May 20, 2015

Unionoida Mussel and Non-Pulmonate Snail Survey and Status in the Jordan River, UT, 2014

Final Report

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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 rich molluskan fauna of the Bonneville Basin area, including drainages that enter terminal Great Salt Lake (e.g. Utah Lake, Jordan River, Bear River, etc.). There are at least seventy freshwater mollusk taxa reported from UT, many of which are endemics to the Bonneville Basin and their evolution and distribution are strongly linked with the geological and geomorphic history of pluvial Lake Bonneville. 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. Despite this unique and irreplaceable natural heritage, the taxonomy, distribution, status, and ecologies of Utah's freshwater mollusks are poorly known. Very few mollusk specific surveys have been conducted in UT. In addition, specialized training, survey methods, and identification of freshwater mollusks are required.

EPA recently recommended changes in freshwater ammonia criteria based primarily on sensitive freshwater mollusks, including non-pulmonate snails and unionid taxa found in the eastern USA. Because these taxa may not occur in a region or potentially impacted areas, EPA also developed a recalculation procedure to develop site- specific water quality criteria 'to better reflect the organisms that occur at a specific site", based on the presence or absence of Unionoida and non-pulmonates. If Unionidae mussels and prosobranch snails are determined to be absent from a site then states and tribes may decide to adopt site-specific criteria based either on alternative criteria values or on their own criteria values resulting from application of the recalculation procedure. It therefore is imperative to determine the presence/absence of mollusk taxa and in particular, Unionoida mussels and non-pulmonate snails in the main stem and tributaries of the Jordan River, to determine if recalculation of EPA's ammonia criteria is warranted. These surveys are particularly important in areas potentially affected by water treatment facilities whose discharge empties into the Jordan River and the very high costs associated with ammonia reduction.

The objectives of this survey were to determine presence/absence and estimate the probability of occurrence/absence of Unionoida mussels and non-prosobranch snails in the Jordan River and nearby tributaries and examine reasons for their distribution and status. Results of this mollusk survey can be used to initiate site-specific recalculations of ammonia criteria based on those sensitive taxa that are present or assumed absent following EPA's guidelines.

A combination of reconnaissance and qualitative mollusk surveys was conducted. Reconnaissance surveys were cursory visual searches in the most promising habitats and provided a preliminary understanding of mollusk presence or absence in the Jordan River drainage and helped determine if additional more comprehensive qualitative surveys were warranted. Approximately 7.5 miles of the Jordan River, UT were surveyed for the presence/absence of mollusk taxa focusing on sections of the river directly upstream and downstream of wastewater treatment facilities, in May and October 2014. Surveyors were trained for one full day by the author prior to conducting the formal surveys. Three to

four mussel surveyors using aquascopes, shoreline sampling, and kick nets surveyed for a total of about 270 surveyor hours in May and about the same number of hours in October but without the use of aquascopes. Habitats examined included: riffles, runs, pools, and back eddies with substrate ranging from boulders/large cobbles to fine silt and clay. An estimated 70% of the Jordan River substrate was viewed in the survey for an estimated total of 58,000 to 76,000 m^2 surveyed in May.

We did not find any live Unionoida or native non-prosobranchs in any sections of the Jordan River, although we found native non-prosobranchs in tributaries of the Jordan River. At least one Unionoida taxon is known to still exist in the Jordan River drainage upstream of the river and outside of our study area. We did however find two highly invasive mollusks in the Jordan River, the New Zealand mudsnail, *Potamopyrgus antipodarum* and the Asian clam, *Corbicula fluminea*, both of which dominated the benthic macroinvertebrate assemblage. We also found several taxa of live native clams and prosobranch snails. Reasonable probability estimations for Unionoida in the Jordan River would be < 1 individual for 270 hours of visual examination or about < 1 individual/ 50,000 m^2.

