Bivalves may serve as a nutrient sink while a population is growing (i.e. accumulating biomass) or if biomass is being lost from the ecosystem (Strayer 1999, Newell 2004).

Corbicula Life History

Corbicula sp. burrow in the substratum and filter and deposit feed, however, they differ from unionids in many important ways (Vaughn and Hakenkamp 2001). *Corbicula* are less sedentary, shorter-lived (1 to 5 year), grow rapidly, mature earlier, reproduce two to three times per year, and disperse both actively and passively throughout their life cycle (Prezant and Chalermwat, 1984; McMahon, 1991). Like unionids, *Corbicula* often occurs in dense aggregations that can consist solely of *Corbicula* or be intermixed with native assemblages (Vaughn and Hakenkamp 2001). *Corbicula* biomass can far exceed that of all other benthic invertebrates in sandy streams (e.g. Jordan River)(Poff et al. 1993). *Corbicula* are typically smaller than unionid bivalves but have markedly greater mass-specific filtration rates (Kraemer, 1979; Mattice, 1979; McMahon, 1983) and typically higher abundances (Kraemer, 1979; McMahon, 1991). This results in community filtration rates that often exceed those of native bivalve assemblages (Strayer et al., 1999; Vaughn and Hakenkamp 2001).

Arguably, *Corbicula* sp. are the most invasive of all freshwater bivalves (McMahon 1999). As stated earlier, *Corbicula* are adapted for rapid population growth, including traits such as rapid individual growth, early maturity, short life spans, a limited number of reproductive periods, high fecundities, small egg–offspring size, and extensive dispersal capacity (McMahon 2002). Such traits are generally characteristic of r-selected species that are adapted to unstable habitats and where intraspecific competition is low or unlikely due to frequent population density reductions or extirpations associated with unpredictable, catastrophic, natural environmental events (Sibly and Calow 1986, McMahon 2002).

Corbicula sp. grow rapidly, in part because they have higher filtration and assimilation rates than other freshwater bivalve species (McMahon 2002). Only a relatively small proportion of their assimilation (29%) is devoted to respiration, the majority (71%) being allocated to growth and reproduction. This species allocates a high proportion (85–95%) of non-respired assimilation to growth, allowing individuals to reach 15–30 mm in shell length in the first year of life and 35–50 mm in the terminal third to fourth year (McMahon 1999). Thus, *Corbicula* sp. has the highest net production efficiencies recorded for any freshwater bivalve, reflected by short turnover times of 73–91 days (McMahon 2002). Newly released juveniles of *Corbicula* sp. are small (shell length ≈ 250 µ m) but completely formed, with a well-developed, bivalved shell, adductor muscles, foot, statocysts, gills, and digestive system (McMahon 2002). They anchor to sediments or hard surfaces with a mucilaginous byssal thread but can be re-suspended in turbulent flows to be dispersed long distances downstream (McMahon 1999). A relatively low percentage of non-respired assimilation in *Corbicula* sp. is allocated to reproduction (5–15%, equivalent to that expended by unionoideans); however, its elevated assimilation rates allow higher absolute energy allocation to reproduction than in other freshwater bivalves (McMahon 2002). Fecundity is high, estimated at almost 70,000 juveniles on average per adult per year (Aldridge and McMahon 1978). Juvenile survivorship, while higher than that of unionoideans, is still low, and unlike unionoideans, mortality rates remain high throughout adult life (74–98% in the first year, 59–69% in the second year, and 93–97% in the third year of life) (McMahon 2002). Low adult survivorship leads to populations dominated by juveniles and immature individuals (McMahon 1999). Most North American *Corbicula* sp. populations have two annual reproductive periods (i.e., spring through early summer and late summer through early fall; McMahon 1999). *Corbicula* fluminea is hermaphroditic and self-fertilizing (Kraemer et al. 1986), allowing single individuals to found new populations. Maturation occurs within 3 to 6 months at a shell length of 6–10 mm, thus spring-born juveniles can participate in autumn reproduction (McMahon 2002). Maximum life span is highly variable, ranging from 1 to 4 years, within which early maturity and bivoltine reproduction allows individuals to participate in one to seven reproductive efforts (McMahon 2002).

Effects of Corbicula on Native Bivalves

Invasive *Corbicula* are assumed to have negatively impacted native bivalve abundance and diversity throughout North America and have the potential to affect native unionids in several ways (Gardner et al.1976, Taylor and Hughart 1981, Clarke, 1988, Araujo et al. 1993, Williams et al. 1993, Strayer 1999, Aldridge & Muller 2001, McMahon 2002, Sousa et al. 2005, 2006a, 2006b, 2007b, 2008, in press, and Vaughn and Hakenkamp 2001). *Corbicula* have been accused of greater impacts on the native bivalves of North America than any invader, other than the zebra mussel (Strayer 1999). At very high density the burrowing activity of *Corbicula* may uproot unionids in sandy sediments (Fuller & Richardson, 1977). *Corbicula* may also suspension and deposit feed on juvenile unionids, which may negatively impact juvenile unionid recruitment (Yeager et al., 1994; Vaughn and Hakenkamp 2001). Strayer (1999) suggested that *Corbicula* may compete for benthic food resources with sphaeriids (native fingernail clams) and juvenile unionids, and that bioturbation by *Corbicula* could reduce available habitat. *Corbicula* also have much greater filtration rates (on a per biomass basis) than sphaeriids or unionids (McMahon, 1991) and thus have the potential to limit availability of planktonic food to native bivalves (Vaughn and Hakenkamp 2001). *Corbicula* allocate a higher percentage of non-respired energy to somatic growth than unionids (McMahon, 1991) and with their ability to deposit feed have broader diet breadths than is known for unionids (Vaughn and Hakenkamp 2001) particularly when there is little food available in the water column or when flow conditions make suspension feeding difficult (e.g. during floods) than is known for unionids (Vaughn and Hakenkamp 2001). Deposit feeding by *Corbicula* is likely to have contributed to their invasion success, especially in streams with smaller sediment sizes (e.g. sandy streams) that would allow easy burrowing and feeding (Vaughn and Hakenkamp 2001) (i.e. Anodonta habitat).

Reductions in native bivalve populations have been documented to coincide with the arrival of *Corbicula*. Gardner et al. (1976) found precipitous declines in populations of native bivalves that coincided exactly with the explosive growth of a *Corbicula* population in the Altamaha River, Georgia. Although dense populations of *Corbicula* and unionids are often seen to apparently be coexisting (Clarke 1988, Miller and Payne 1994); declines in recruitment or growth may not be apparent for decades (Elton 1958). Detailed information on the density and recruitment of native bivalve populations before and after the *Corbicula* invasion is required to fully understand competitive effects.

If bivalves perform similar ecological processes at similar rates (i.e. they are `functionally redundant' sensu Walker, 1992), the replacement of native mussels by Corbicula may make little difference in an ecosystem context, as long as the overall bivalve biomass is maintained. If species play distinct roles, however, this loss of biodiversity may permanently alter ecosystem functioning. In many rivers *Corbicula* biomass may replace, or compensate for, lost unionid biomass. If *Corbicula* functions in a manner similar to unionids, then the decline in bivalve biodiversity may have little impact on the functional roles of mollusks in these systems. However, it is more likely that these taxa have distinct roles and functions. While unionids and *Corbicula* share many functional roles, differences in the range of processes and the rates at which these processes are performed may be leading to a dramatic shift in the current functional role of burrowing bivalves in the Jordan River-Utah Lake drainage (Vaughn and Hakenkamp 2001). In the case of the highly-perturbed Jordan River and other tributaries in the drainage, *Corbicula* is now the dominant bivalve and conditions may not be suitable for native unionids to exist, as long as Corbicula populations thrive.

There is some scientific literature that suggest that native unionids and Corbicula can coexist, however most of these findings are based on large spatial scales (Vaughn and Spooner 2006). At small spatial scales such as those in the Jordan River-Utah Lake where native mussel populations are highly fragmented and isolated and relegated to small areas, native mussel abundances are often negatively related to Corbicula abundances (Vaughn and Spooner 2006). Vaughn and Spooner (2016) hypothesized that successful Corbicula invasion likely decreases with increasing abundance of adult native mussels and that lack of space for Corbicula to colonize, physical displacement by actively burrowing mussels, and locally reduced food resources in patches where native mussels are feeding were the likely mechanism preventing Corbicula establishment. The opposite of what Vaughn and Spooner suggested should also hold true: When native mussel abundances are low, then Corbicula are more likely to invade and eventually dominate.

Food limitation

As with all organisms, food limitation can reduce *Anodonta* and *Margaritifera falcata* population viability. However, it is unknown if food limitation was partially responsible for the disappearance of these taxa from past suitable habitats in Utah and specifically the loss of populations in the drainage. Certainly, food availability in oligotrophic Beaver Creek has some influence on *M. falcata* population dynamics but may not be a problem for Anodonta in the drainage. Human caused nutrient enrichment, including from water treatment facilities, has been shown to increase growth rates and fertility of unionids via increased primary production and increased food resources (Strayer 2008). Most Jordan River-Utah Lake waters are certainly not nutrient limited. Anodonta individuals observed in Beer Creek were substantially larger than most Anodonta empty shells that we found in other locations in UT during surveys, indicating that they were either very old or were growing rapidly, or both (Figure 105).

Figure 105. Live Anodonta from Beer Creek, UT. Note large size and growth rings suggesting this population is not food limited.

The absence of smaller individuals and size classes in Beer Creek suggest that successful reproduction and survival to adulthood was not occurring. Several reasons could have caused this absence of size classes other than large adults including: absence of suitable secondary fish hosts, unsuitable conditions for juvenile mussel survival, or smaller mussels were present but not observed. The latter seems unlikely because once the small isolated population of large *Anodonta* in Beer Creek was discovered, intensive surveys ensued. Beer Creek is a small creek and almost an entire section of it was censused for about 1 km upstream and 1 km downstream. No other mussels were found.

Unionids in Mill Creek and the Jordan River if they occur also do not appear to be food limited. Contrarily, these waters appear to contain more than enough abundance of food items such as phytoplankton, zooplankton, and bacteria as they are predominately receiving waters from hyper eutrophic Utah Lake. However, large green algae or cyanobacteria blooms could have severe detrimental effects including cessation of feeding activities, reduced fitness, or even increased mortality rates (see section: ***Inorganic Suspended Matter***). The only obvious potential food limitation in Mill Creek/Jordan River would be from the large populations of Corbicula filtering and competing for food resources (Strayer 2008, Richards 2015). The effects of Corbicula filterer feeding in the Jordan River are obvious starting from phytoplankton laden water entering from Utah Lake in the river to low levels of phytoplankton throughout the mid reaches where Corbicula dominate the benthos (Richards personal observation and unpublished data, UDWQ unanalyzed data).

Substrate Habitat

Unionids, particularly juveniles, need substrate habitat that is 'just right', not too hard and not too soft (Strayer 2008). Much of Jordan River-Utah Lake drainage waters substrates are soft organic matter, silt, and clay. This can make it very difficult for juvenile mussels to survive and could reduce their viability. It is also not the best substrate habitat for adults either (Strayer 2008). For example, Utah Lake, a potential source of dispersing mussels (in the off chance that any exist), has basically two types of substrate habitat; very soft silts in the deeper portions of the lake and hard pack clays along the shorelines. Both types of substrates are poor habitat for Unionids (Strayer 2008). Although we did not survey areas of Utah Lake other than wadeable shoreline areas for mussels, we are in the process of conducting an intensive nutrient and food web study of the lake including areas with depths that can only be accessed via boat. We have made semi quantitative estimates of substrate depths at many of sample locations in Utah Lake and invariably the very soft substrate in many locations is $\geq$ 1.0 m thick. This soft substrate would likely not support any Unionids, adults or juveniles. In addition to the hard pack clays along Utah Lakes shorelines, which are poor mussel habitat, the lake shoreline fluctuates greatly seasonally and yearly depending on a variety of factors not the least of which is irrigation water demands. Unpredictable wetting and drying are not suitable habitat for mussels (Strayer 2008). Therefore, it appears that most of Utah Lake's substrate is currently poor mussel habitat. Poor substrate habitat combined with no known extant populations of mussels in Utah Lake preclude it as a potential source of recruitment to Mill Creek or the Jordan River, regardless of whether their habitats are now suitable or continue to be unsuitable. It is unknown if Utah Lakes substrate differed from what is observed today and what it was pre-settlement @ 1850's however, there appears to have been major sediment loading since settlement.

Water Quality

Water quality including oxygen depletion, NH_3, metals, and other toxicants can affect mussel viability (Strayer 2008). These toxicants can be particularly detrimental to juvenile mussels residing in the sediments where concentrations are often an order of magnitude greater than the surface water (Strayer 2008). As an example, the anoxic layer of Mill Creek sediments and the Jordan River sediments in surveyed reaches are often < 3mm below the sediment surface and likely would prevent establishment of juvenile mussels in the unlikely event that they were to be released by a migrating infected fish. Heavy inputs of silt and clay can reduce sediment permeability and reduce interstitial oxygen further contributing to unsuitable conditions for juvenile recruitment. In addition, upstream sections of Mill Creek as well as most Jordan River-Utah Lake drainage tributaries flow through heavily urbanized landscapes. Mill Creek also passes under Interstate 15, and through the Union Pacific rail yard. These areas likely contribute toxicants into Mill Creek sediments and would also likely prevent establishment and viability of mussels. There is a historic legacy of toxicants in many waters of the Jordan River-Utah Lake drainage. Methane also appears to be a recently acknowledged problem (Dr. Theron Miller, WFWQC, personal communication) however, we don't know what the relationship is between methane production and Corbicula densities but suspect it is relevant.

Ammonia and Present Distributions of Unionoida in Utah Lake Drainage

Ammonia is known to negatively affect Unionoida viability (Strayer 2008, USEPA 2013a). However, there is no evidence that ammonia toxicity was a direct factor resulting in the decline of native mussel populations in UT or that ammonia is affecting remaining populations. Given our limited knowledge of comparative *Anodonta* and *M. falcata* life history and ecology, we suggest that *M. falcata* may possibly be more sensitive to ammonia than *A. californiensis/nuttalliana.* There is only one known small population of *M. falcata* in the Utah Lake drainage area (Beaver Creek), therefore determining the effect of ammonia on its present distribution and viability or inferring ammonia effects on past distributions is not possible. However, ammonia concentrations taken at three locations during mussel surveys in Beaver Creek on July 30, 2015 ranged from 0.20 to 0.39 mg/L, which are very low. Alternatively, ammonia concentrations taken at two locations with known *Anodonta* populations, Beer Creek and Salt Creek, had an order of magnitude greater values than did Beaver Creek; 2.30 mg/L (Beer Creek measurement August 20, 2015 at 1:25pm) and 1.84 mg/L (Salt Creek measurement July 28, 2015, time not recorded). This seems to indicate that *Anodonta* is somewhat more ammonia tolerant compared to *M. falcata* and is consistent with EPAs findings that species mean acute ammonia toxicity values within the family Unionidae can vary by 471% (range from 23.12 mg TAN/L to 109 mg TAN/L)(USEPA 2013a). Of course, *M. falcata* is not in the family Unionidae and given the tendency to rationalize sensitivities based on phylogenetic relationships, we would expect *M. falcata* sensitivity to ammonia to be less related to *Anodonta* than *Anodonta* sensitivity is to other members in the family Unionidae. Obviously, ammonia toxicity tests are urgently need on these two species. Ammonia concentrations can vary widely throughout the day, week, month, and location in a stream depending on many factors including the timing of irrigation return flows (our unpublished data, Appendices). This was the case for Beer Creek and Salt Creek, at the two locations where *Anodonta* survives. The morning NH_3 reading at the Beer Creek population on August 20, 2015 was 0.58 mg/L and a morning reading at the Salt Creek population on August 21, 2015 was 0.36 mg/L (Appendix 5).

Low NH_3 and native mussel absence from Spring Creek: Case Study example

NH_3 concentrations in Spring Creek, as expected were variable. At its source, NH_3 levels were not even detectable. Mill Pond NH_3 ranged from 0.01 mg/L to 0.49 mg/L on June 26, 2015. Spring Creek NH_3 levels downstream of Mill Pond ranged from non-detect to 0.17 mg/L on June 26, 2015, and between 0.84 to 1.05 mg/L on July 22, 2015 downstream of irrigation return flows to Utah Lake (Appendix 5). These levels suggest that NH_3 was not important in the disappearance of *Anodonta* from Spring Creek.

Other locations with NH_3 data collected during mussel surveys

We collected NH_3 data from many of the 2015 mussel survey locations (Appendix 5). Preliminary analysis showed that 49 out of 81 (60%) of the NH_3 readings had $NH_3 < 1.0$ mg/L, where *Anodonta* were absent (Figure 106). This is supportive evidence that NH_3 was not the root cause of their demise.

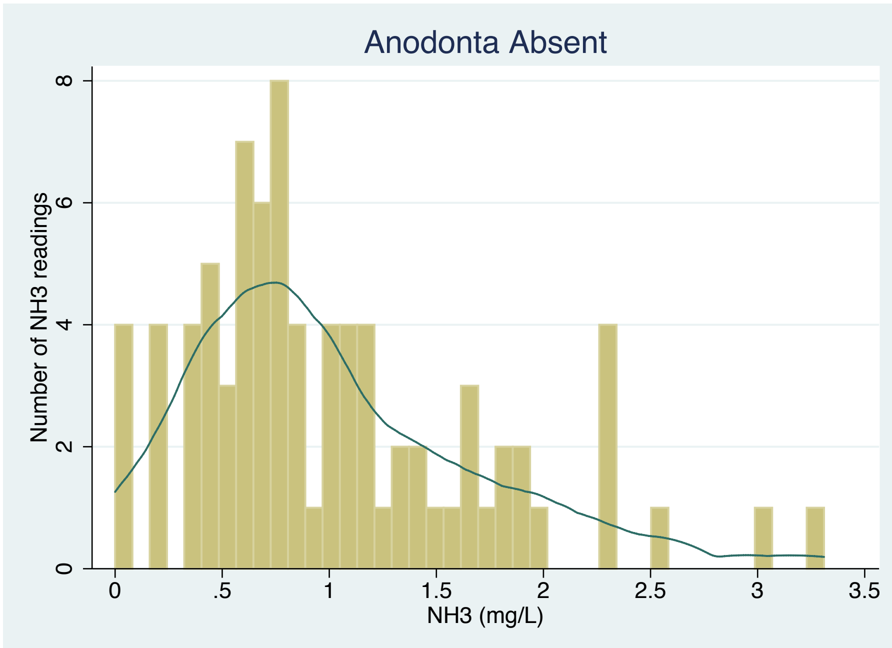


Figure 106. Preliminary analysis of relationship between locations where Anodonta were not found (absent) and NH_3 levels. 60% of the NH_3 readings were < 1.0 mg/L

Inorganic Suspended Matter

High concentrations of inorganic solids (sand, silt, clay, etc.) often originate from erosion related to agriculture, forestry, and urbanization, and can alter feeding patterns, substrate composition, and food web dynamics (Waters 1995). Concentrations of suspended inorganic matter (SIM)(e.g. suspended inorganic solids) are well known to affect mussel respiration, growth, parasite infestation and reproduction (Box and Mossa 1999, Robinson et al. 1984, Alexander 1994, Rosewarne et al 2013, and Tokumon et al. 2016). These effects subsequently can reduce native mussel population viability and increase extinction risk.