Based on historical records and this survey, it appears that native Unionoida mussels and possibly non-pulmonate snails no longer occur in the main stem of the Jordan River and possibly Utah Lake, or they occur at such extremely low densities and in isolated locations so as to be almost non-detectable. Isolated populations of non-pulmonate snails may occur in sections of the Jordan River in very limited areas where spring creeks enter the Jordan River or spring upwelling occurs for a few short meters downstream in the river. Unionoida taxa likely no longer survive even as metapopulations but as small isolated populations in a highly fragmented landscape upstream of Jordan River within the drainage. Because of this, Unionoida extinction probabilities are much greater than if they would have remained as large continuous populations or as metapopulations. In addition to the extinction risk of native Unionoida caused by isolation and fragmentation, a multitude of other factors that negatively effect the physical, chemical, and biological integrity of the Jordan River drainage increases their extinction risk with little likelihood of natural recolonization of the Jordan River including:

- Dewatering
- Non natural flow regime
- Channelization
- Sedimentation
- Unprecedented urbanization
- Dredging
- Flood event scouring
- Loss of floodplain connection (e.g. flood dynamics are not the same as when Jordan River was allowed to inundate flood plain. Floodplains also dissipate flood scour energy/intensity).
- Global climate change. Expected increased temperatures, decreased precipitation, and increased and unpredictable/ extreme storm events that likely will have deleterious but unquantifiable effects on physical, chemical, and biological integrity

- Lowered dissolved oxygen, particularly under winter ice
- Point and non-point sources of pollutants
- Increased salinity (evaporative loss in Utah Lake exceeding input)
- Nutrients
- High summer temperatures
- The chemical integrity of Utah Lake
- Invasive species
- Loss of biodiversity
- Loss of species interactions (the extinction or loss of ecological interactions often accompanies or even precedes loss of biodiversity)
- Loss of population interactions (e.g. metapopulation dynamics, isolated populations)
- Loss or change in genetic diversity
- Unknown changes in species interactions resulting from loss of biodiversity and species interactions
- Effects of demographic and environmental stochasticity on small, isolated populations

All of these factors likely have pushed native Unionoida in the Jordan River drainage to enter what is known as the ‘extinction vortex’ and it is likely they are now ecologically irrelevant to the ecosystem. If conditions do not improve or additional populations don’t exist they can be considered as part of the ‘extinction debt’ and may not persist into the foreseeable future. Native non-pulmonate snails are also becoming scarce in the Jordan River drainage and spring -stream tributary habitats may be the last refugia for these species in the Jordan River if they are able to coexist with the already present invasive New Zealand mudsnails and Asian clams. Additional surveys are urgently needed and comprehensive metapopulation viability analyses should be conducted for all of these taxa and particularly for *A. californiensis/nuttalliana*. The multitude of physical, chemical, and biological impairments discussed in this report and by others combine to prevent re- establishment of Unionoida taxa into the Jordan River. Proposed monetarily expensive efforts to further reduce ammonia concentrations in the Jordan River will likely have no net -benefit until these other more deleterious factors are remedied. Monies could be better spent to help reduce the negative effects of those factors.

The following are recommended to determine the distribution and status of Unionoida and non-pulmonate snails in the Jordan River drainage and help reduce extinction risk:

- Expand the mollusk survey area and revisit Jordan River sites at least every 3 years.

- Survey the location that the BLM/USU BugLab reported as having live *Fluminicola* and *Pyrgulopsis* in 2004. Snail population abundances can fluctuate yearly and may naturally have greater or lesser abundances in the future and therefore detectability rates may change.

- Increase mollusk survey efforts in Utah Lake and tributaries.

- Develop and add eDNA sampling methods to the program.

- Resurvey known locations of *Anodonta* populations in the Jordan River drainage and conduct quantitative surveys to estimate abundances and size classes for each population.
- Conduct metapopulation viability analyses and quantitative risk assessments for Unionoida and non-pulmonate snails in Jordan River drainage.
- Conduct acute and chronic ammonia toxicity tests on mussels native to UT.
- Conduct detailed distribution, life history, and ecological studies of invasive New Zealand mudsnails and Asian clams in the Jordan River drainage.
- Immediate and increased protection of remaining Unionoida populations and their habitat in the Jordan River drainage. **This is critical**.
- Immediate and increased protection of spring tributaries of the Jordan River to help insure that native non-pulmonate snail populations do not follow down the path towards extinction in UT that *Anodonta* appears to be traveling on. **This is also critical**.
- Educate Utah citizens regarding their unique natural heritage of native mollusks, which is rapidly being lost.

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INTRODUCTION

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. Freshwater mollusks serve vital functions in freshwater ecosystems, are excellent indicators of water quality, and are increasingly recognized as important ecosystem providers (Mock et al 2004). Clams and mussels are water filterers whereas; snails are the principal grazers in many aquatic habitats (Huryn et al. 1995). Mollusks significantly influence algal primary productivity (e.g., Brown and Lydeard 2010) and play a pivotal role in aquatic food webs and nutrient cycling (Covich et al. 1999). Mollusks can easily dominate benthic stream communities in numbers (Hawkins and Furnish 1987; Johnson and Brown 1997) and often exceed 50% of invertebrate biomass (Brown et al. 2008; Brown and Lydeard 2010). Because mussels are filter feeders, they contribute greatly to water quality by removing suspended particles of sediment and detritus. According to Allen (1914), an average-sized mussel can filter over eight gallons of water during a 4-hour period. In high-density mussel beds, the filtering effect of thousands of mussels can be ecologically significant. It is well known that snails, particularly at high densities, have a strong effect on nutrient cycling (Hall et al. 2003). For example, when snails are present in streams there can be less C as DOC and more C as CO_2 in the water column (Morales and Ward 2000). Many mollusk species in the western USA, particularly non pulmonate snails, are narrow endemics associated with lotic habitats, often isolated in a single spring, river reach, or geographically restricted river basin and throughout the region their populations are in sharp decline.

Freshwater mollusks are one of the most disproportionally imperiled species groups on earth. The Nature Conservancy recognized 55% of North American mussels as extinct or imperiled compared with 7% of bird and mammal species (Master 1990); future extinction rates for North American freshwater fauna are projected to be five times higher than those for terrestrial fauna (Riciardi and Rasmussen 1999). Of the 297 freshwater North American mussel taxa, 213 (72%) are considered endangered, threatened or are species of concern. Similarly 74% of the 703 freshwater snail taxa in N.A. are imperiled (Johnson et al., 2013). Freshwater snails thus have the dubious distinction of having the highest modern extinction rate yet observed, at > 9000 times background rates (Johnson et al. 2013). This alarming decline is almost entirely due to human activities (Williams et al. 1992).

The greatest diversity of North America's freshwater mollusks, particularly mussels, occurs in the southeast, whereas in the western half of N.A. the molluskan fauna is relatively depauperate. However, the area consisting of Great Basin, Snake River Basin and Bonneville Basins, including the Great Salt Lake area, is a freshwater mollusk hotspot, particularly for freshwater non-pulmonate snails.

FRESHWATER MOLLUSKS IN UTAH

There are at least seventy freshwater mollusk taxa reported from UT (mostly snails) (Oliver and Bosworth 2009), many of which are 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 (Johnson and Jordan 2000, Hershler and Sada 2002, Johnson 2002, Polhemus and Polhemus 2002, Smith et al. 2002, Mock et al. 2004)(Figure 1).