Feeding is strongly impeded for many filter feeding bivalves due to high levels of SIM (Robinson et al. 1984, Jorgensen 1996, Lei et al. 1996, Cheung and Shin 2005, Velasco and Navarro 2005, and Tokumon et al. 2016). The reasons for negative effects of SIM on mussel feeding are numerous and can include decreases in the proportion of organic material (i.e. food) in suspension, which can then result in much higher energy expenditures in sorting out and eliminating energetically unprofitable particles (Jorgensen 1990, Velasco and Navarro 2005, Safi and Hayden 2010). Tokumon et al. (2016) suggested that water pumping activity of the invasive bivalve, *Limnoperna fortunei* (Family Mytilidea) did not differ noticeably at different SIM concentrations, but at low sediment loads the production of pseudofaeces was moderate whereas at high concentrations mussels expelled mucus-embedded strings of material at noticeably higher rates. This indicates that the ability of mussels to sort and ingest organic particles from total suspended solids can be severely reduced by SIM (Robinson et al. 1984, Berg et al 1996, Baker et al 1998).

Gascho Landis et al. (2013) showed that total suspended solids (TSS) interfered with fertilization and caused reproductive failure of *Ligumia subrostrata* (Family Unionidae). They found that clearance rates dropped abruptly and remained uniformly low at a threshold level of total suspended solids > 8 mg l^{-1}. Gascho Landis et al. (2013) proposed that "reduced clearance rates could decrease the chance of females encountering suspended sperm during filter feeding, or an increase in pseudofeces production could bind sperm in mucus and lead to its egestion before fertilization". They also concluded that "interruption of fertilization coincident with high TSS (total suspended solids) is a potential mechanism to explain the lack of mussel recruitment in many locations".

TSS can have profound effects on reproduction. In the Gascho Landis et al. (2013) study, the percentage of brooding *Ligumia subrostrata* females decreased sharply with increasing TSS and complete reproductive failure occurred in hypereutrophic ponds with TSS > 20 mg l^{-1}. They found that the proportion of females that became gravid during the experiment was strongly related to TSS best characterized by an exponential decline. At the lowest mean TSS, most females were gravid, but this percentage declined rapidly with increasing mean TSS. No gravid unionid females were found at TSS >20 mg l^{-1} (Gascho Landis et al. 2013). Gascho Landis et al. (2013) also reported that *L. subrostrata* mussels were largely extirpated from lakes with the shallowest Secchi depths (hyper- eutrophic lakes), possibly indicating a threshold above which increased nutrients and resultant organic solids have a negative effect.

In other studies, decreased clearance rates (the volume of water cleared of particles per unit time) for 3 unionid species subjected to intermittent exposure to extremely high levels of suspended sediment was proposed as a cause of decreased growth or starvation (Aldridge et al. 1987). Recruitment strength of *Margaritifera margaritifera*, the European version of *M. falcata* was negatively related to turbidity and deposited sediment, but the mechanism for this relationship was unclear (Osterling et al. 2010). Others have also shown that unionid filter feeding is often disrupted at levels > 20 mg l^{-1} (Hornbach et al. 1984, Way et al. 1990).

Even relatively pollution tolerant invasive Asian clams (*Corbicula* sp.) and fingernail clams (Sphaerium) initiated pseudofeces production at 17 to 20 mg l^{-1} TSS (Fuji 1979, Hornbach et al. 1984, Way et al. 1990). Invasive Zebra mussels (*Dreissena polymorpha*) can initiate pseudofeces production at 27 mg l^{-1} (Lei et al. 1996, Schneider et al. 1998) and TSS loads dominated by inorganic particles can decrease their growth rates (Osterling et al. 2007).

SIM and Native Mussel Viability in the Utah Lake/Jordan River Drainage

Total suspended solids and increased salinity in Utah Lake and Jordan River proper, although relatively low compared to many other waters in the world (Meybeck 2003), have levels that are likely detrimental to native mussel viability. By itself, high levels of TSS could explain the absence of *M. falcata* and the near extirpation of Anodonta from this drainage. Combined with the other factors discussed in this report; the likelihood of recolonization of either mussel taxon in the drainage is infinitely approaches zero.

Jordan River Farmington Bay Water Quality Council researchers reported TSS levels of 56.3 mg l^{-1} (VSS = 11.7 mg l^{-1}) in Utah Lake at its outlet into the Jordan River. Background TSS levels are typically between 23 and 38 mg l^{-1} (VSS about 5 mg l^{-1}) downstream in the Jordan River. These TSS levels are well within and above the known ranges that have been shown to severely affect mussel reproduction. High levels of TSS in Beer Creek that supports one of the last remaining Anodonta populations could also partially explain why no apparent reproduction has been observed. TSS will likely continue to negatively affect remaining native mussel viability and their recolonization potential in the Utah Lake/Jordan River drainage until TSS levels are drastically reduced from sources such as erosion related to agriculture, forestry, industrialization, and urbanization. Utah Lake is now often slightly saline (brackish) due to high rates of evaporation and loss of freshwater inputs and salinity levels are expected to increase. Neither native mussel taxon is known to tolerate salinity.

Metapopulation Viability

Anodonta and *M. falcata* populations in the Jordan River/Utah Lake drainage were likely continuous populations or metapopulations prior to Mormon settlement in the late 1880s. Metapopulations consist of several distinct populations connected by areas of suitable unoccupied habitat, where each population cycles in relative independence of the other populations and eventually goes extinct because of demographic stochasticity. However, in metapopulations, limited connectivity can provide for recolonization of the extinct populations: thus, metapopulations have less extinction risk than completely isolated, fragmented, populations (Hanski 1999). Anodonta and *M. falcata* most certainly no longer continue to persist as continuous populations or possibly even metapopulations in the Jordan River/Utah Lake drainage, but now survive as small, fragmented, isolated, remnant, populations.

It is well known that isolated- fragmented populations are substantially at higher risk of extinction than metapopulations or continuous populations (Hanski 1999, MacArthur and Wilson 1967, Fagan et al. 2002, Strayer 2008). Unionoida mussels are extremely poor dispersers and are dependent on fish hosts for larvae dispersal (e.g. parasitic glochidia). Those resident to the Jordan River/Utah Lake drainage likely depended on past large populations of migratory native fish hosts (e.g. Bonneville cutthroat trout, June suckers) for their dispersal (see also Glochidial success, fish host abundance, and mortality rates). Fish populations that are currently present in the Jordan River/Utah Lake, native or introduced, are but a small fraction of past population densities and may not provide enough individual hosts for glochidia dispersal (Strayer 2008). The possible exception are carp; however, carp are not known to be secondary hosts to either Anodonta or *M. falcata*, and carp are being aggressively reduced by State of Utah fisheries biologists in Utah Lake. Also, the negative effect of carp predation on native mussels likely far outweighs any beneficial effect that they may have as poor glochidial dispersers. Much of the survival of glochidia to adulthood is density dependent, both by the number of sexually mature actively reproducing Unionoida individuals and by the number (density) of potential fish hosts (see Glochidial success, fish host abundance, and mortality rates). In addition, the highly invasive Asian clam, *Corbicula* sp., has been documented to filter feed on Unionoida glochidia drifting in the water column. *Corbicula* sp. densities can be extremely high in both Utah Lake and tributaries of the Jordan River and have the potential to consume a large portion of glochidia that may possibly be produced. Thus, viability decreases and extinction probability increases for any remaining Unionoida populations as these three density dependent factors interact.

Dispersal and Connectivity, Suitable and Unsuitable Habitat

Dispersal and connectivity are the two most important components of metapopulation viability (Hanksi 1999, Levins 1969, Strayer 2008). Of all the freshwater fauna, Unionoida are perhaps the most dispersal limited. Dispersal rates of Unionoid mussels are dependent on dispersal rates of host fish and connectivity between populations (Strayer 2008). Mock et al. 2004 using genetic analyses showed that Anodonta had very low dispersal rates between remaining fragmented populations in UT. Connectivity between remaining populations of Anodonta and *M. falcata* has for the most part been completely lost due to multitudes of dams and diversions in the Utah Lake/Jordan River drainage.

Metapopulation viability is also determined by the relationship between suitable and unsuitable habitat. Suitable habitat can be occupied or unoccupied by mussel populations, likewise unsuitable habitat may be occupied or unoccupied by mussels. The proportion of suitable habitat that is occupied is a major driver in viability. Suitable habitat may be unoccupied solely due to lack of dispersal and connectivity from other populations (Strayer 2008). If water quality conditions that became unsuitable for mussels from past human activities were to become suitable in the future, the lack of dispersal and connectivity between populations will still prevent these suitable habitats from becoming occupied. It is likely that Anodonta and *M. falcata* occupied most of the suitable habitats in UT prior to settlement but now have near- zero occupancy rates due to loss of connectivity and dispersal. Loss of habitat also increases dispersal distances between populations which causes a loss in the proportion of unoccupied suitable habitat and therefore increases the extinction debt (Strayer 2008). Loss of dispersal ability and loss of suitable habitat are not additive but multiplicative (Strayer 2008). For example, if only 30% of suitable habitat remains and only 60% remains occupied due to reduced migration for example, then only 18% of the previously suitable habitats that were once occupied are now unoccupied.

The remaining isolated Anodonta populations in Beer Creek and Currant Creek are at such critically low densities that they may also have entered what is known as the 'extinction vortex' (Gilpen and Soule 1986), where in addition to the factors just described; genetic factors such as inbreeding depression, genetic drift, and 'mutational meltdown' (Lynch and Burger 1993) and demographic and environmental stochasticity combine in positive feedback loops that accelerate their extinction probabilities (Lynch et al. 1993, and Lynch and Gabriel 1990, Mock et al. 2004, Fagen and Holmes 2006).[1] It is also likely that they are now ecologically irrelevant and can be considered as part of the 'extinction debt' (i.e. the future extinction of a species due to past events)(Kuusaari et al. 2009). Unfortunately, Anodonta populations may simply no longer be viable without massive management intervention and monetary expenditures.

Dispersal of Anodonta from Beer Creek to Other Waterbodies

There is practically no chance of natural glochidia dispersal and survival from the Anodonta population in Beer Creek to other water bodies in the Jordan River-Utah Lake drainage. Beer Creek, downstream of the known Anodonta population is completely dewatered during summer months for irrigation and does not again flow to Utah Lake until after summer irrigation returns occur. Unfortunately, summer months are when Anodonta are most active and typically release glochidia. For example, there are also no known migratory fish species in Beer Creek that can bypass diversion dams on the tortuous journey downstream into Utah Lake. Downstream dispersal of migratory infected fish hosts, if any such fish species exist, is needed if glochidia are to be transported into Utah Lake, the likelihood of which is reduced dramatically if there is no water during much of the year.

Dispersal from Utah Lake

> "Utah Lake is drained by the Jordan River, which begins at the lake's north end. The river flows north through Utah, Salt Lake, and Davis counties and then into the southeast

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[1] The importance of metapopulation dynamics should not be underestimated and it should be noted that metapopulation dynamics and genetic diversity were included as important components in Karr's 1999 original definition of 'biological integrity' but are now widely ignored by most, if not all water quality management agencies.

portion of the Great Salt Lake. Given the lake's semi-arid climate, large surface area, and shallow average depth, evaporation accounts for 42% of Utah Lake's outflow (UDWQ 2007).

After several years of drought, irrigation companies were arguing over their share of Utah Lake's water from the Jordan River. Judge Morse of the Third District Court issued his judgment that became known as the Morse Decree of 1901. The decree stated that the irrigation companies "are entitled to a decree awarding to them, subject to the limitations hereinafter set forth, the right to the use of all the balance of the waters of the Jordan River, for municipal, irrigation, culinary, and domestic purposes, to the extent of the capacity of their several canals, and the right to impound and store all of the waters of said river in Utah Lake."(Salt Lake City 1989) In response to the drought, a pumping plant was installed at the outlet of the Jordan River from Utah Lake. It was the largest pumping plant in the United States at the time. The plant contained seven pumps with a total capacity of 700 cubic feet (20 m^3) per second (http://www.waterrights.utah.gov/wrinfo/policy/ut_lake/plan.htm). After the decree was released, Utah Lake essentially became an irrigation reservoir and the Jordan River's flow was highly regulated.

Because of the 1983-1984 flooding, a lawsuit was filed for compensation due to flooding based upon breach of contract of the previous compromise level. In 1985, a new compromise level was reached which governed the maximum level of the lake. The new level was chosen to be 4,489 feet (1,368 m) above sea level. When the water level in Utah Lake exceeds this level, the Jordan River pumps and gates are left open(http://www.waterrights.utah.gov/wrinfo/policy/ut_lake/plan.htm). The new compromise level also meant that the lake's elevation was below Jordan River's stream bed." (https://en.wikipedia.org/wiki/Utah_Lake).

Note: Jordan and Salt Lake Canal exchanges approximately 65,000 acre-feet of low quality water from Utah Lake and Jordan River for irrigation with higher quality water from Parleys Creek, Mill Creek, Big Cottonwood Creek, and Little Cottonwood Creek that are used for culinary purposes (http://hiddenwater.org/saltLakeCanal.html).

Utah Lake levels have been below compromise (0 ft.) 72% of the time from 1992 to 2015 (Figure 107)(See Appendix 2. for Utah Lake level, monthly values from 1992 to 2015). This means that most of the time Utah Lake water is pumped into the canal and no water flows from Utah Lake into the Jordan River. In the extreme unlikely event that a secondary fish host infected with glochidia from the last known remaining small population of *Anodonta* in Beer Creek or Currant Creek swims across Utah Lake; odds are it will be pumped through the pumping plant and into the canal. In addition: 1) future climate predictions are for intensified drought in summer, 2) Utah's human population is expected to continue to rapidly grow, 3) the demand for water in the area is expected to increase, and 4) Utah Lake's water elevation is expected to decrease, further reducing the likelihood of any migratory, infected, secondary fish hosts entering directly into the Jordan River from Utah Lake. No Anodonta have been reported in Jordan River or the canal in recent years, therefore, recolonization from upstream dispersal into the Jordan River or its tributaries does not appear possible.

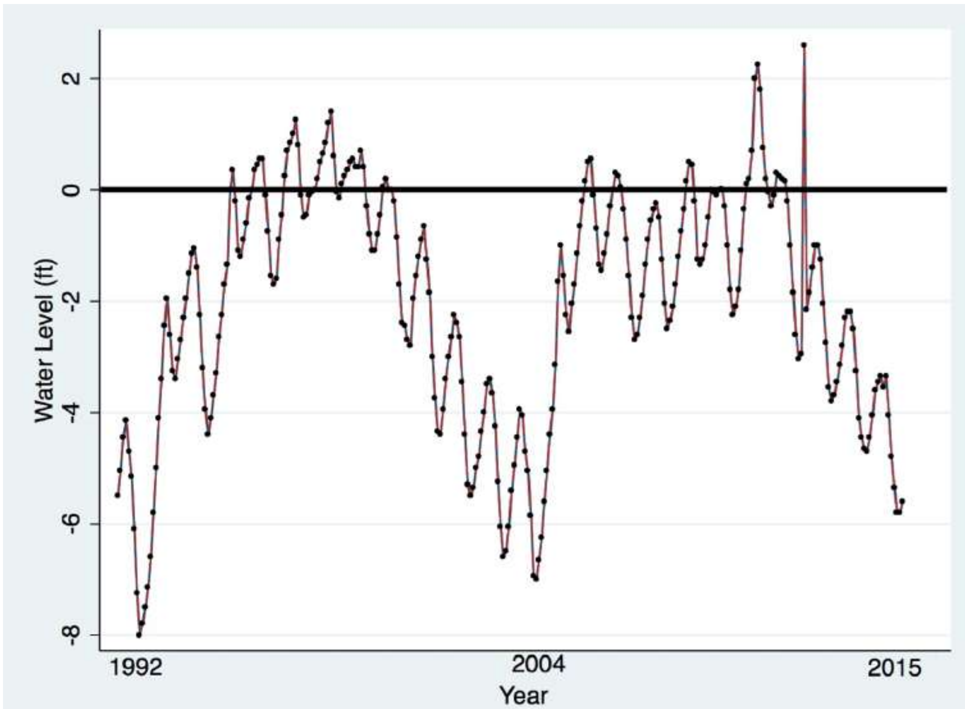

Figure 107. Utah Lake levels from 1992 to 2015. Horizontal black line at 0 is compromise level. 2017 appears to be a near record high lake level year.

Unknown populations

There is a very remote possibility that a yet undiscovered small population of Anodonta or *M. falcata* exists in the drainage. This would be an important and extraordinary rare find given that all the literature that we have examined, the knowledgeable biologists that we have interacted with, and results of the most up to date survey in the area that was conducted by us including probability of detection estimates, suggests that this discovery is highly unlikely. If another population(s) is found, the problem of dispersal via suitable fish hosts and connectivity still exists and "alterations to habitat' and 'conditions" (i.e. dispersal and connectivity) "are not likely to change within reasonable planning horizons".

Unionoida Status in Utah and the Clean Water Act

The Clean Water Act states as one of its goals, "…to maintain and improve the physical, chemical, and biological integrity of our nations water so as to provide for the protection and propagation of fish, ***shellfish***,…." (the definition of 'shellfish' includes mussels and snails). The continued survival and viability of native mussels (shellfish) in Utah is directly linked to these three interacting elements of integrity: physical, chemical, and biological.

The **physical integrity** of many Jordan River-Utah Lake waterbodies has been severely compromised. Human induced factors that have compromised the physical integrity of these waters include, but are not limited to:

- Dewatering
- Non-natural flow regimes
- Channelization
- Sedimentation
- Urbanization
- Loss of flood event scouring
- Loss of floodplain connection (e.g. flood dynamics are not the same as when Jordan River was free to inundate its flood plain. Floodplains also dissipate flood scour energy/intensity).

These factors have negatively affected the physical integrity of the Jordan River-Utah Lake drainage waters and have also been documented to strongly contribute to the rapid decline and extinction of Unionoida and non-pulmonate snails worldwide (Lydeard et al. 2004) and to their rapid decline and potential extinction in the Jordan River-Utah Lake drainage (Hoving 2004). Populations of already critically low densities of native mollusks in the Jordan River—Utah Lake drainage, particularly Unionoida taxa, will likely not persist without drastic improvements to these physical factors that compromise the integrity of these waters.