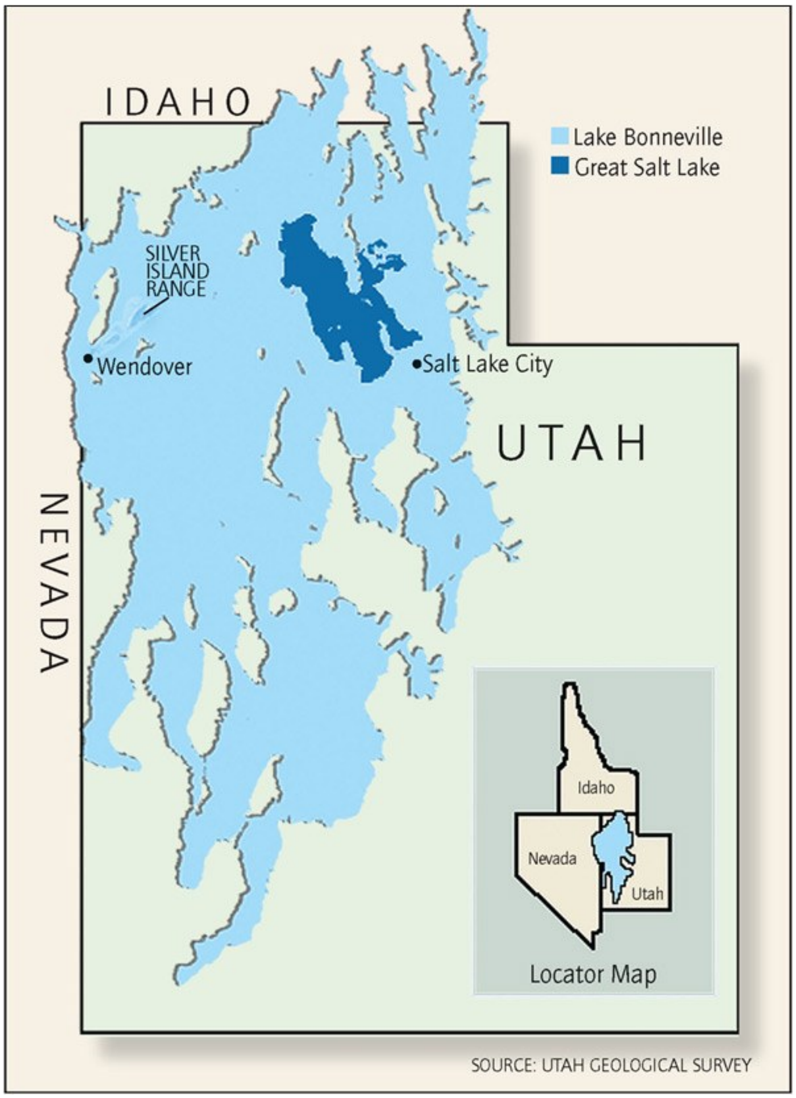

Figure 1. Location of Ancient Lake Bonneville at its maximum area (about 17,000 years ago) and what remains, Great Salt Lake (Utah Lake not shown).sss

Despite this unique and irreplaceable natural heritage, the taxonomy, distribution, status, and ecologies of Utah's freshwater mollusks are poorly known. Very few mollusk 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 mollusks or they identify mollusks at a taxonomic resolution greater than genus level, often only to family level. 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 and on non-pulmonate snails in the families Hydrobiidae and Valvatidae surveyed in the Jordan River (Figure 2) in 2014.

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 californiensis/nuttalliana* (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 occured 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

Non-pulmonate Snails

Two families of non-pulmonate snail taxa in UT are the prosobranch snails in the family Hydrobiidae with two main genera, *Fluminicola* (pebblesnails) and *Pyrgulopsis* (springsnails) and two smaller genera, *Colligyrus* and *Tryonia*; and the heterobranch family, Valvatidae which includes one genus, *Valvata* (valve snails). The distribution and status of these taxa are also poorly known, however these are known to occur or have occurred in tributaries of the Great Salt Lake, including the Jordan River drainage.

Historical Records of Unionoida and non-pulmonate mollusks in the Jordan River drainage

Several Unionoida and non-pulmonate mollusk genera have been reported in the Jordan River area. These include *Anodonta* (Family Unionidae), *Margaritifera* (Family Margaritiferidae), *Fluminicola* (Family Hydrobiidae), *Pyrgulopsis* (Family Hydrobiidae), *Colligyrus* (Family Hydrobiidae), *Tryonia* (Family Hydrobiidae), and *Valvata* (Family Valvatidae). The unionid species *Gonidea angulata* is also included in this report because it has the remote potential to exist in the area. A brief description of these taxa and their reported distribution in UT and the Jordan River drainage area follows.

UNIONOIDA MUSSELS

Anodonta californiensis Lea 1852
Common Name: California floater

The range of Western *Anodonta* spp. extends from Alaska south to Mexico and as far east as Utah (Taylor 1966, 1981, 1985, Burch 1975, Clarke 1981, Warren and Harington 2000, Hovingh 2004). 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 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). Unionid 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). Further studies are urgently needed to determine which fish species in the Jordan River are suitable hosts. 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 (Figure 3 and Figure 4). Additionally, several researchers reported possible *Anodonta* spp. shells along the shoreline of Utah Lake and Mill Pond in Utah County. More intensive and extensive native mussels surveys are clearly needed to document existing populations as well as continued compilation of recently reported locations. Recent genetic analyses have suggested that *A. californiensis* and *A. nuttalliana* are within the same clade (Mock et al. 2004) and for the purpose of this report will be identified as *Anodonta californiensis/nuttalliana*.