The **chemical integrity** of waters in the Jordan River-Utah Lake drainage has also been severely compromised. Factors that have compromised the chemical integrity of these include, but are not limited to:

- Low dissolved oxygen
- Point and non-point sources of pollutants
- Increased salinity
- Nutrients
- High summer temperatures
- Increased total dissolved solids and
- The chemical integrity of Utah Lake

As with the physical factors, until remedied, chemical factors preclude the viability of Unionoida in the drainage. For example, high summer temperatures and low dissolved oxygen are intimately linked and are detrimental to Unionoida and non-pulmonate snails. Utah Lake water dominates Jordan River, particularly in summer. Warm summer Utah Lake water which enters the Jordan River is low in DO and may be less than saturation, particularly if Utah Lake becomes stagnant due to low surface wind velocities, which reduce surface water-atmospheric aeration. In addition, increased sedimentation in Utah Lake due to human economic activities over the last century has led to an average depth in Utah Lake of < 10 ft. Shallow water heats up faster than deeper water and is less able to hold DO. This contrasts with historically Jordan River water, which in addition to the Utah Lake water source was supplemented by cold-water streams originating in the Wasatch, which were much colder than irrigation return flows from Utah Lake. These tributary waters were also well oxygenated via turbulence from higher velocities and riffles/cascades in the canyons. Likely these waters were near saturation when entering the Jordan River.

The **biological integrity** of waters in the Jordan River-Utah Lake drainage have also been severely compromised. Factors that have compromised the biological integrity of these waters include, but are not limited to:

- Invasive species (e.g. Corbicula, Potamopyrgus, carp, etc.)
- Loss of biodiversity
- Loss of species interactions (the extinction or loss of ecological interactions often accompanies or even precedes loss of biodiversity (Valiente-Banuet 2015))
- Compromised metapopulation dynamics and increasingly isolated/fragmented populations
- Loss of genetic diversity
- Unknown changes in species interactions resulting from loss of biodiversity and species interactions
- Demographic and environmental stochasticity effects on small isolated populations

As with the physical and chemical factors and until remedied, these biological factors reduce the viability of native mollusks in the Jordan River-Utah Lake drainage.

Human Population Growth and Global Climate Change

Perhaps the greatest threat to remaining mussel dispersal and viability in the Utah Lake/Jordan River drainage not discussed so far in this report is the burgeoning human population growth, the economic activities associated with this growth, and the predicted effects of decreased water supplies due to global climate change. Human population growth in the Jordan River-Utah Lake drainage is 'ground zero'; the fastest growing area of UT (Salt Lake Tribune 2015) and one of the fastest in the country. Consumption of water will likely increase and instream water availability will likely decrease (McCool 2015, Rowe 2015,). If technological methods are implemented, then the overall water availability may decrease more than predicted and waters that remain will inevitably be removed from upstream sections of streams for human consumption and then remaining waters will be replaced much further downstream, if at all (Dr. Theron Miller, Wasatch Front Water Quality Council personal communication, Miller 2017). This will further reduce connectivity and the dispersal ability of mussels and habitat and reduce viability.

Discussion

Problems with probability of detection estimates for very rare or absent mussel populations

We demonstrated throughout this report that Anodonta in JRUL drainage have life histories that predispose themselves to increased extinction risk when: 1) their densities decrease, 2) glochidial fish host densities decrease, and 3) predation and competition increase. We have also shown that their population viability within the drainage is precarious. Although we did not attempt formal viability analyses, they could help solidify our conclusions and are highly recommended. The probability of detection (POD) results (based on Smith (2006) and accepted by UDWQ) that we presented in the results section were mostly developed to illustrate how extremely rare native mussels are in JRUL drainage and that these POD methods lose their effectiveness when densities are at such critically low, unviable population levels. In the following discussion, we discuss some of the short comings and further discuss our search efficiencies, density, and POD estimates.

Obviously, only those mussels that are epibenthic or not buried can be found in searches restricted to the substrate surface (Amyot and Downing 1991). If an area is searched thoroughly so that all mussels on the substrate surface have been found, then search efficiency will be capped at the proportion of mussels that are on the surface (Smith 2006). Smith reported that 30 to 50% of two species of unionids were found at the substrate surface and that $632m^2$ needed to be surveyed with a mussel density of $0.01/m^2$ to obtain 85% POD. EPA (2013) cited ORVET (2004) suggesting that “50% of mussel community is present at the substrate surface”. Other researchers reported similar findings. For example, Haukioja and Hakala (1974) found that surveys that only included the epibenthic unionid mussels underestimated populations by an average of 14.5%. Amyot and Downing (1991) reported that the fraction of *Elliptio complanata* (Family Unionidae) in a lake in Ontario which was endobenthic (below the surface) varied from 0 to 63% from spring to autumn; thus visual surveys may have missed about 18% of the population in that study. Seasonality mostly affected whether mussels were either epi- or endobenthic and 100% of marked mussels were epibenthic in summer months in the Amyot and Downing (1991) study. The Amyot and Downing (1991) study is consistent with the literature that mussels tend to become endobenthic when water temperatures decline and remain so until water temperatures increase seasonally. All our surveys occurred during warm water months (especially compared to Ontario spring and autumn water temperatures) and we suggest that the greatest proportion of mussel populations during our surveys were epibenthic and our search efficiencies of visible mussels were little effected. Assuming that we thoroughly searched all the substrate surface areas, then search efficiency should also have been somewhere near 30 to 50% and again, our conclusion that Anodonta are at such low densities throughout the drainage that they may no longer be viable, although disheartening, is valid. However, if we are interested in monitoring and population viability assessments of the remaining Anodonta populations in JRUL drainage, perhaps careful examination of the sediments may reveal more individuals, including juveniles (Amyot and Downing 1991).

Smith (2006) defined search efficiency (detectability) as the probability of detecting an individual mussel given that it is "within the search area." However, for most of our survey sites, *a priori* evidence suggested that mussels weren't in the search area. For example, UDNR:DWR (2015) concluded that Anodonta were extinct in Utah Lake, Hoving (2004) had similar conclusions: absent from the drainage (see Native Mussel Taxa Historically Found in the Jordan River-Utah Lake Drainage for more information). Our surveys turned up zero individuals in the drainage prior to developing the POD models presented in the results section, except for our discovery of two previously unknown Anodonta populations. Our resultant POD models were thus based on densities that approached zero or were zero and although somewhat helpful; the utility of the POD models was over extended or possibly trivial. For example, if we are strictly attempting to detect presence and not biologically meaningful densities, then one individual would count as presence. If there was only one individual Anodonta in the entire Jordan River (50 miles by 15 meters or approximately 1,207,005 m^2) (mussel density of 0.00000083/m^2) it would technically be considered present but obviously not a viable population. Even with a search efficiency of 100% then 2,780,000 m^2 would have to have been surveyed to obtain a 90% POD or 2.3 times the area of the Jordan River using the Smith (2006) equation recommended by UDWQ. Of course, the Smith (2006) models were primarily developed for designing survey studies for biologically meaningful density thresholds; not for after- the- fact estimates of efficiencies, densities or PODs in sites where densities approach zero or are zero (absence).

Smith (2006) touched on a very important fact, which is; "if the primary objective of a survey is to detect the presence of a rare population (in our case to help illustrate critically low densities), then one important element of the survey design is based on "a species abundance or density that is deemed biologically meaningful". Certainly, native mussels are considered extremely rare in the JRUL drainage. Smith (2006) also states that: "the determination of a biologically meaningful threshold should involve multiple considerations including legal mandates, life history, populations viability, and comparisons of densities throughout local watershed, region, or range." Our surveys were primarily designed to determine presence/absence, not biologically meaningful density thresholds, however we discussed at length population viability as it relates to biologically meaningful thresholds.

Anodonta density estimates in other areas are highly variable. Clarke (2010) estimated densities in pools in a tributary to the Yakima River, WA at mean = 5.41/m^2 (95% CIs from 0.80 to 21.63). The Yakima River drainage is one of the remaining strongholds of Anodonta. Mueller et al. (2011) estimated densities ranging from 0.0 to 8.4/100m^2 in the Hanford Reach of the

Columbia River however, the viability of this population is unknown. Hegeman (2012) estimated Anodonta densities at $0.52/m^2$ and Brim Box et al. (2006) estimated densities as high as $275/m^2$ for one of the most well studied Anodonta populations in the Middle Fork John Day River, Oregon. If these higher values reflect somewhat viable population density estimates (except for the $0/m^2$ estimates), then results from our studies show that we have very strong evidence that overall, Anodonta population viability in the JRUL drainage is critically low and they are likely near extinction.

UDWQ (2017) recommends that, "When feasible, survey designs that have at least an 90% probability of detecting unionid mussels when they are present at a density of $0.1/m^2$ are desired." Although this density value is an order of magnitude greater than Smith (2006) density threshold for rare mussel species of $0.01/m^2$, $0.1/m^2$ appears to be baseline adequate for biologically meaningful densities and is consistent with Green and Young's (1993) definition of rare.

Because Anodonta have been found in a wide range of habitats including; lakes, ponds, reservoirs, large rivers, small streams with gravelly riffles, pools, silt, sand, and embedded vs unembedded substrates, etc., any implied habitat model for selecting sample location and efforts is unwarranted at this time and will certainly be inefficient and could very well be misleading (Smith 2006, Strayer and Ralley 1993). The only habitat model that we support for Anodonta in the JRUL drainage at this time is 'Anodonta are where you find them'.

Native mussel populations are not randomly or uniformly distributed, however for statistical relevance, PODs require uniform distributions (Smith 2006, Green and Young 1993). Often mussel populations are clumped and clumped distributions may now be critical for their survival in JRUL drainage when densities are so dangerously low. Uniform or random spatial distributions at such low densities will likely preclude sperm from being inhaled by females and prevent fertilization. Clumped distributions with enough male and female individuals in close enough proximity for successful fertilization is mandatory in water bodies where mussels are so widely dispersed and densities so low. Clumped mussel 'beds' with enough individuals to successfully produce glochidia in large enough numbers also need to be in close enough proximity to suitable host fish at suitable densities. Without concurrent fish host density estimates, any biologically meaningful mussel density values will likely be meaningless.

Because we optimistically don't want to declare native mussels extinct in sites where we did not find them or in locations that we did not survey, even though our results lead us to this conclusion; understanding life histories of potential suitable host fish including suitable habitats could help direct any future survey site selections. We still wishfully hope that very small, isolated populations still may be found in unsurveyed locations in the JRUL drainage. As is the case with any rare species; the more you look, the more likely you are to find.

As a pertinent example of more robust estimates of rare mollusk densities, Richards and Arrington (2009), Richards et. al. (2009a), (2009b) and (2009c), and Stephenson et al. (2009) referenced Green and Young's (1993) definition of a rare or low-density mussel population of $0.1m^2$ extensively throughout their formal risk assessment, metapopulation viability analyses, and population estimates of a rare, threatened, cryptic, < 4 mm sized mollusk in the Snake River (a large river by any account). Their research showed that these tiny mollusks were not spatially random or uniform in their known range but for statistical purposes a poisson distribution of spatial uniformity such as that used by Green and Young (1993) was helpful in preliminarily estimating densities in the Snake River. However, because these mollusks were federally listed as threatened and the focus of the research was to estimate densities, not presence/absence determination; more sophisticated spatially explicit models that included anisotropic semi-variograms, kriging, and mixed probability distribution models were developed. These models resulted in more accurate density estimates, which were instrumental for maintaining the threatened status of these tiny mollusks by the U.S. Fish and Wildlife Service and guided development of Federal Energy Regulatory Commission regulations for several large hydroelectric facilities on the mid-Snake River. Methods used by these authors in conjunction with metapopulation viability analyses and quantitative risk assessments should be strongly considered when estimating Anodonta densities and population viability in the JRUL drainage and may be useful for determining biologically meaningful density thresholds for future population surveys and management.

A crude but informative estimate of how many native mussel populations may exist in locations in the JRUL drainage that were not surveyed in this study is simply that we surveyed roughly 1.6 million m^2 and found two new populations or the equivalent of one new populations per 0.8 million m^2 surveyed. However, we surveyed the more promising locations and this estimate should be considered a minimum.

Conclusion

Based on recent searches conducted by the author and trained surveyors (Richards 2015a and 2015b and this report), it appears that Anodonta populations in the Jordan River-Utah Lake drainage are in serious condition and their continued viability is precarious. The western Pearlshell mussel, *Margaritifera falcata*, is likely extinct in the drainage. Native fingernail clams (Family Sphaeriidae) also appear to be in severe decline throughout the drainage and particularly in the lower valley waters including Utah Lake. The invasive Asian clam, Corbicula now appears to be the drainage's resident bivalve replacing the natives and can often occur at incredible densities; densities that were once reserved for native bivalves. Even though two Anodonta populations and several fingernail clam populations still exist; native bivalves in the Jordan River-Utah Lake drainage are functionally extinct and contribute little to ecosystem function and can be considered ‘ghost’ or ‘relict’ species. Utah Lake was once a tremendous haven for freshwater mollusks but this in no longer the case (Figure 108 and Figure 109). The likely ultimate driver pushing these mussel taxa to extinction in the drainage is their poor dispersal abilities, low densities of suitable hosts for glochidia, extreme low abundances of individual mussels, and their isolation from other populations.

Figure 108. Wave washed piles of thousands of mollusk shells, mostly heterobranch and prosobranch snails but including fingernail clams, Corbicula, and an occasional Anodonta fragment, along the east shore of Goshen Bay, Utah Lake, September 2016. Utah Lake was once home to this amazing assemblage of mollusks and its loss is tragic.

Figure 109. Piles of wave washed mollusk on eastern shore of Goshen Bay, Utah Lake, September 2016. Shell piles are white curved lines and shell layer is several cm thick.

Dr. Richards, Dr. Miller, and colleagues are also currently conducting ecological research on Utah Lake. They are collecting benthic invertebrate samples from several locations on the lake and are finding that in most sites there is a thick sediment layer often several centimeters to almost a meter thick in the northern most portion of the lake, under which is a layer of empty mollusk shells. Richards is also finding this to occur along the now dry shores of Utah Lake; a layer of sediment followed by the layer of mollusk shells. This is strong evidence that Utah Lake underwent a ‘catastrophic ecosystem shift’ and that the lake’s mollusk assemblage was extremely diverse and continuous across most of the lake but was rapidly lost during this shift due to increased and rapid sedimentation rates likely starting with the first settlers in the late 1800's and which was also while invasive carp were rapidly increased their populations. The Miller and Richards team is planning on conducting analyses to determine the dates and rates of this sedimentation and timing of the subsequent demise of Utah Lakes unique and irreplaceable mollusk assemblage.

Finally, if we want to reduce the likelihood of native mussels going extinct in the JRUL drainage it is imperative to understand the differences between the 'small' population paradigm and the 'declining' population paradigm (Caughley 1994). The declining population paradigm is the identification of the processes that depress the demographic rate of native mussels and causes their populations to decline deterministically (i.e. predation by carp, competition and predation by Corbicula, fewer secondary fish hosts, loss of suitable habitat connectivity, etc.); whereas the small population paradigm is the dynamics of small mussel populations that have already declined due to deterministic perturbation (s) and which are now more susceptible to extinction via chance (stochastic) events (ex. dewatering last remaining habitat, local toxic spill, algal blooms, cattle trampling, and other environmental stochastic events, etc.). The factors that drove native mussel populations in the JRUL drainage into decline aren't necessarily those that will drive the final nail into their coffin. Therefore, we must manage for both types of processes simultaneously and for the synergistic interatctions between them.

Recommendations

Continued surveying in additional locations and monitoring of the last remaining known populations are needed. Also, population dynamic studies for each of the remaining native bivalves in the drainage are urgently required and are indispensable to determine the causes of their disappearance, predict their extinction risk, and suggest management strategies that may circumvent or postpone their extinction. Ammonia toxicity tests would also be beneficial for establishing meaningful regulatory criteria in lue of additional costly surveys when densities and probabilities of detection are so low. Finally, Richards and Miller with potential support from the Wasatch Front Water Quality Council are initiating a feasibility study for a critically needed captive rearing and release program for our two native mussel species. Support for these efforts is needed by all concerned groups.

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Appendices

Appendix 1. Stream Profile including flow velocity, widths, depths, and substrate of Mill Creek

Introduction/Justification

Native Unionoida mussels and other aquatic benthic invertebrates are strongly associated with flows (velocities) and substrate types (Miller et al. 2014). After temperature, flows and substrates are the predominant determinants of benthic invertebrate assemblages (Miller et al. 2014). As discussed briefly in this report, Anodonta and Margaritifera often occur in different types of habit, and there doesn't appear to be a sharp change, or is there expected to be, in temperatures between Mill Creek Section 1 (non-game fishery) and Mill Creek Section-2 (cold-water fishery). However, temperatures are more consistent throughout the year downstream of CVWRF outfall and more variable upstream of the outfall. Any difference in fish and invertebrate assemblages, including Unionoida mussels between Mill Creek Section 1 and 2 are therefore likely mostly due to flows and substrate conditions, except for downstream of the outfall where temperature likely plays and important role in these differences. Richards et al. are presently conducting macroinvertebrate studies comparing Mill Creek downstream and upstream of outfall assemblages. However, no recent data existed on flows and substrates in the sections of Mill Creek where the mussel surveys took place. This lack of flow and substrate data prompted the following study.