Figure 3. ***Anodonta californiensis/nuttalliana*** **(California floater/Winged Floater). Shell lengths up to 5 inches; reach sexual maturity 4 to 5 years, and maximum life span about 15 years (© Ethan Jay Nedeau, reproduced from the field guide** ***Freshwater Mussels of the Pacific Northwest*** **(Nedeau et al. 2009).**

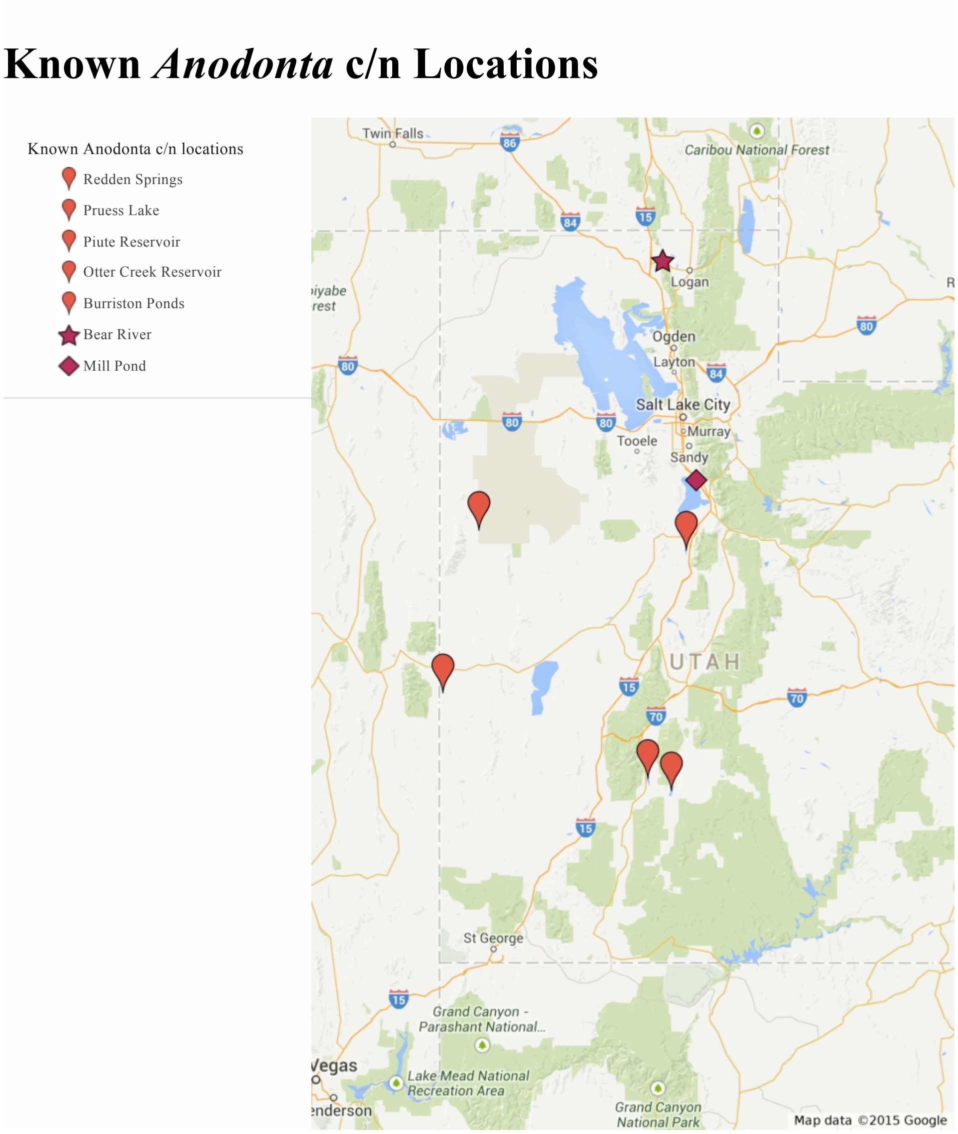

Figure 4. Known locations of *Anodonta californiensis/nuttalliana* in UT from Xerces Society web site, literature, and this survey. Red teardrops are geo-referenced locations; red star is location only reported as Bear River, and red diamond is location where only shells were found, no live individuals.

Gonidea angulata (Lea 1838)

<u>Common Name</u>: western ridged mussel

The mobile *G. angulata* (Figure 5) is well adapted to survive in streams with high sediment deposits and can reach high densities on gravel and stabilized sandbars (Vannote and Minshall 1982). *Gonidea angulata* has not been reported in the Jordan River drainage; however, there is a slight possibility of its presence in the system because it can occur in the types of substrate habitat found in the Jordan River. The BLM/USU BugLab database has no records of *G. angulata* from UT.

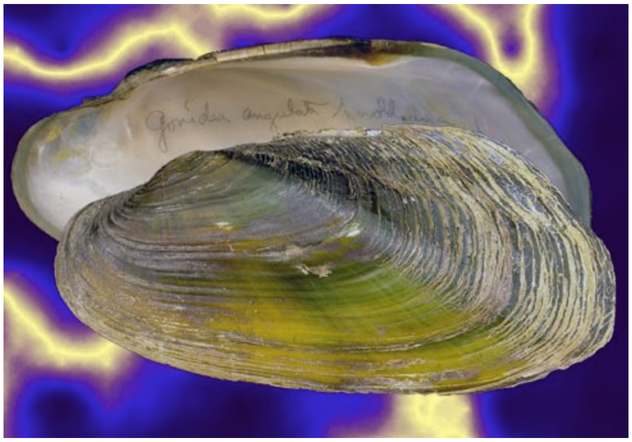

Figure 5. ***Gonidea angulata*** **(Western Ridged Mussel) (http://mussel-project.uwsp.edu/motm/2008/08-01.html)**

Margaritifera falcata Gould 1850
Common Name: western pearl shell mussel

M. falcata (Figure 7) 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). 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). It is likely that additional small isolated colonies may be found using mussel specific surveys and more intensive and extensive native mussels surveys are clearly needed to document existing populations.