Methods

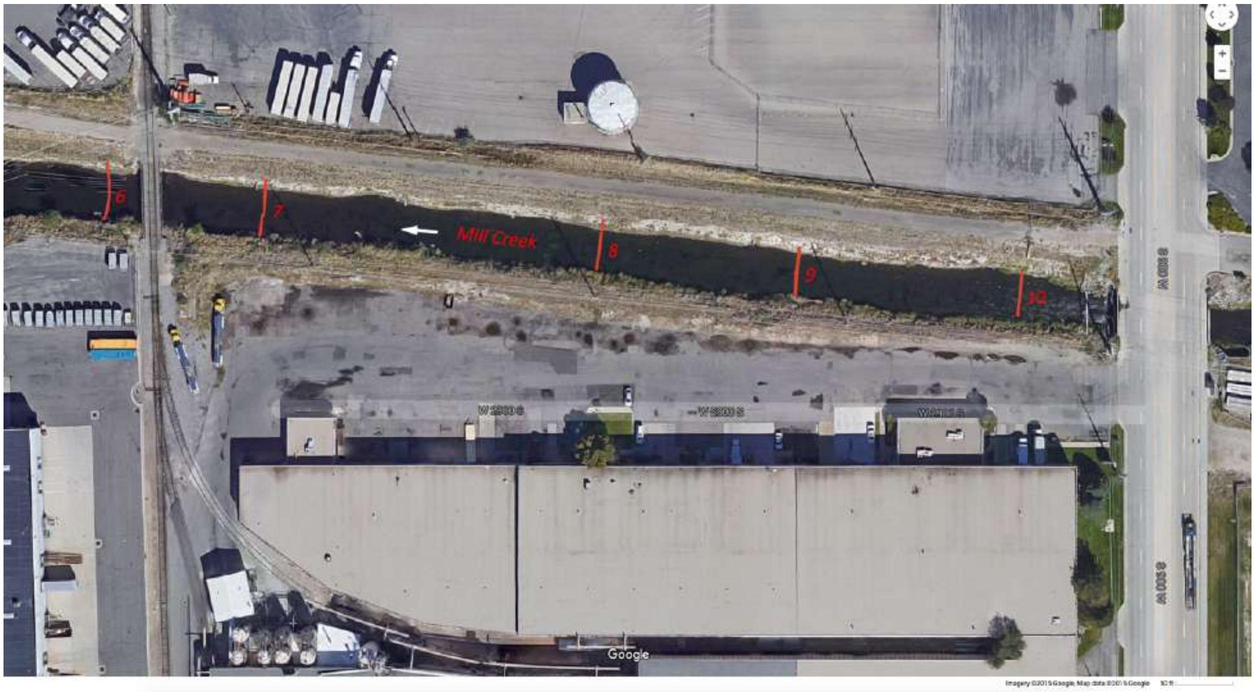
Richards and two to three field technicians collected flow and substrate data from 23 sections of Mill Creek from the confluence with the Jordan River to upstream of Interstate 15 (Appendices 1a-1f), September 14 and 17, 2015. They measured wetted stream width and depth and velocities along these transects. They also estimated substrate type at each of the depth/velocity readings (N = 195 depth/velocity/substrate measurements). Substrate categories were:

1. Organic matter
2. Silt[1]
3. Fine sand
4. Coarse sand
5. Small gravel
6. Large gravel
7. Cobble
8. Boulder
9. Large Woody Debris
10. Trash

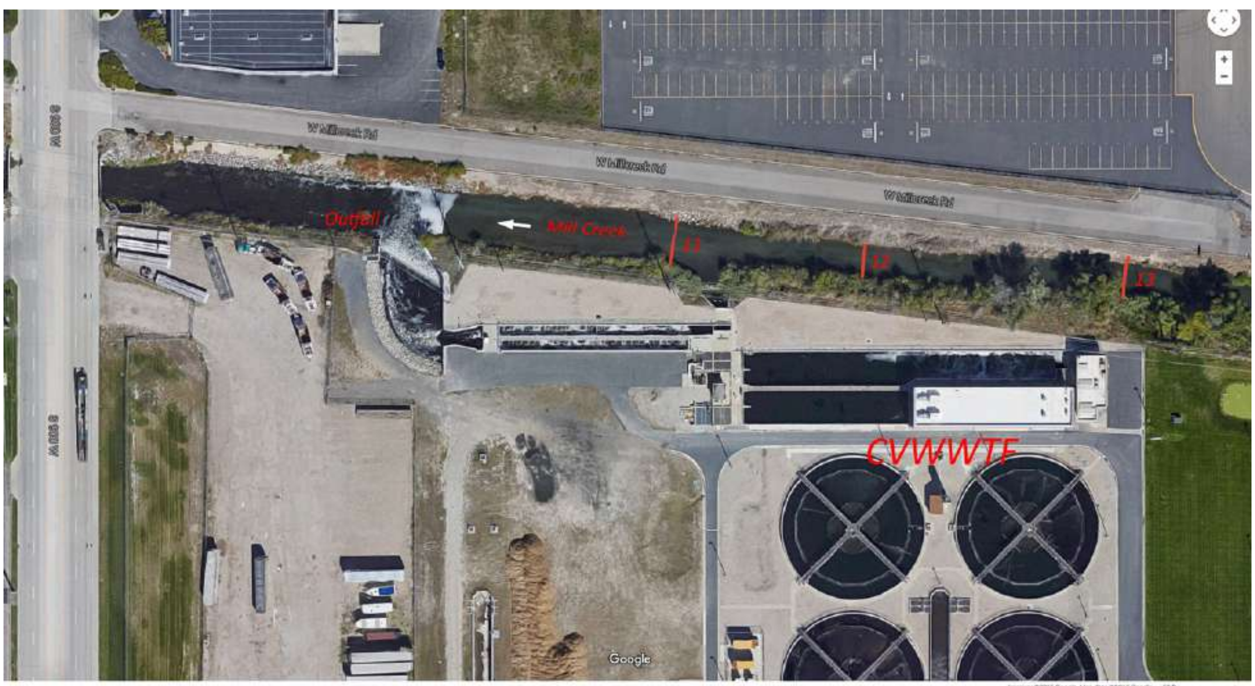
11 Submerged Aquatic Vegetation

[1]Silt also was comprised of clay

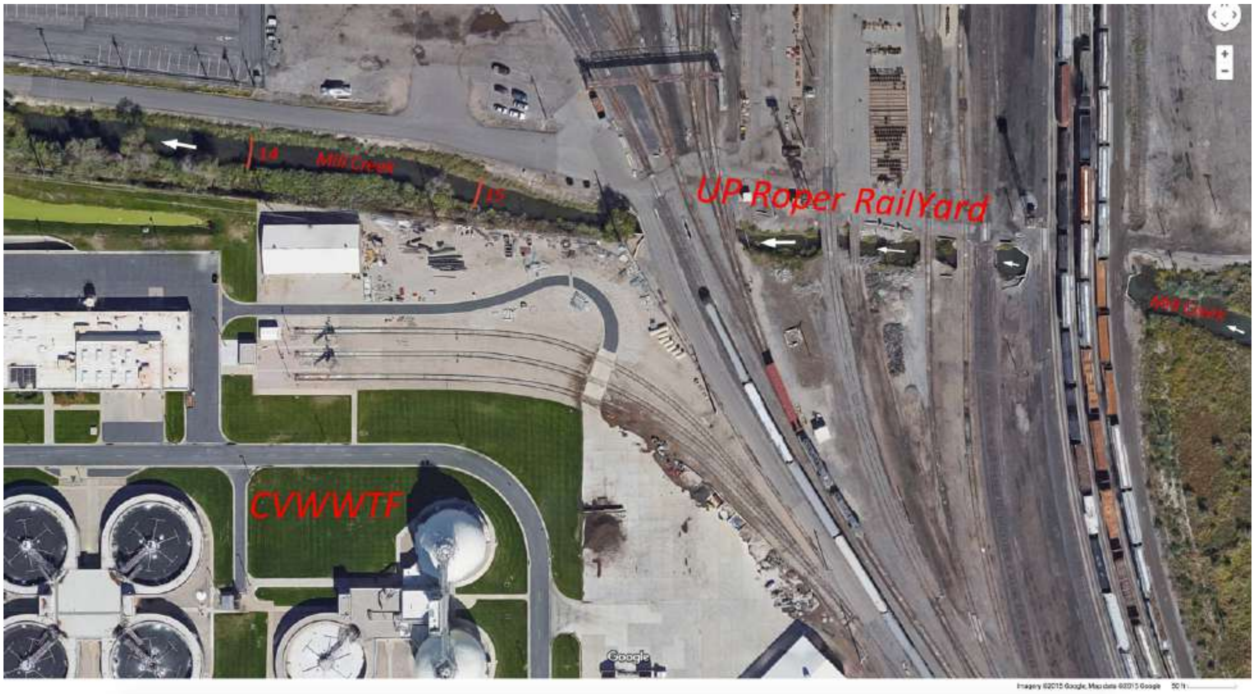
Appendix 1a. Mill Creek flow and substrate measurement Sites 1-6.



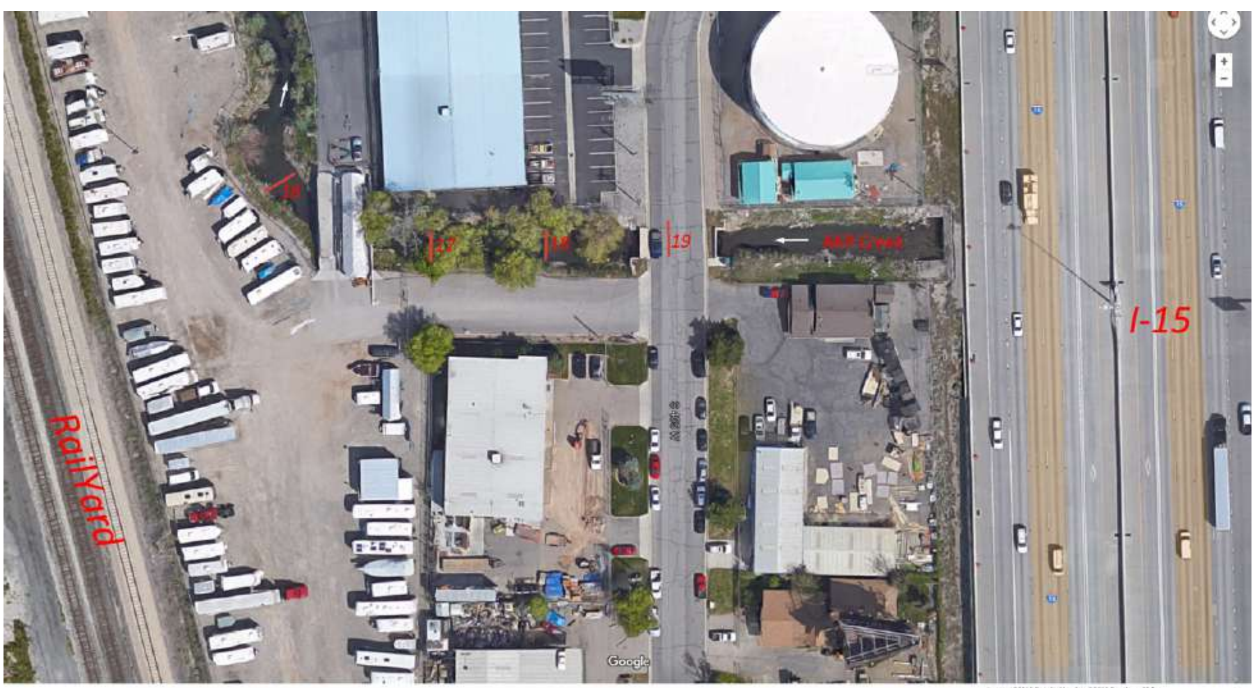
Appendix 1b. Mill Creek flow and substrate measurement Sites 6-10.



Appendix 1c. Mill Creek flow and substrate measurement Sites 11-13.



Appendix 1d. Mill Creek flow and substrate measurement Sites 14-15.



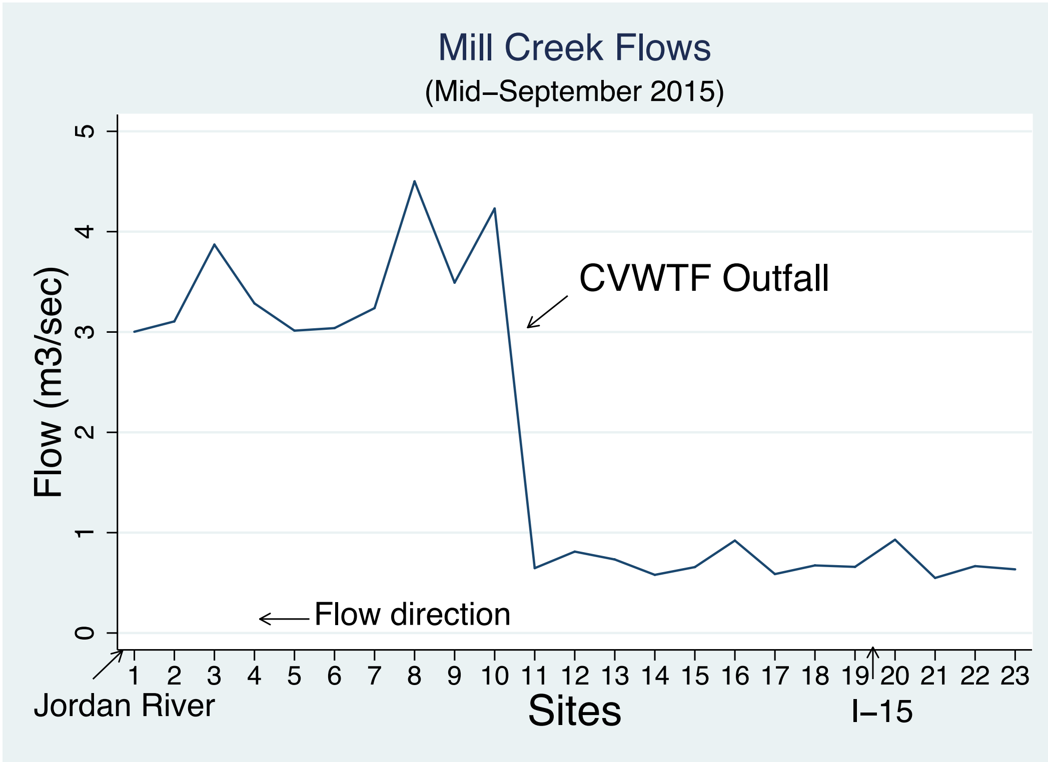
Appendix 1e. Mill Creek flow and substrate measurement Sites 16-19.

Appendix 1f. Mill Creek flow and substrate measurement Sites 20-23.

Results

Flows

Flows (m^3/s) differed dramatically between portions of Mill Creek upstream and downstream of CVWRF outfall as expected. Flows were >4 times downstream of the CVWRF outflow than upstream. There was a major storm event on September 15/16, 2015 and water levels fell thereafter when measurements resumed on September 17. Flows were quite variable in sections where SAV was abundant and even negative upstream flows were encountered near SAV.



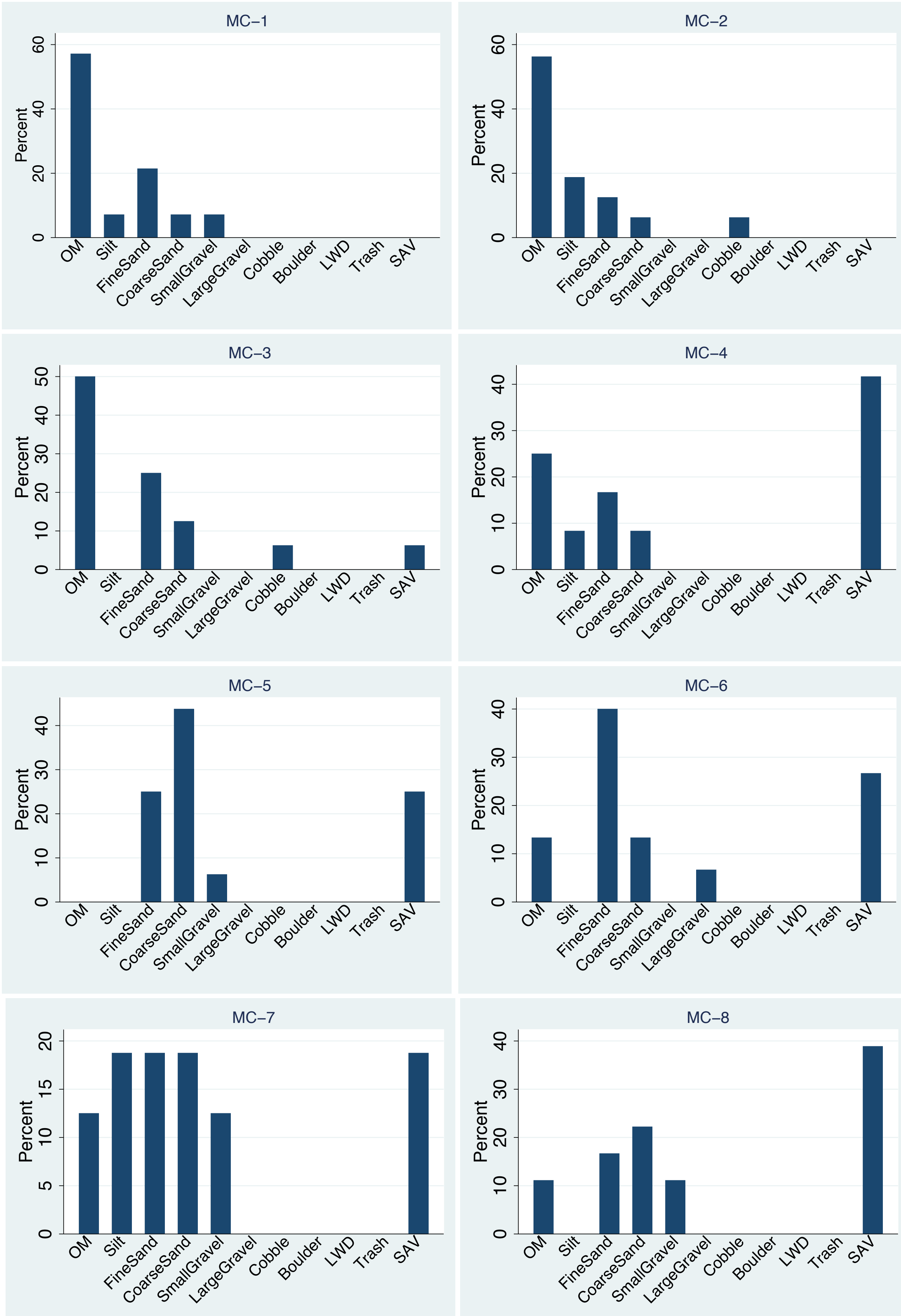
Appendix 1g. Mill Creek flows (m^3/sec) at 23 locations between Jordan River and upstream of Interstate-15 (see Appendices 1a-1f above for locations of sites). Flow data was collected on September 14, 2015 downstream of Site 13 and on September 17, 2015 upstream of Site 13 after a large storm event on September 15, 2015. Flows were receding at the upstream sites on September 17, 2015 but were still much higher than baseflow for that time of year in the upstream sections of Mill Creek and were approximately one half flow volume than the high water marks remaining from the storm event. CVWRF outfall obviously adds >4 times the flows the Mill Creek at this time of year. The sporadic nature of the flow data is likely due to flow measurements taken in and near SAV that have large impacts on velocities and in sections where riffle habitat occurred.

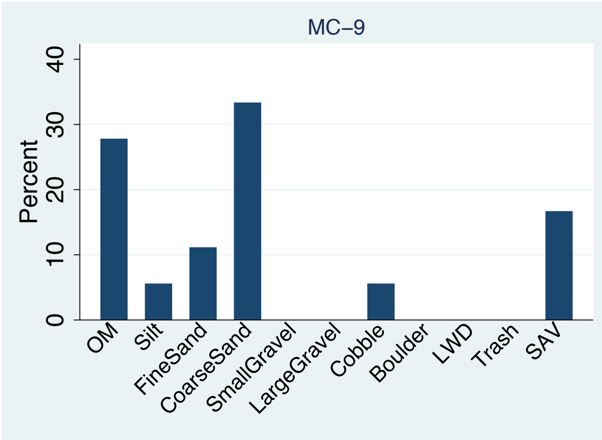
Appendix h. Descriptive statistics of velocities at 23 measurement sites on Mill Creek, September 14, 17, 2015.

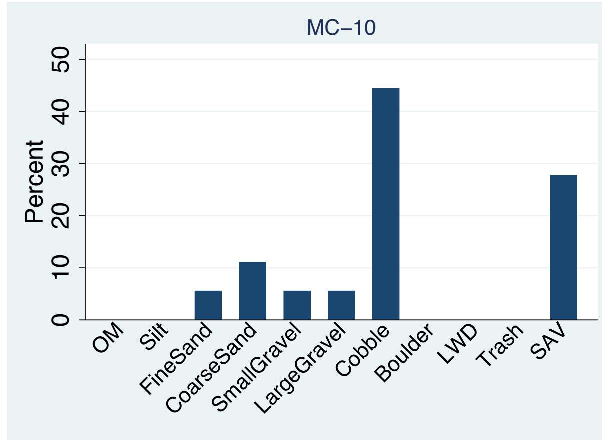
Variable	N	Mean	Std. Dev.	Min	Max
mc1velocity	8	0.18	0.09	0.02	0.26
mc2velocity	9	0.17	0.07	0.08	0.27
mc3velocity	9	0.24	0.15	0.00	0.44
mc4velocity	9	0.24	0.07	0.14	0.33
mc5velocity	9	0.22	0.08	0.12	0.34
mc6velocity	10	0.30	0.10	0.16	0.47
mc7velocity	9	0.25	0.11	0.08	0.40
mc8velocity	8	0.45	0.16	0.23	0.66
mc9velocity	8	0.27	0.11	0.10	0.44
mc10velocity	9	0.47	0.26	0.17	0.85
mc11velocity	8	0.10	0.05	0.00	0.16
mc12velocity	9	0.12	0.09	0.00	0.23
mc13velocity	8	0.18	0.08	0.09	0.30
mc14velocity	9	0.14	0.08	0.02	0.26
mc15velocity	8	0.29	0.08	0.13	0.40
mc16velocity	7	0.28	0.09	0.18	0.38
mc17velocity	7	0.27	0.13	0.08	0.47
mc18velocity	9	0.31	0.12	0.18	0.47
mc19velocity	9	0.38	0.19	0.06	0.63
mc20velocity	9	0.37	0.09	0.18	0.48
mc21velocity	8	0.23	0.15	0.08	0.41
mc22velocity	8	0.21	0.12	0.00	0.34
mc23velocity	8	0.18	0.08	0.04	0.29

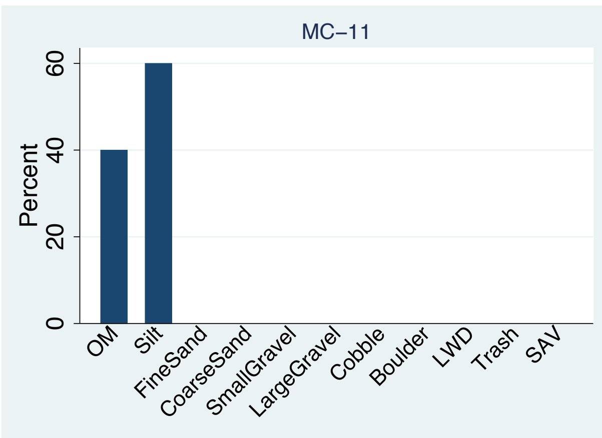
Substrate

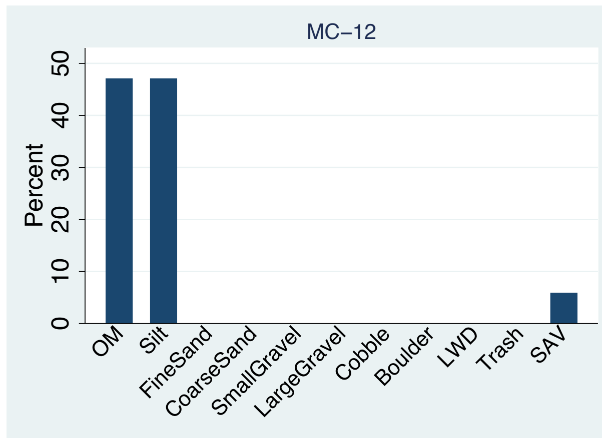
In general, finer sediments were encountered just upstream of Mill Creek's confluence with the Jordan River and immediately upstream of CVWRF outfall. SAV occurred throughout Mill Creek but was slightly more abundant downstream of Union Pacific rail yard. The fines (OM, silt, and clay) were often so thick in some locations that wading was difficult. Trash was more prevalent upstream of Union Pacific rail yard. Mid sized substrates were mostly encountered downstream of of CVWRF outfall and upstream of I-15. Sites upstream of I-15 were more heterogeneous than other sites.

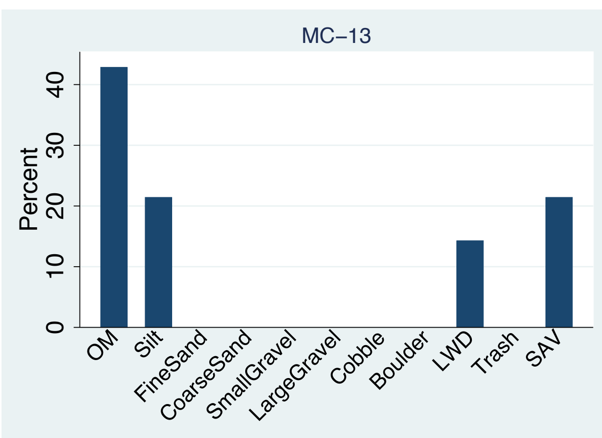

MC–1
MC–2
MC–3
MC–4
MC–5
MC–6
MC–7
MC–8
Percent
OM
Silt
FineSand
CoarseSand
SmallGravel
LargeGravel
Cobble
Boulder
LWD
Trash
SAV

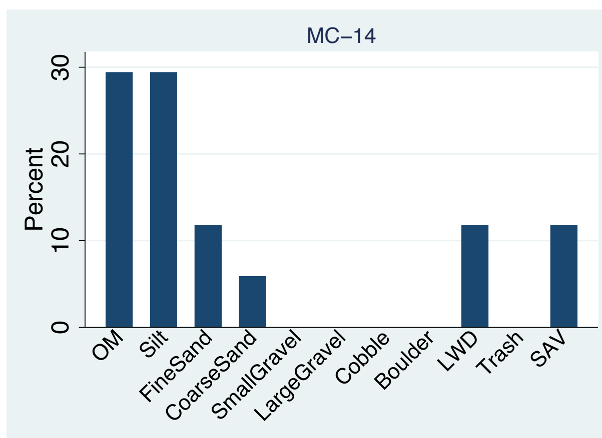

MC–9
Percent
0
10
20
30
40
OM
Silt
FineSand
CoarseSand
SmallGravel
LargeGravel
Cobble
Boulder
LWD
Trash
SAV

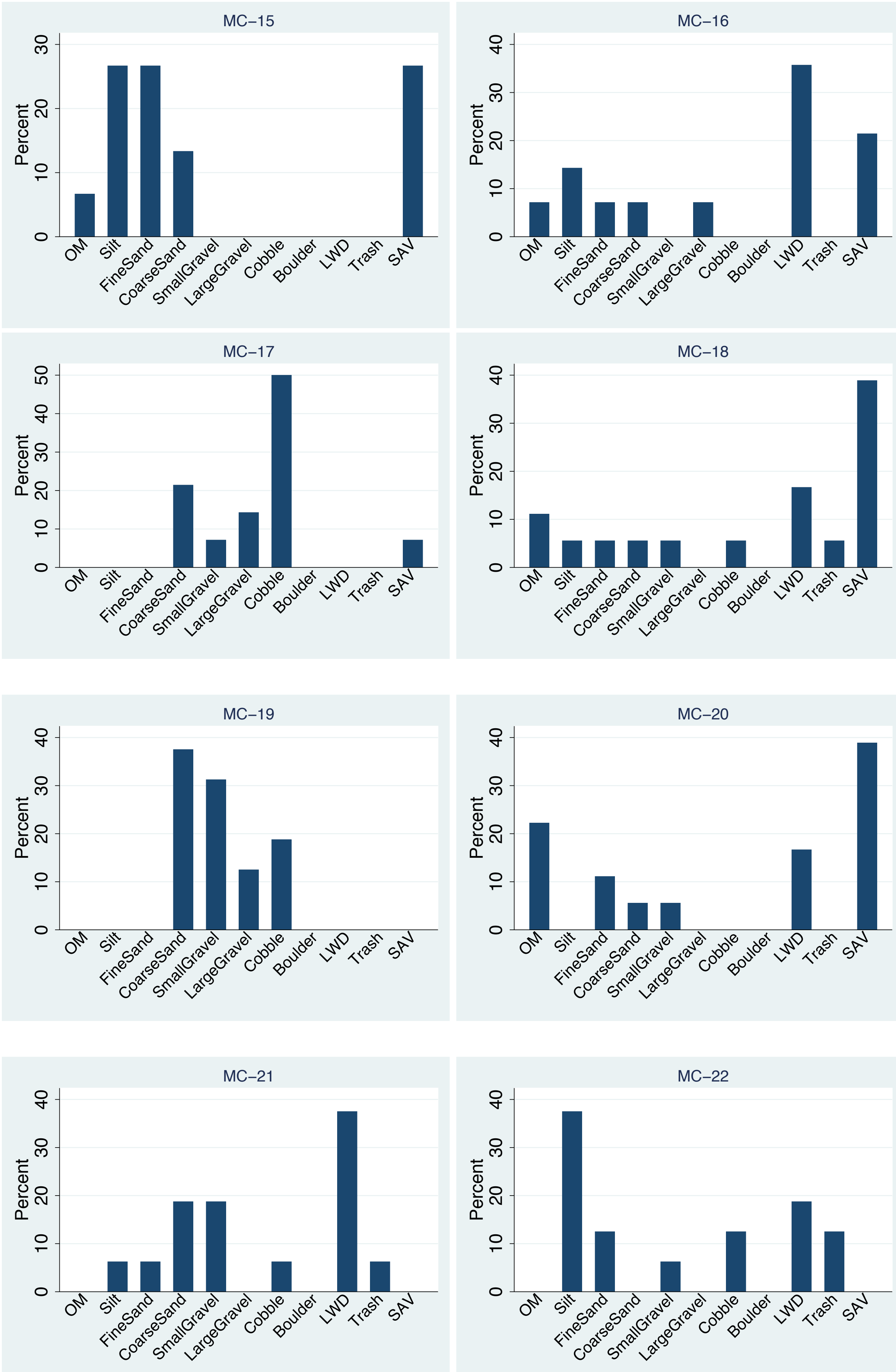

MC–10
Percent
0
10
20
30
40
50
OM
Silt
FineSand
CoarseSand
SmallGravel
LargeGravel
Cobble
Boulder
LWD
Trash
SAV

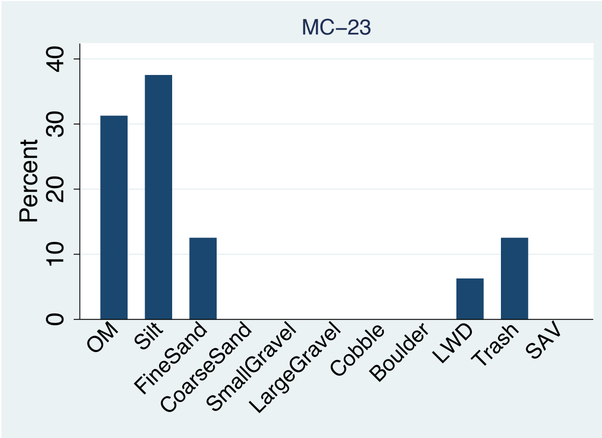

MC–11
Percent
0
20
40
60
OM
Silt
FineSand
CoarseSand
SmallGravel
LargeGravel
Cobble
Boulder
LWD
Trash
SAV


MC–12
Percent
0
10
20
30
40
50
OM
Silt
FineSand
CoarseSand
SmallGravel
LargeGravel
Cobble
Boulder
LWD
Trash
SAV


MC–13
Percent
0
10
20
30
40
OM
Silt
FineSand
CoarseSand
SmallGravel
LargeGravel
Cobble
Boulder
LWD
Trash
SAV


MC–14
Percent
0
10
20
30
OM
Silt
FineSand
CoarseSand
SmallGravel
LargeGravel
Cobble
Boulder
LWD
Trash
SAV


MC–15
MC–16
MC–17
MC–18
MC–19
MC–20
MC–21
MC–22
Percent
OM
Silt
FineSand
CoarseSand
SmallGravel
LargeGravel
Cobble
Boulder
LWD
Trash
SAV



Appendix 1i. Substrate conditions in Mill Creek at 23 sites measured on September 14 and 17, 2015. See Appendices 1a-1f for site locations.

Discussion and Conclusion

Flow and substrate habitats differed somewhat between sections of Mill Creek although organic matter, silt and clay often dominated. In almost all of the sample locations fine sediment was thick enough to likely be uninhabitable by juvenile mussels if any ever occurred. The variations in substrate at different locations in Mill Creek likely have historically played an important role in where Anodonta and *M. falcata* became established and prospered prior to their extermination. Other than the differing effects of temperature regimes upstream and downstream of the CVWRF outfall, macroinvertebrate assemblages that Richards et al. are analyzing and have been reported in the past are likely predominately affected by differences in flows and substrates. Further analyses of this data and relationships between mussel and other macroinvertebrate assemblages are recommended.

Appendix 2. Utah Lake level from 1992 until 2015. (https://docs.google.com/spreadsheets/d/1Fyvuhy2yNY_Q4KBAPm3eFuKK6wsBInKbnoMrEXBf2VY/edit?hl=en&pli=1#gid=0)

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Jan	-5.5	-6.6	-2.3	-3.3	-0.15	-0.45	0	0.35	-0.45	-1.95	-3.4	-4.8	-5.4	-5.6	-1.15	-0.3	-1.9	-1.7	-0.5	-1.1	-0.1	-2.15	-3.15	-4.05
Feb	-5.05	-5.8	-1.95	-2.65	0	0.25	0.2	0.5	0.05	-1.55	-3	-4.35	-4.95	-5.05	-0.65	0	-1.35	-1.2	0	-0.35	0.3	-1.85	-2.8	-3.6
Mar	-4.45	-5	-1.5	-2.25	0.35	0.7	0.5	0.55	0.2	-1.2	-2.65	-4	-4.45	-4.4	-0.2	0.3	-0.9	-0.75	-0.05	0.1	0.25	-1.4	-2.3	-3.45
Apr	-4.15	-4.1	-1.15	-1.7	0.45	0.85	0.65	0.4	0	-0.9	-2.25	-3.5	-3.95	-3.95	0.15	0.25	-0.55	-0.35	-0.1	0.2	0.2	-1	-2.2	-3.35
May	-4.7	-3.4	-1.05	-1.35	0.55	1	0.85	0.4	0	-0.65	-2.4	-3.4	-4.05	-3.15	0.5	0.05	-0.35	0.15	0	0.7	0.15	-1	-2.2	-3.55
Jun	-5.15	-2.45	-1.4	0	0.55	1.25	1.2	0.7	-0.2	-1.25	-2.65	-3.65	-4.7	-1.65	0.55	-0.35	-0.25	0.5	0.01	2	-0.2	-1.25	-2.5	-3.35
Jul	-6.1	-1.95	-2.25	0.35	-0.1	0.8	1.4	0.4	-0.85	-1.85	-3.45	-4.25	-5.05	-1	-0.1	-0.9	-0.5	0.45	-0.3	2.25	-1	-2.05	-3.25	-4.05
Aug	-7.25	-2.6	-3.2	-0.2	-0.75	-0.1	0.6	-0.3	-1.7	-3	-4.4	-5.25	-5.85	-1.55	-0.7	-1.55	-1.25	-0.2	-1	1.8	-1.85	-2.75	-4.1	-4.8
Sep	-8	-3.25	-3.95	-1.1	-1.55	-0.5	-0.05	-0.8	-2.4	-3.75	-5.3	-6.05	-6.95	-2.25	-1.35	-2.3	-2.05	-1.25	-1.8	0.75	-2.6	-3.55	-4.45	-5.35
Oct	-7.8	-3.4	-4.4	-1.2	-1.7	-0.45	-0.15	-1.1	-2.45	-4.35	-5.5	-6.6	-7	-2.55	-1.45	-2.7	-2.5	-1.35	-2.25	0.2	-3.05	-3.8	-4.65	-5.8
Nov	-7.5	-3.05	-4.1	-0.9	-1.6	-0.1	0.1	-1.1	-2.7	-4.4	-5.35	-6.5	-6.65	-2.05	-1.15	-2.6	-2.35	-1.25	-2.1	-0.05	-2.95	-3.7	-4.7	-5.8
Dec	-7.15	-2.7	-3.7	-0.6	-0.9	-0.05	0.25	-0.8	-2.8	-3.95	-5	-6.05	-6.25	-1.7	-0.8	-2.3	-2.1	-1	-1.8	-0.3	2.6	-3.45	-4.45	-5.60*

Appendix 3. Qualifications of Dr. David C. Richards

Summary

Dr. Richards has conducted life history, taxonomic, and ecological studies on freshwater mollusks in the western U.S.A. for almost two decades. He is considered an expert on several hydrobiid taxa including invasive and threatened species. He is presently conducting the most extensive/intensive native mussel surveys in the Jordan River-Utah Lake drainage to date.

- Ph.D. dissertation: "Competition between threatened Bliss Rapids Snail (BRS) and invasive New Zealand mudsnail in Snake River"
- Research Threatened hydrobiid and other gastropods in mid Snake River
    - 9-year project Metapopulation Viability and Risk assessment of BRS
    - Estimated population size of 3 mm, uncommon, non-randomly distributed snail in 50 miles of Snake River
- Mollusk Survey Hells Canyon, ID
    - Included surveys for newly discovered *Taylorconcha inspirata*
    - Located and documented several unionoida colonies not previously known
- Numerous other T and E and species of concern mollusk surveys
    - *Pyrgulopsis robusta*
    - *Valvata utahensis*
    - *T. serpenticola*
    - *Margaritifera falcata, Gonidea angulata, Anodonta sp.*
- Raised/reared native and invasive hydrobiids in lab including:
    - *Fluminicola coloradensis, Taylorconcha serpenticola*, NZMS
- Merced River, CA restoration and *Margaritifera falcata* relocation
    - 100% relocation success approximately 23 tagged individuals
- Conducted freshwater mollusk identification workshop
- Mollusk Taxonomist for 10 years
- Member of Science panel for USFWS T & E mollusk species status review
- Senior author of several publications and numerous technical reports on mollusks
- Member
    - Freshwater Mollusk Conservation Society
    - American Malacological Society
    - Malacological Society of London
    - Society Freshwater Sciences

C.V. 2015

DAVID CHARLES RICHARDS
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Moab, UT 84532
Email: oreohelix@icloud.com

February 10, 2014

Research Interests: Ecological studies of freshwater ecosystems; biological and ecological assessment and monitoring; and quantitative risk assessments focusing on freshwater mollusks His complete C.V. follows:

Professional Experiences:

2014-Present Director and Senior Research Ecologist, OreoHelix Consulting, Moab, UT
2013- 2014 Aquatic Ecologist, Cramer Fish Sciences, West Sacramento, CA
1999-2012 Senior Research Ecologist, EcoAnalysts, Inc.
2009 Instructor. Introduction to Ecological Statistics. Northwest Environmental Training Center, Seattle WA.
2007-2009 Adjunct Assistant Professor, Department of Ecology, Montana State University, Bozeman, MT
2006-2008 Affiliate Assistant Professor, Land Resources and Environmental Sciences, Montana State University, Bozeman, MT
1997-1999 Biologist, USFWS/Puerto Rico Dept. Natural Resources, San Juan, Puerto Rico
1986-1997 Backcountry Ranger and Trail Crew Leader, Absaroka-Beartooth and Bob Marshal Wilderness, and Yellowstone and Glacier National Parks, fisheries technician Yellowstone National Park

Education

Ph.D. 2004 Montana State University; Biology (Dept. Ecology) with minor in Statistics
M. S. 1996 Montana State University; Entomology and Mountain Research Center
B. S. 1987 Montana State University; Biology, Fish and Wildlife Management Option

Awards, Achievements, and Certificates

2011 PADI Open Water Scuba Certification
1983-2004 Red Cross Advanced First Aid and CPR
1993 Montana Board of Regents Academic Scholarship
1993 Outstanding Biology Student of the Year, Flathead Valley Community College

Professional and Public Service Activities

2006-present Topic-Editor
Encyclopedia of Earth, http://www.eoearth.org/
2001–present Peer-review referee:
American Malacological Society Bulletin
Journal of North American Benthological Society
Western North American Naturalist
Southwest Naturalist
Biological Invasions
Northwest Science
North American Journal of Aquaculture
2001-2005 Initiated and organized 1st, 2nd, 3rd, 4th, and 5th Annual Conference on New Zealand Mudsnail in Western USA, July 9-10, 2001, August 26-28, 2002, August 26-27, 2003, 2005, Bozeman, MT and June 2007, Davis, CA

<u>Field and classroom lecturer:</u> Aquatic Ecology, Stream Ecology, Science Teachers Institute of the Rockies, Montana State University; and local grade schools, Freshwater Mollusk Identification Workshops

<u>Professional Societies, Conservation Organizations, and Committees</u>

American Malacological Society
Freshwater Mollusk Conservation Society
Malacological Society of London
American Fisheries Society
Ecological Society of America
Montana Academy of Science
Society for Freshwater Science
PADI Diving Society
Snake River Snail Conservation Plan Technical Committee
Society for Conservation Biology
Working Group for Ecological Economics and Sustainability Science
Western Regional Panel Aquatic Nuisance Species

<u>Publications</u>

Carling, G.T, Richards, D.C., Hoven, H., Miller, T., Fernandez, D.P., Rudd, A, Pazmino, E., and W. P. Johnson. Accepted: November 2012. Relationships of surface water, pore water, and sediment chemistry in wetlands adjacent to Great Salt Lake, Utah and potential impacts on plant community health. Science of the Total Environment.

Richards, D. C., T. Arrington, S. Sing, and B. L. Kerans. In revision. Competition and coexistence between an invasive aquatic snail and its threatened native congener. American Malacological Society Bulletin.

Richards, D. C. and T, Arrington. In review. Spatial and environmental relationships of three snail taxa in a freshwater spring: with estimates of their abundance. Journal North American Benthological Society.

Richards, D. C., C. M. Falter, G. T. Lester, and R. Myers. In revision. Mollusk survey of Hells Canyon reservoirs and free flowing Snake River, Idaho and Oregon, USA: with focus on rare and listed taxa, including a newly described Taylorconcha sp. American Malacological Society Bulletin.

Richards, D. C., P. O'Connell, and D. C. Shinn. In preparation. Growth Rates of the threatened Bliss Rapids Snail, Taylorconcha serpenticola and the invasive New Zealand mudsnail Potamopyrgus antipodarum at six temperatures.

Richards, D. C. 2010. Mollusk diversity and estimated predation rates by gastropod shell borehole drillers on Turritella spp. at Playa Grande, Las Baulas National Park, Costa Rica. American Malacological Society Newsletter. Vol. 41. No. 2. Pg 5-7.

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Richards, D. C. and D. C. Shinn. 2004. Intraspecific competition and development of size structure in the invasive snail, Potamopyrgus antipodarum. American Malacological Society Bulletin. 19. 1.2.
Richards, D. C., P. O'Connell, and D. C. Shinn. 2004. Simple control method for the New Zealand mudsnail, Potamopyrgus antipodarum. Journal North American Fisheries Management. 24:114-117.
Richards, D. C., L. D. Cazier, and G. T. Lester. 2001. Spatial distribution of three snail species, including the invader Potamopyrgus antipodarum, in a freshwater spring. Western North American Naturalist.61: 375-380.
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Dunkel F. V. and D. C. Richards. 1998. Effect of an azadirachtin formulation of six nontarget aquatic macroinvertebrates. Environmental Entomology. Vol. 27. no. 3. pp 667-674.
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Sriharan, S., A. Wright, P. Singh, F. V. Dunkel, D. C. Richards, W. Bertsch, and C. Wells. 1994. Insecticidal activity of floral and root extracts of Tagetes minuta and Tagetes patula (marigold against the Mexican bean weevil, (Zabrotes subfasciatus), a non-target fish (Gambusia affinis), and the predatory warehouse pirate bug (Xylocoris flavipes). in D. L. Weigmann, ed. New directions in pesticide research, development, management, and policy. Proc. Fourth National Conference on Pesticides. Blacksburg, Virginia, November 1-3, 1993. pp. 542-556.
Weaver, D.K, F.V. Dunkel, L. Van Puyvelde, D.C. Richards, and G.W. Fitzgerald. 1996. Toxicity ad protectant potential of the essential oil of Tetradenia riparia (Lamiales: Lamiaceae) against Zabrotes subfasciatus (Coleoptera: Bruchidae) infesting dried pinto beans (Fabales: Leguminosae) J. App. Entomology. pp. 126-131.

Technical Reports

Richards, D. C. 2012. Development of an Arizona Intermittent Streams Macroinvertebrate IBI. Final Draft Report to Arizona Department of Water Quality. 95pp.
Richards, D. C., J. Rensel, and Z. Siegrist. 2011. Rufus Woods Lake – Columbia River reservoir morphometrics, initial food web, and rainbow trout fishery studies. Report to Colville Confederated Tribes. Nespelem, WA. 138pp.
Miller, T. G., D. C. Richards, Hoven, H. M., Johnson, W. P., Hogset, M., and G. T. Carling. 2011. Macroinvertebrate communities in Great Salt Lake impounded wetlands and their relationship to water and sediment quality and plant communities. Preliminary report to: Jordan River / Farmington Bay Water Quality Council, Salt Lake City, UT. 67pp.
Hoven, H. M., D. Richards, W. P. Johnson, and G.T. Carling. 2011. Plant metric refinement for condition assessment of Great Salt Lake impounded wetlands. Preliminary report to: Jordan River / Farmington Bay Water Quality Council, Salt Lake City, UT. 44pp.
Johnson, W. P., G. T. Carling, and D. Richards. 2011. Chemistry of surface water, pore water, and sediment in seven impounded wetlands bordering Great Salt Lake. Preliminary report to: Jordan River / Farmington Bay Water Quality Council, Salt Lake City, UT. 31pp.

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Richards, D. C. 2010. Characterization of temperature, dissolved oxygen, and macroinvertebrate communities of targeted intermittent streams. Report to Idaho Department of Environmental Quality, Boise, Idaho. 189 pp.

Richards, D. C., W. VanWinkle, and T. Arrington. 2009. Metapopulation viability analysis of the threatened Bliss Rapids Snail, Taylorconcha serpenticola in the Snake River, Idaho: effects of load following. EcoAnalysts Center for Aquatic Studies. Bozeman, MT. 162 pp.

Stephenson, M., D. Bates, D. C. Richards, and T. Arrington. 2009. Risk Assessment of Hydroelectric Operations on the Bliss Rapids Snail in the Middle Snake River, Idaho with a Focus on Load Following. 63pp.

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Richards, D. C., Gustafson, D.L., Kerans, B.L., and C. Cada. 2002. New Zealand mudsnail in the Western USA. Web site. www2.montana.edu/nzms

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Richards, D. C. 2002. The New Zealand Mudsnail invades the Western United States. Aquatic Nuisance Species Digest. Vol. 4. (4): 42-44.

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Richards, D. C. and L.D.Cazier Shinn. 2001. Distribution and abundance of the Bliss Rapids Snail, Taylorconcha serpenticola in Banbury Springs in relation to two hydrobiid snail species and eight environmental gradients. EcoAnalysts Inc. Report. 23pp.

Richards, D. C. and L.D. Cazier Shinn. 2001. Taylorconcha serpenticola densities at Banbury Springs 1999-2001. EcoAnalysts Inc. Report. 16pp.

Richards, D. C. and L.D.Cazier Shinn. 2001. Densities of Taylorconcha serpenticola and Potamopyrgus antipodarum in cobble habitat at the outlet of Banbury Springs 1999-2001. EcoAnalysts Inc. Report. 11pp.

Richards, D. C., L. D. Cazier, and G. T. Lester. 2001. Spatial distribution of three snail species, including the invader Potamopyrgus antipodarum, in Banbury Springs, Snake River Drainage, Southern Idaho, USA. EcoAnalysts Inc. Report.19 pp.

Richards, D. C. and D. L. Gustafson. 2001. Compilation workbook for Mollusk Identification Workshop: New Zealand mudsnail in Western USA . First Annual Conference. July 9 and 10, 2001. Montana State University, Bozeman, MT.

Richards, D. C. and G. T. Lester. 2000. Intraspecific competition of Potamopyrgus antipodarum (Gray) at different densities for a limiting resource under laboratory conditions. EcoAnalysts Inc. Report. 22 pp.

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Richards, D. C. and G. T. Lester. 2000. Comparison of the number of Potamopyrgus antipodarum neonates produced seasonally, between habitats, and in two freshwater springs, Idaho and Montana: a preliminary investigation. EcoAnalysts Inc. Report. 18 pp.

Richards, D. C. and G. T. Lester. 1999. Seasonal changes in densities of three snail species at Banbury Springs, 1999. EcoAnalysts Inc. Moscow, Idaho. 9 pp.

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Richards, D. C. and G. T. Lester. 1999. Evidence for competition between two freshwater snail species, the exotic, biological invader Potamopyrgus antipodarum and the native, threatened Taylorconcha serpenticola in an enclosure study. EcoAnalysts Inc. Moscow, Idaho. 30 pp.

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Richards, D. C. 1998. Assessment of the 1997 release of captive-reared Hispaniola amazons (Amazona ventralis) in the Dominican Republic as related to their training at the parent facility training cage (PFTC), Rio Abajo Aviary, Puerto Rico. Report to Puerto Rico Department of Natural Resources and Environment. San Juan. 14 pp.

Richards, D. C. 1996. Relationship of the number of taxa and the number of organisms in macroinvertebrate samples from mountain streams of Montana. Report to State of Montana, Water Quality Division Department of Environmental Quality. Helena, MT. 5pp.

Richards, D. C. 1996. Effects of an unbiased 300 organism subsample on macroinvertebrate samples from mountain streams of Montana. Report to State of Montana, Water Quality Division Department of Environmental Quality. Helena, MT 12pp.

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Marcus, W. A., J. A. Stoughton, S. C. Ladd, and D. C. Richards. 1995. Trace metal concentrations in sediments and their ecological impacts in Soda Butte Creek, Montana and Wyoming. In: Meyer G (ed), 1995 Field conference guidebook, friends of the Pleistocene-Rocky Mountain cell: Late Pleistocene-Holocene evolution of the northeastern Yellowstone landscape, Middlebury College, Vermont, 9 pp.

<u>Invited Presentations</u>

Richards, D. C., J. Rensel, and Z. Siegrist. 2012. Food web and fisheries studies: Rufus Woods Lake, Columbia River, WA. Large river ecology section moderator; Society for Freshwater Science Annual Meeting. Louisville, KT.

Richards, D. C. and T. Arrington. 2012. Predicting and monitoring the effects of a habitat restoration project on metapopulation viability of two federally listed species in a tributary of the Columbia River. Columbia River Estuary Conference. Astoria, OR. May 15-17.

Farley, J. and D. C. Richards. 2008. A critique of economic valuation of ecosystem services and its applicability to sustainable economic policy. Symposium on Economic Growth and Biodiversity: The Elemental Arguments. Society for Conservation Biology Annual Meeting. Chatonooga, TN. July 13-17.

Richards, D. C. and T. Arrington. 2007. Morgan Lake restoration project: Does Lanx sp. have a problem with that? Mid-Snake River Technical Work Group: Quarterly Meeting. September 19. Boise, ID.

Richards, D. C. and T. Arrington. 2007. Evolutionary consequences of a rapidly evolving invasive species to the viability of a native threatened species. Presented Poster. International Summit: Evolutionary Consequences of a Changing Environment. University of California. Los Angeles, CA. February, 2007.

T. Arrington and D. C. Richards. 2007. Predicting the effects of a habitat restoration project on the population viability of one threatened and one endangered lotic gastropod. Mid-Snake River Technical Work Group: Quarterly Meeting. September 19. Boise, ID.

T. Arrington and D. C. Richards. 2007. Predicting the effects of a habitat restoration project on the population viability of one threatened and one endangered lotic gastropod. World Malacological Congress Annual Meeting. Antwerp, Netherlands. July.

Richards, D. C. and T. Arrington. 2006. Empirical estimates of extinction and colonization rates of the threatened Bliss Rapids Snail for use in metapopulation viability analyses. Presented Paper. Snake River Snail Technical Committee Quarterly Meeting. December 12.

Richards, D. C., C. Smith, and B. Marshall. 2006. Effects of New Zealand mudsnail on water quality bioassessment metrics. Presented paper. California Water Quality Bioassessment Annual Meeting. Davis California. November 28-29th.

Richards, D. C., C. M. Falter, G. T. Lester, and R. Myers. 2005. Mollusk survey and basic ecological studies in Hells Canyon, Snake River, USA. Presented paper. 38th Annual Western Society of Malacologists Conference. Asilomar, Pacific Grove, CA. June 26th-30th.

Richards, D. C. ,B. L. Kerans, G. T. Lester, and D. C. Shinn. 2004. Competition between a threatened and invasive snail in a freshwater spring. Presented paper. North American Benthological Society Annual Meeting. Vancouver, BC.

Richards, D. C. 2004. The invasive New Zealand mudsnail: case study. Invited speaker. Western Division American Fisheries Society Annual Meeting. Salt Lake City, Utah. March 1-4.

Richards, D. C. 2004. Conducted New Zealand mudsnail identification workshop. Western Division American Fisheries Society Annual Meeting. Salt Lake City, Utah. March 1-4.

Richards, D. C. and D. C. Shinn. 2003. Spatial distribution of Bliss Rapids Snail and New Zealand mudsnail in a freshwater spring, Idaho, USA. Presented paper. North American Benthological Society Annual Meeting. Athens GA.

Richards, D. C. and D. C. Shinn. 2003. Intra and interspecific competition between Bliss Rapids Snail and New Zealand mudsnail. Presented paper. Society for Conservation Biology Annual Meeting. Duluth, MN.

Richards, D. C. 2002. The New Zealand Mudsnail in the Western USA. 2002. Presented paper. American Malacological Society Annual Conference. Charleston, SC. August 2002.

Richards, D. C. 2002. The New Zealand Mudsnail in the Western USA. Presented paper. Orvis Fishing Guides National Rendezvous, Cody, Wyoming. April 12.

Richards, D. C. 2002. New Zealand mudsnail in the western USA. Invited paper. Western Regional Panel on Aquatic Nuisance Species Annual Meeting. Las Vegas, Nevada. January 9-10.

Richards, D. C. 2001. The New Zealand mudsnail in the western USA. Presented paper. New Zealand mudsnail in Western USA. First Annual Conference. July 9 and 10, 2001. Montana State University, Bozeman, MT.

Richards, D. C. 2001. Competition between the invader Potamopyrgus antipodarum and a threatened snail species in the Snake River. Presented paper. Aquatic Ecology Group, Montana State University, Bozeman, Montana.

Richards, D. C., G. T. Lester, and D. Cazier. 1999. Basic ecological findings on the New Zealand mudsnail (Potamopyrgus antipodarum) in the Middle-Snake River and the Thousand Springs Complex, Southern Idaho. Presented paper. Seventh Annual Yellowstone National Park Symposium on Exotic Species in Yellowstone. October 11-12, 1999.

Richards, D. C., G. T. Lester, and D. Cazier. 1999. The invasion of the New Zealand mud snail (Potamopyrgus antipodarum) in the Middle Snake River: potential impacts. Presented paper. Ninth Annual Nonpoint Source Water Quality Workshop. Boise, Idaho.

Richards, D. C., M. Rolston, and F. V. Dunkel. 1997. The distribution and abundance of Pteronarcys californica in the Madison River, MT. Presented paper. Montana Chapter of American Fisheries Society Annual Meetings. Bozeman, MT

Richards, D. C. 1996. Macroinvertebrates as water quality indicators in Soda Butte Creek. Presented paper. The Third Interagency Conference on the Soda Butte Creek Watershed. Yellowstone National Park, September 10-11, 1996.

Richards, D. C., M. Rolston, and F.V. Dunkel. 1995. The distribution and abundance of Pteronarcys californica in the Madison River, MT. Poster presentation. Entomological Society of America. Las Vegas, Nevada.

Richards, D. C. and R. Bukantis. 1995. The use of aquatic insects as indicators of water quality in mountain streams in Montana using modified Rapid Bioassessment Protocols. Presented paper. Montana Academy of Sciences; Clark Fork Symposium, Missoula, MT.

Richards, D. C. and F. V. Dunkel. 1994. The use of aquatic insects as indicators of water quality in mountain streams in Montana. Poster presentation. Entomological Society of America. Dallas Texas.

Richards, D.C., F.V. Dunkel, L. VanPuyvelde, and S. Sriharan. 1992. Effect of insecticidal plant extracts on the pirate bug, Xylocoris flavipes. Poster presentation. Entomological Society of America. Baltimore, MD

Rodriquez, D.C., F.V. Dunkel, D.C. Richards, and D.K Weaver. 1992. Fumigative, repellent, and oviposition deterrent properties of mountain sagebrush, Artemesia tridentata, for stored grain insects. Poster presentation. Entomological Society of America. Baltimore, MD.

Appendix 4. Mollusk surveyors involved in the Mill Creek/Jordan River surveys

All of the following mussel surveyors that participated on the Mill Creek/Jordan River survey were trained by Dr. David Richards and had at least 80 hours of mussel survey field experience prior to the survey, August 2015:

Dr. Theron Miller, JRFWWQC
Jedd Powell, South Davis Sewer District, SLC, UT.
W.D. Robinson, South Davis Sewer District, SLC, UT.
Frank Fluckiger, South Davis Sewer District, SLC, UT.

Appendix 5. Raw NH_3 data collected during native mussel surveys in 2015.

Location	Date	Time	Latitude	Longitude	NH_3 (mg/L)
Walmart	June 26, 2015		40.387088	-111.826482	Under Range
Mill Pond #1	June 26, 2015		40.378535	-111.829951	0.49
Mill Pond #2	June 26, 2015		40.384355	-111.826759	0.01
Spring Crk #1	June 26, 2015		40.386791	-111.826506	0.02
Spring Crk #2	June 26, 2015		40.386743	-111.826513	0
Spring Crk #3	June 26, 2015		40.385771	-111.826859	0.17
Burraston Pond 1A	July 1, 2015	16:20	39.797815	-111.864944	0.76
Burraston Pond 1B	July 1, 2015	16:45	39.797131	-111.864047	0.64
Burraston Pond 2A	July 1, 2015	13:20	39.793522	-111.862527	0.22
Burraston Pond 2B	July 1, 2015	13:25	39.793481	-111.863802	0.19
Burraston Pond 3A	July 1, 2015	14:40	39.799367	-111.866124	0.55
Burraston Pond 3B	July 1, 2015	14:45	39.798666	-111.865289	0.62
Current Creek #4	July 1, 2015	15:10	39.796078	-111.867981	0.39
Timp Water Treat. Outflow	July 2, 2015	10.55	40.336531	-111.776884	0.86
Timp Outflow	July 2, 2015	10.51	40.336383	-111.777043	0.75
Timp Outflow Confluence with UL	July 2, 2015	13:22	40.335876	-111.777196	0.65
Lindon Marina	July 2, 2015	12:56	40.325636	-111.766036	0.7
Utah Lake Orem Outflow 1	July 17, 2015		40.276933	-111.744394	0.55
South Pelican Point	July 20, 2015		40.267851	-111.848098	1.57
North Pelican Point	July 20, 2015	13:50	40.273943	-111.859302	1.13
Middle Pelican Point	July 20, 2015	14:18	40.268584	-111.853459	0.73
Saratoga Springs Marina	July 20, 2015	14:57	40.302281	-111.878431	1.07
Spring Creek (Lehi) A	July 22, 2015		40.371943	-111.834603	1.01
Spring Creek (Lehi) B	July 22, 2015		40.370099	-111.835493	0.84
Spring Creek (Lehi) C	July 22, 2015		40.362046	-111.83801	1.04
Spring Creek (Lehi) Outflow	July 22, 2015		40.358678	-111.850021	1.05
Hobble Creek (Springville) A	July 23, 2015		40.188366	-111.444554	0.44
Hobble Creek (Springville) B	July 23, 2015		40.163115	-111.50797	0.88
Hobble Creek (Springville) C	July 23, 2015		40.149476	-111.560568	0.99
Salt Creek (IBIS Pond)	July 28, 2015		41.669363	-112.236253	1.84

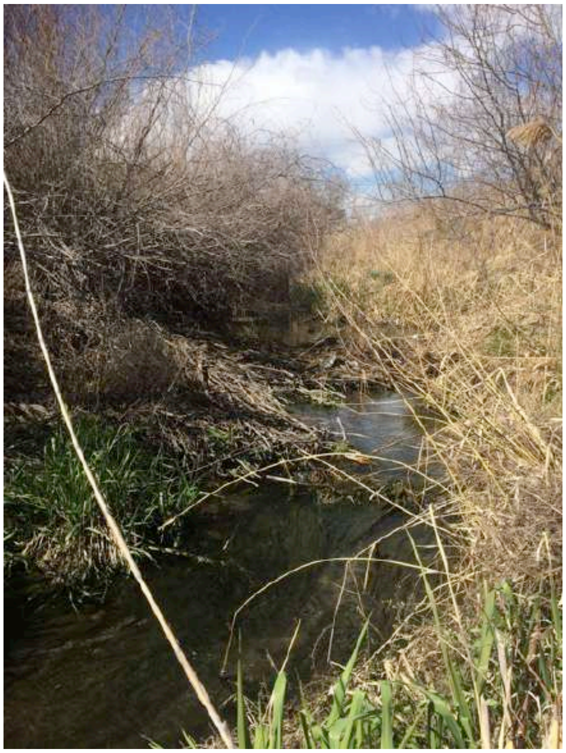
Pintail	July 28, 2015		41.577763	-112.30269	2.06
Provo River @ Utah Lake	July 29, 2015		40.236237	-111.742644	0.43
Provo River 2	July 29, 2015		40.23669	-111.731969	0.58
Provo River 3	July 29, 2015		40.238205	-111.721611	0.57
Beaver Creek 1	July 30, 2015		NA	NA	0.39
Beaver Creek 2	July 30, 2015		NA	NA	0.27
Beaver Creek 3	July 30, 2015		NA	NA	0.2
Beer Creek	August 17, 2015	11:30	40.114336	-111.793159	1.19
Spanish Fork Confll Utah Lake A	August 17, 2015	10:20	40.150498	-111.726553	0.34
Spanish Fork Confll Utah Lake B	August 17, 2015	12:10	40.16558	-111.735172	0.44
Spanish Fork Confll Utah Lake C	August 17, 2015	12:18	40.167011	-111.748613	0.66
Jordan River @ 12300 South	August 18, 2015	12:00	40.526858	-111.919306	0.24
Bingham Crk Confl JR 7800 South	August 18, 2015	15:11	40.604743	-111.920703	0.78
Jordan River @ 4800 South	August 18, 2015	16:10	40.666283	-111.908446	0.78
Beer Creek	August 19, 2015	11:20	40.081558	-111.744633	0.53
Beer Creek 1	August 20, 2015	6:44	40.081558	-111.744633	0.58
Beer Creek Up Stream 1	August 20, 2015	7:30	40.082329	-111.731313	0.71
Beer Creek 2	August 20, 2015	13:45	40.081558	-111.744633	2.3
Beer Creek Up Stream 2	August 21, 2015	9:45	40.082329	-111.731313	1.52
Beer Crk Benjamin Slough W 6400 S	August 24, 2015	10:40	40.114115	-111.793117	0.39
Benjamin Slough W 7300 S	August 24, 2015	11:55	40.097666	-111.775782	0.76
Beer Creek Arrowhead	August 24, 2015	14:00	40.065237	-111.707345	0.34
Beer Creek N 460 W	August 24, 2015	14:25	40.063303	-111.682693	1.66
Mill Creek 1 Below Plant	August 25, 2015	11:35	40.708291	-111.916445	2.55
Mill Creek 2 Below Plant	August 25, 2015		40.70837	-111.917386	2.28
Mill Creek 3 Below @ Outfow Conv.	August 25, 2015	12:20	40.70837	-111.917386	2.3
Mill Creek 4 Above CV Outflow	August 25, 2015	12:30	40.708153	-111.914813	0.99
Mill Creek @ 300 West	August 26, 2015		40.706259	-111.899921	0.83
Mill Creek Willow Park	August 26, 2015	15:00	40.704556	-111.879682	1.14
Unknown @ Willow Park	August 26, 2015		40.704967	-111.877751	1.66
Jordan River @ Up Stream MCC	August 27, 2015		40.707327	-111.922852	0.7
Jordan River @ 100 Yds Dn Stream MCC	August 27, 2015		40.71028	-111.923626	3.31
Jordan River @ 200 Yds Dn Stream MCC	August 27, 2015		40.711593	-111.923741	0.77
Jordan River @ 300 Yds Dn Stream MCC	August 27, 2015		40.713244	-111.923912	2.99
Jordan River @ 400 Yds Dn Stream MCC	August 27, 2015		40.715081	-111.924159	1.82
Jordan Riv @ 100 Yds Dn Stam MCC 1B	August 27, 2015		40.71028	-111.923626	1.32

Jordan Riv @ 200 Yds Dn Stam MCC 2B	August 27, 2015		40.711593	-111.923741	1.37
Jordan Riv @ 300 Yds Dn Stam MCC 3B	August 27, 2015		40.713244	-111.923912	1.79
Jordan Riv @ 400 Yds Dn Stam MCC 4B	August 27, 2015		40.715081	-111.924159	1.89
East Bay Golf Cour@ Hwy Over Pass	August 28, 2015		40.207797	-111.652335	0.93
Jordan Riv @ Above Mill Crk Confl	August 31, 2015	15:45	40.707327	-111.922852	0.72
Jordan Riv @ 100 Yds Dn Stream East	August 31, 2015	15:40	40.71028	-111.923626	1.71
Jordan Riv @ 200 Yds Dn Stream East	August 31, 2015	15:37	40.711593	-111.923741	1.95
Jordan Riv @ 300 Yds Dn Stream East	August 31, 2015	15:35	40.713244	-111.923912	1.18
Jordan Riv @ 400 Yds Dn Stream East	August 31, 2015	15:30	40.715081	-111.924159	1.92
Jordan Riv @ 100 Yds Dn Stream West	August 31, 2015		40.71028	-111.923626	0.78
Jordan Riv @ 200 Yds Dn Stream West	August 31, 2015		40.711593	-111.923741	2.33
Jordan Riv @ 300 Yds Dn Stream West	August 31, 2015		40.713244	-111.923912	1.66
Jordan Riv @ 400 Yds Dn Stream West	August 31, 2015		40.715081	-111.924159	1.42

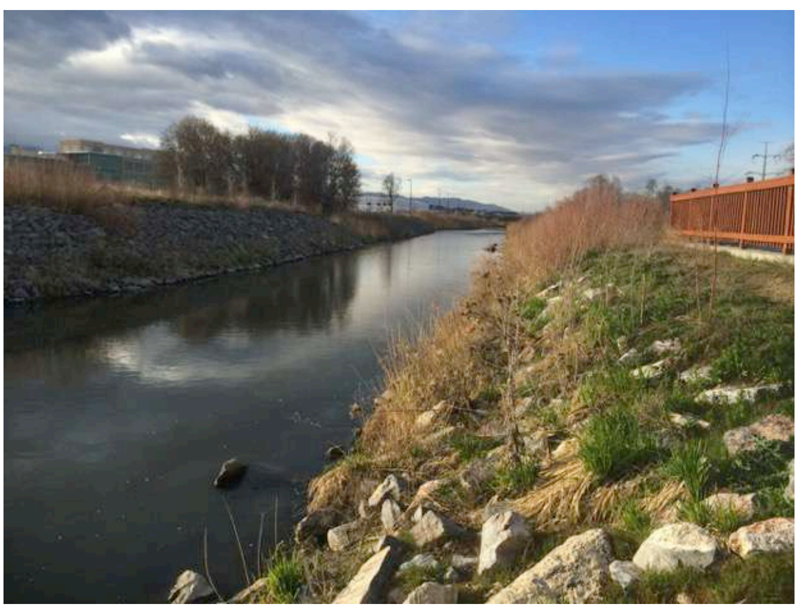
Appendix 6. Photos of Mollusk Survey Sites in Jordan River.

Jordan River "Narrows" section. Furthest upstream site surveyed on Jordan River.

Side channels of Jordan River were also surveyed.



Spring creek tributary of Jordan River. No native unionid mussels were found in these tributaries but live non-pulmonate snails, primarily *Fluminicola* coloradoensis and *Pyrgulopsis* sp., were common and empty shells were abundant.



Typical channelization of Jordan River. Channelization and associated dredging is not conducive to native unionid mussel population viability.

Mill Creek upstream of CVWTF and Jordan River.

Many downstream sections of the Jordan River have substrates of mostly silt, sand, clay, and organic matter.

Muskrat midden of invasive clam, *Corbicula fluminea*. No native unionids were found in this midden.

Jordan River bank stabilization rip rap.

Mollusk surveyor examining Jordan River substrate.

Typical upstream section of Jordan River. Mostly gravel and sand substrate. Very good *Corbicula* habitat.

Mollusk surveyor positioning aquascope for visualizing substrate and mollusks.

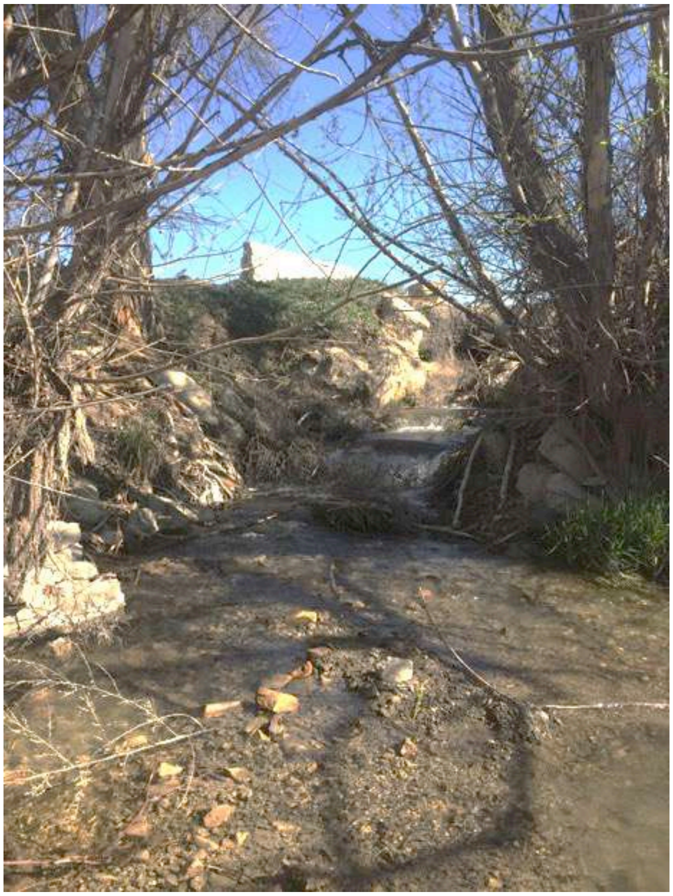
Common Jordan River habitat. Side bars were visually examined for mollusk shells.

Large Jordan River sidebar that was extensively examined for mollusk shells (mostly *Corbicula* shells were found).

Mollusk surveyor preparing to use aquascope along channelized section of Jordan River.

Shoreline of Mill Pond, Utah County. Several *Anodonta* shells were collected about 50 meters from this site. Thousands of *Corbicula* shells were observed along shores of Mill Pond.

Mill Pond, Utah County.



Outlet of Mill Pond, Utah County.

Spring Creek, upstream of Mill Pond, Utah County.

Spring Creek downstream of Mill Pond where *Anodonta* shells were collected amidst the hundreds of *Corbicula*.

Appendix 7. Jordan River-Utah Lake Drainage Native Mussel Surveys, 2014-2016: Summary Spreadsheet

The summary spreadsheet for the 2014-2016 native mussel surveys is in the attached Excel spreadsheet:
“Appendix 8 Native Mussel Spreadsheet FINAL read only. xlsx

Appendix 8. Defining Native Mussel Historical and Current Data for Regulatory Purposes

Defining 'historical' data as related to native mussel presence or absence is mostly arbitrary from an ecological or conservation based perspective. Management agencies have different definitions of 'historical' data used to set regulatory criteria. For example, EPA (2013) reports that:

> "Among states, the definition of historical and current data varies. In general, "current data" are less than 10-20 years old, while "historical data" are older than this range. However, some states consider records older than 1970 to be historical. Similarly, West Virginia categorizes its data into one of three different groupings: historical (information collected prior to 1975), so-called "Taylor data" (collected from 1977-1989), and new data (collected 1990-present).
>
> The use of historical and current data also varies among states and other entities. In some states, data older than 10-20 years either do not carry as much weight or are not considered when assessing current conditions in relation to regulatory decision-making (e.g., Georgia, New Jersey, and Illinois). Likewise, Maryland assumes that data less than 20 years old are representative of current conditions unless enough evidence is available to contradict that assumption. In Montana, data older than 10 years are considered to be unreliable without backup verification. In contrast, some entities use historical data dating back to 1919 (e.g., The Partnership for the Delaware Estuary) and do not think that a specific time frame for acceptable data should be used due to the recolonization potential of mussels."

However, EPA (2013b, page 11) also suggests that:

> "At a minimum, to protect existing uses of the waterbody, the use of historical data should be considered for presence determinations if the survey found mussels on or after November 28, 1975. This position is similar to that previously expressed by EPA in 1999 for determination of the presence of early life stages (ELS) of fish, which is quoted below:
>
> According to the Clean Water Act, States and Tribes are to protect existing uses, and therefore should protect for the most sensitive uses that have occurred in a given waterbody since November 1975. 40 CFR 131.12(a)(1) and 40 CFR 131.3(e). Hence, States and Tribes should consider both current and historical species that have used a waterbody for spawning and rearing since November 1975. Even where water quality is protective of designated uses, the current species composition in a waterbody may not reflect all species that have used the waterbody for spawning or rearing since 1975. It is EPA's position that any ELS-absent provision should not prevent the return of any species associated with an existing or designated use. Therefore, States and Tribes should evaluate both current and historical data back to November 1975, in determining a presence or absence of sensitive life stages (Environmental Protection Agency, FRL-6513-6, Notice of availability, 64 Federal Register 245 (December 22, 1999), pp. 71973-71980).
>
> Accordingly, a state or tribe that has mussel presence survey data dating on or after November 28, 1975, should assume mussels are present to protect existing uses."

Utah Department of Water Quality has adopted EPA's minimum 'historic' date as November 28, 1975, as of the writing of this report.

Margaritifera falcata in JRUL drainage

There is only one known *M. falcata* population in the entire state of UT, which is outside of JRUL drainage. Available historic records support this. Hovingh (2004) suggested that, "in

Utah's Jordan River drainage, populations could have been extirpated in 1948. UDNR: DWR (2015) Appendix A states that regarding *M. falcata* "No populations have been found at historical localities in recent times (Clarke 1993)."

We could not find *Margaritifera falcata* presence survey data in JRUL drainage on or after November 28, 1975 other than a possible but unverified anecdotal report of a population in the headwaters of the Provo River (Danny Potts, fisheries biologist, personal communication). No exact date or location when and where that observation was made could be determined other than the population was observed 'when he was a young boy somewhere in the Upper Provo River'. We did not find any live, recently dead, or unweathered *M. falcata* shells in any waterbody in the JRUL drainage that we surveyed and consider *M. falcata* to be absent in mid to lower elevation waters in the JRUL drainage, including Utah Lake and the Jordan River, and they are also very likely absent in upper elevation tributaries.

Anodonta in JRUL drainage

UDNR: DWR (2015) Appendix A states that based on the inclusion of the two species of Anodonta into one clade (sensu Mock et al. YEAR), "The (Anodonta) population formerly occurring in Utah Lake was likely to be among the largest in Utah, yet it was the first population reported to have been extirpated". We could find no Anodonta presence survey data in other waters in the JRUL drainage on or after November 28, 1975, other than the two previously unknown extant population locations that we discovered and discussed in this report and for the previously reported known extant Anodonta population surviving in Currant Creek. We also consider Anodonta to be present in Spring Creek on or after November 28, 1975 after finding several somewhat unweathered shells. Based on our literature reviews and surveys it appears that there are only three locations in the JRUL drainage where Anodonta can be considered 'present' using EPAs' and UDWQs' November 28, 1975 and 'unweathered shell' criteria: Beer Creek, Currant Creek, and Spring Creek.

Appendix 9. Defining "resident" ("occur at the site") and "not resident" ("do not occur at the site") as it pertains to EPA and UDWQ ammonia criteria recalculation

Determining whether native mussels are "resident" or "not resident" has important implications for setting ammonia criteria by UDWQ and EPA. Both agencies adhere to the definitions of "resident" and not resident" outlined by EPA (2013b), page 5:

"The Recalculation Procedure is dependent on the species that occur at the site. As stated in *Revised Deletion Process for the Site-Specific Recalculation Procedure for Aquatic Life Criteria* (USEPA 2013b), the equivalent terms "resident" and "occur at the site" include life stages and species that meet one of the following elements:

- Are usually present at the site.
- Are present at the site only seasonally due to migration.
- Are present at the site intermittently because they periodically return to or extend their ranges into the site.
- Were present at the site in the past, are not currently present at the site due to degraded conditions, but are expected to return to the site when conditions improve, or
- Are present in nearby bodies of water, are not currently present at the site due to degraded conditions, but are expected to be present at the site when conditions improve.

The terms "resident" or "occur at the site" do not include life stages and species that meet one of the following elements:

- Were once present at the site but cannot exist at the site now due to permanent (physical) alterations of the habitat or other conditions that are not likely to change within reasonable planning horizons.
- Are still-water life stages or species that are found at a flowing-water site solely and exclusively because they are washed through the site by stream flow from a still-water site."

We determined that *Margaritifera falcata* were once present throughout portions of the JRUL drainage, particularly higher elevation streams, but cannot exist there due to the following permanent alterations of the habitat and other conditions that are not likely to change within reasonable planning horizons (Table 3); and we consider *M. falcata* as "not resident" in the JRUL drainage particularly in lower elevation waters, including Utah Lake. The only potential exception to *M. falcata* being "not resident" is the remote possibility that a small population still exists in the Provo River headwaters.

Table 3. Reasons for *M. falcata* "not resident" in JRUL drainage[a] conclusion:

1. Absence or extreme low *M. falcata* population abundance/density for glochidia production and survival (see Glochidial success, fish host abundance, and mortality rates)
2. Inadequate secondary fish host densities for successful glochidial attachment, including severe lack of migratory secondary fish hosts (see Glochidial success, fish host abundance, and mortality rates)

3. Dispersal barriers including dams, diversions, and dewatering, high water temperatures in lower elevations including Utah Lake (see Dispersal and Connectivity, Suitable and Unsuitable Habitat)
4. Loss of connectivity between suitable habitats (see Dispersal and Connectivity, Suitable and Unsuitable Habitat)
5. Loss of genetic diversity and associated negative effects including: inbreeding depression, mutational meltdown, and the extinction vortex phenomenon (see Metapopulation Viability)
6. Introduced and native predators including; carp, muskrats, crayfish, Asian clams (which filter feed on glochidia), etc., (see Predation; Competition, Predation, and the Invasive Ecosystem Engineer, Corbicula)
7. Interspecific competition with Asian clams for food resources and habitat space (see Competition, Predation, and the Invasive Ecosystem Engineer, Corbicula)
8. Increased human population growth, urbanization, and economic activities that require additional water use and reduce suitable habitat, and predicted decrease in water availability due to global climate change (see Human Population Growth and Global Climate Change)
9. Loss of suitable juvenile and adult habitat including; non-natural flow regimes, channelization, sedimentation, water quality, and loss of flood event scouring (see Substrate Habitat; Dispersal and Connectivity, Suitable and Unsuitable Habitat and other sections throughout the report)
10. Demographic and environmental stochasticity effects on declining and small populations (see Conclusion)

[a]The only exception to *M. falcata* being "not resident" is the remote possibility that a small population still exists in the Provo River headwaters.

We determined that Anodonta were once present throughout most portions of the JRUL drainage, particularly lower elevation streams and Utah Lake, but cannot exist in most locations due to the following permanent alterations of the habitat and other conditions that are not likely to change within reasonable planning horizons (Table 4). We consider Anodonta as "not resident" in the JRUL drainage except for three highly fragmented and isolated populations consisting of very few individuals (see Beer Creek ; Spring Creek; Beer Creek; Currant Creek: *Last Hope for Anodonta?*; and Appendix 8).

Table 4. Reasons for Anodonta "not resident"[a] conclusion:

1. Extreme low Anodonta population abundance needed for glochidia production and survival (see Native Mussel Surveys 2014-2015; Native Mussel Surveys 2016; Glochidial success, fish host abundance, and mortality rates)
2. Inadequate secondary fish host densities for successful glochidial attachment including severe lack of migratory secondary fish hosts (see Glochidial success, fish host abundance, and mortality rates)
3. Dispersal barriers including dams, diversions, and dewatering, high water temperatures in lower elevations including Utah Lake (see Dispersal and Connectivity, Suitable and Unsuitable Habitat)
4. Loss of connectivity between suitable habitats (see Dispersal and Connectivity, Suitable and Unsuitable Habitat; Metapopulation Viability)
5. Loss of genetic diversity and associated negative effects including: inbreeding depression, mutational meltdown, and the extinction vortex phenomenon (see Metapopulation Viability)
6. Introduced and native predators including; carp, crayfish, muskrats, Asian clams (which filter feed on glochidia), etc. (see Predation; Competition, Predation, and the Invasive Ecosystem Engineer, Corbicula)
7. Interspecific competition with Asian clams for food resources and habitat space (see Competition, Predation, and the Invasive Ecosystem Engineer, Corbicula)
8. Increased human population growth, urbanization, and economic activities that require additional water use and reduce suitable habitat, and predicted decrease in water availability due to global climate change (see Human Population Growth and Global Climate Change)
9. Loss of juvenile and adult suitable habitat including; non-natural flow regimes, channelization, sedimentation, and loss of flood event scouring (see Substrate Habitat; Dispersal and Connectivity, Suitable and Unsuitable Habitat and other sections throughout the report)
10. Demographic and environmental stochasticity effects on declining and small populations (see Conclusion)

[a]We consider Anodonta as "not resident" in the JRUL drainage except for three highly fragmented and isolated populations consisting of very few individuals.

Appendix 10. Anodonta Genetics

The following results are from Anodonta genetic analyses conducted for the Wasatch Front Water Quality Council by USU Molecular Ecology Laboratory.

FINAL REPORT

Date: 15 January 2016

Project: 1511 – OreoHelix Mussels

Prepared for: David C. Richards, Ph.D.
OreoHelix Consulting
P.O. Box 996
Moab, UT 84532

Prepared by: Jim Walton, Research Technician
Karen Mock, Laboratory Director
Molecular Ecology Laboratory
Utah State University

Scope of Work: Services to be provided:

(1) Genotyping 3 freshwater mussel samples (presumably *Anodonta* spp.; whole voucher specimens provided in 95% ethanol).

   a. DNA extraction using Qiagen Blood & Tissue kit
   b. DNA quality assessment
   c. Amplification and sequencing of mitochondrial COI locus in samples, using published PCR primers and protocols, for comparison to preexisting data from other western US Anodonta populations and major phylogenetic species groups.
   d. Amplification and scoring of seven nuclear microsatellite loci known to be polymorphic in the *Anodonta californiensis/ nuttalliana* clade.

(2) Microsatellite genotyping of 15 individual *A. californiensis/nuttalliana* (previously genotyped) from laboratory archives representing a wide range of allele sizes, for the purpose of establishing an 'allele ladder' as an allelic size reference. Standardizing allele sizes allows

comparison of the samples (above) to existing data from rangewide *Anodonta* populations.

(3) Analysis of mitochondrial haplotypes and microsatellite genotypes from the three provided samples, in the context of genotypes from other western U.S. *Anodonta* populations, to determine population/watershed affiliations.

Introduction

A total of 3 freshwater mussel samples were provided to the USU Molecular Ecology Laboratory by OreoHelix Consulting. Mitochondrial COI sequences and 7 polymorphic microsatellite loci were analyzed for comparison to other western U.S. *Anodonta* populations with respect to phylogeographic groups previously identified in Mock *et al.* (2010).

Methodology and Results

DNA Extraction and Quality Assessment

Genomic DNA extraction and quality assessment for two of the samples (MUS0001 and MUS0002) provided October 1, 2015 was carried out as per the Preliminary Report, dated October 26, 2015. Both samples were represented by small foot snips. MUS0002 showed significant DNA degradation. A third *Anodonta* sample marked "Salt Creek", dated July 2015 (MUS0003) was received on November 5, 2015. MUS0003 consisted of most or all of the soft tissues apparently excised from a whole specimen.

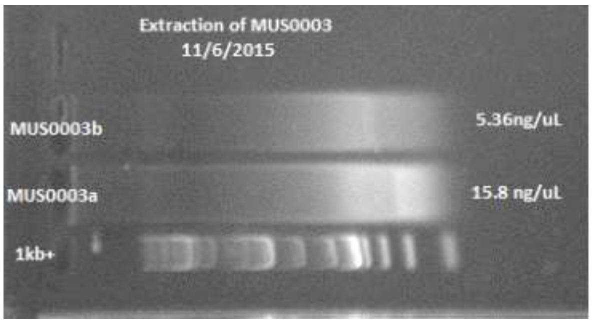
Genomic DNA from MUS0003 was extracted in two separate microcentrifuge tubes (MUS0003a and MUS0003b). Both extracted MUS0003 samples were found to have degraded DNA, similar to that of MUS0002, as reported in the Preliminary Report (October 26, 2015). Assessment via agarose gel showed degradation, with the majority of low molecular weight fragments in the 0 bp to 500 bp range with little-to-no fluorescence >500bp (See Figure 1). MUS0003a contained 15.8ng/µL and MUS0003b contained 5.36ng/µL. MUS0003a was used in all subsequent assays.

Sequencing

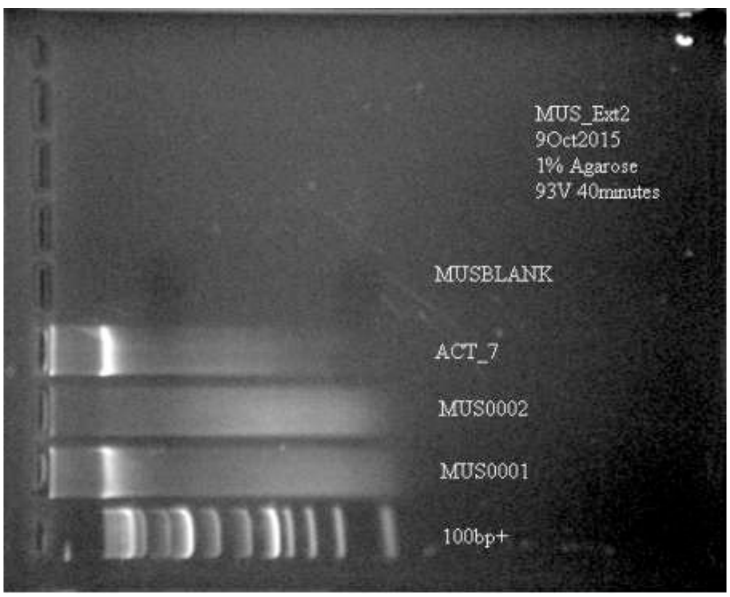
We amplified an approximately 650-bp region of the mitochondrial F-lineage cytochrome c oxidase subunit I (mtCOI) gene following Mock *et al.* (2010). Amplification reactions contained 0.2 mM dNTP's, 1X Reaction buffer, 1.5 mM $MgCl_2$, 1U *Taq* DNA polymerase (Frontier Genomics), 0.1 mg/mL BSA, and 0.5 µM of each forward and reverse primer. The reaction was denatured at 94 °C for 4 min, followed by 35 cycles of 92 °C for 30 s, 54 °C for 60 s, 72 °C for 90 s, with a final extension step of 72 °C for 10 minutes. Reactions were then analyzed for quality assurance via 1.4% agarose gel prior to sequencing, which was performed by Eton Biosciences (San Diego, CA). Bidirectional sequences were obtained using primer pairs LCO1490 / HCO2198 and LCO1550 / HCO2100 for each sample (Chong *et al.* 2008; Mock *et al.* 2010). Contiguous sequences were aligned and trimmed using Geneious (v5.3.6, Biomatter Ltd.) software. The final sequence (consensus of bidirectional sequence data) for

Figure 1. (a) DNA quality and quantity assessment results of sample MUS0003 alongside GeneRuler's (Thermo Scientific) 1kb+ DNA Ladder. (b) MUS0001 showed fair quality DNA likely suitable for downstream analysis. The sample from "Salt Creek" (MUS0002) showed poor quality DNA. Sample ACT_7 showed high quality DNA.

(a)



(b)



each sample was aligned with other known haplotype sequences from western US *Anodonta* to determine which haplotypes and species group(s) (Mock *et al*. 2010) were represented by the OreoHelix samples provided to the lab. MEGA (Molecular Evolution Genetic Analysis) (Tamura *et al*. 2011) software was used for comparison to known haplotypes from Mock *et al.* (2010).

Sequencing of the mtCOI locus yielded a single 610 bp sequence (see Figure 2) common to all provided mussel samples. Use of the NCBI BLAST alignment tool resulted in a 99% match to individuals in the *A. californiensis/nutalliana* clade (GenBank Accession #'s EU327355 and EU327357). Assayed samples provided a 572 bp long aligned sequence, which did not allow complete comparison to our database sequences, which are 604 bp long. Nevertheless, those 572 bp are identical to haplotype HH in the *A. californiensis/nutalliana* clade. Haplotype HH is

Figure 2. mtCOI Sequence for MUS0001, MUS0002, and MUS0003 – 610 bp

5'TTAAATTACGATCCGTCAACAGCATTGTAATAGCACCAGCTAAAACCGGTAAAGCAGCAACTAATAACACAGCTGTCACGGC
AACAGCCCAAACAAATAAAGGAATTCGCTCAGCGACCAAACCAGGAGATCGCATGTTTCCAACAGTAGAAATAAAATTAATAG
CCCCCAGAATTGAAGAAGCACCAGCAAGATGTAAAGAAAAAATGGCCAAATCCACAGAAGCCCCGGAATGAGCAACATTTCC
AGATAAAGGTGGATATACCGTCCAACCAGTACCAACACCACTCTCCACTAATGAAGAGCTTAACAACAAAAACAAAGCTGGCA
CAAGTAATCAAAACCTTAAATTATTTAACCGAGGAAAAGCCATATCAGGAGCACCAATTATCAAAGGAATCAATCAATTACCGA
ATCCACCAATCATCATTGGTATTACCAAGAAAAAAATTATCATGAAAGCATGAGCCGTAACAATTACATTGTATAACTGATCAT
CTCCCAATAATCTTCCAGGTTGACCCAACTCAGCTCGAATTAACAGCCTTAAAGCCAACCCAATCAATCCAGACCACAAAGCAA
AAAGTAAGTATAAAGTACCAATATCTTT3'

the only haplotype found in the Bonneville Basin, but is also found in the upper Snake River (AWP) and one population in Washington (ALC), see Table 2 in Mock *et al.* 2010.

<u>Microsatellites</u>

In order to determine affiliations with other, previously genotyped, western U.S. *Anodonta* populations, 7 microsatellite loci from Mock *et al*. (2010) were amplified and scored (CA-C03, CA-C04, CA-C05, CA-C09, CA-E11, CA-F03 and CA-G02). A dye-labelled CAG- or M13R-tag was added to the 5' end of the forward or reverse primer, a third complimentary CAG- or M13R- dye-labelled primer was also added to the reaction, following Chong *et al*. (2009). PCR reactions were carried out in 10 µL reactions and contained 0.2 mM dNTP's, 1X reaction buffer, 2.5mM $MgCl_2$, 0.25 U *Taq* polymerase (Frontier Genomics), 0.25 µM forward and reverse primer, and 0.025 µM fluorescently labeled CAG- or M13-tagged primer. Thermal cycler conditions followed Chong *et al*. (2009).

A subset of samples (15) previously analyzed (Chong *et al.* 2009; Mock *et al.* 2010) were included as part of this assay in order to standardize allele sizes and for comparison to the broader dataset used in Mock *et al.* (2010) (See Table 1). Due to the degraded state of extracted genomic DNA of two of the provided samples (MUS0002 and MUS0003), microsatellite assays, including samples used for size standardization, were completed in triplicate at each locus, each in separate PCR reactions. Additionally, all client-provided samples (n=3), as well as two of the 15 reference samples, were replicated for fragment analysis following PCR. A negative control was also included with all assays to preclude possible contamination issues. Microsatellite data was scored using GeneMarker 2.6.2 (Soft Genetics, LLC.) and subsequently compiled and exported to GeneClass2 (Piry *et al.* 2004) using GenAlEx

Table 1. List of reference samples run to establish allelic size standards for subsequent comparison to Mock *et al.* (2010) study data.

ABR_005	ACT_008	AJH_001	AMI_002	APM_009
ACC_012	AEW_007	AJS_004	AOR_006	APM_010
ACT_007	AJF_005	ALC_001	AOR_011	APT_004

software (Peakall & Smouse, 2012). Scored genotypes were then aligned and allele sizes adjusted to correlate to the reference database for further analysis.

Allelic dropout (amplification failure) was not observed between replicated samples, indicating that microsatellite genotypes are reliable and complete. Using the original 539 samples analyzed in Mock *et al*. 2010, populations with less than 14 (n<14) representative samples (ABR, AMI, and AOT) were removed as they did not provide the statistical power necessary to accurately assign individuals to a population. All three client-provided samples assigned to different populations (Table 2). Using the frequency-based population assignment test in GeneClass2 software (Piry *et al.* 2004). MUS0001 and MUS0003 were strongly assigned to populations ABP (99.9%) and AWD (98.7%), respectively. MUS0002 was assigned to population AEW 55.2% of the time and APL 42.1 % of the time. Populations ABP and APL are located in the Bonneville Basin, while populations AEW and AWD populations are located on the western side of the Lahontan Basin (See Figure 1 in Mock *et al.* 2010). It may be possible for samples to belong to or be associated with populations not sampled in Mock *et al.* (2010). Samples assayed contained no unique microsatellite alleles (Table 3).

Table 2. Population assignment test results. Test results show top three assigned populations for each provided mussel sample with %score being the proportion of time it was assigned to the respective population.

Assigned sample	rank 1	score %	rank 2	score %	rank 3	score %
MUS0001	ABP	99.93	AWP	0.07	ADC	0.01
MUS0002	AEW	55.23	APL	42.12	ABU	0.59
MUS0003	AWD	98.69	AEW	0.59	WiCol	0.29

Table 3. Genotype of each of the client-provided samples. LabID indicates name assigned by USU Molecular Ecology Lab and used for reporting. Client ID indicates distinguishing information placed on client provided samples. CA-"x" refers to each of the microsatellite loci (Mock *et al.* 2010). Allele sizes for each locus and individual is provided.

LabID	ClientID	CA-C03 alleles	CA-C04 alleles	CA-C05 alleles	CA-C09 alleles	CA-E11 alleles	CA-F03 alleles	CA-G02 alleles
MUS0001	Unknown, 8/20/15	321 325	299 299	181 181	254 258	312 328	427 427	178 178
MUS0002	Salt Creek, 8/21/15	321 333	299 301	205 207	258 264	324 352	424 424	178 178
MUS0003	Salt Creek, 7/15	333 333	297 299	201 203	256 270	338 344	424 427	178 178

Remaining tissues and DNA extractions will be held at the USU Molecular Ecology Laboratory for 1 year. OreoHelix Consulting will be contacted prior to disposal of any original samples.

Citations

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