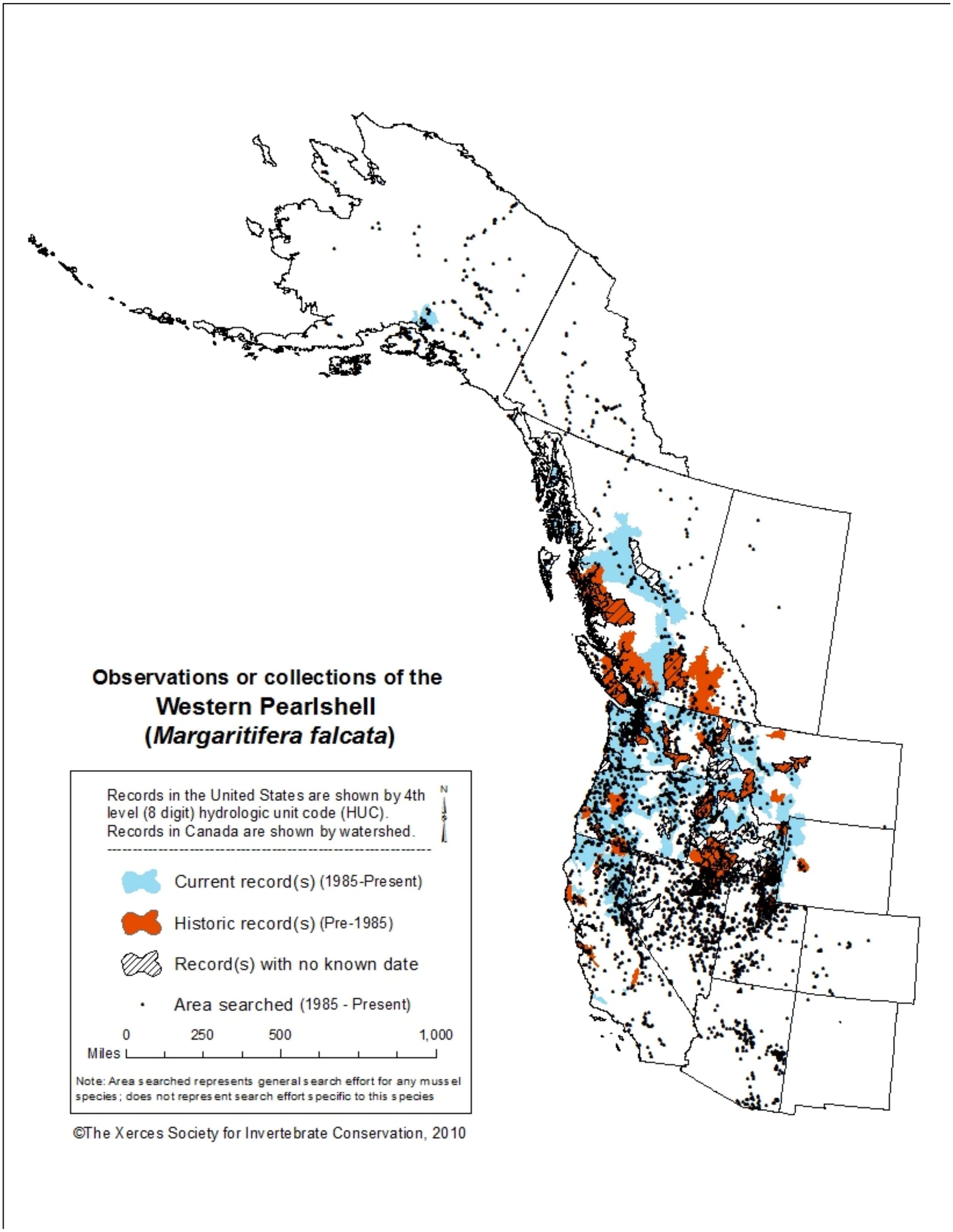

Figure 6. Map of *M. falcata* observations and collections in western USA (http://www.xerces.org/western-pearlshell/).

Figure 7. ***Margaritifera falcata*** **(Western Pearlshell mussel)(http://www.fws.gov/refuge/willapa/wildlife_and_habitat/western_pearlshell_mussel.html)**

NON-PULMONATE SNAILS

Fluminicola, pebble snails

Fluminicola coloradoensis Morrison, 1940
Common Name: Green River pebblesnail
There are currently 24 recognized species of *Fluminicola* in northwestern North American. *Fluminicola* spp. are small 1.2–12.0 mm shell height, gill-breathing gastropods, commonly known as pebblesnails (Hershler and Frest 1996). They are often an abundant member of benthic communities but have recently become a focus of conservation activities (e.g., USDA Forest Service and USDI Bureau of Land Management 2001, Lydeard et al., 2004). Despite their large range, *Fluminicola* spp. have received little taxonomic or ecological study (Hershler and Frest 1996).

Fluminicola spp. occur in portions of the northern Great Basin, Snake- Columbia River system, Sacramento River system, and Pacific coastal drainages (British Columbia, California, Idaho, Nevada, Oregon, Utah, Washington, Wyoming) (Hershler and Frest 1996). They are usually found in clear, cold waters with high dissolved oxygen content. Larger sized species are typically found in streams, whereas smaller sized species are commonly found in either spring or stream environments (Hershler and Frest 1996). Many taxa are lithophiles ('rock loving' e.g. stable substrates) and graze on periphyton. *Fluminicola* spp. can be community dominants and can comprise most of the invertebrate biomass. They are fairly intolerant of impounded waters and soft substrates, as well as of nutrient enhanced or lacustrine habitats (Hsiu-Ping et al. 2013). *Fluminicola* spp. apparently have now been extirpated from large areas of their historic range (Hsiu-Ping et al. 2013).

The only species of *Fluminicola* found in UT is *Fluminicola coloradoensis* Morrison (Hershler and Frest 1996; Hsiu-Ping et al. 2013)(Figure 8). This species is currently ranked as imperiled or vulnerable (G2/G3) by Nature- Serve (2011). Hsiu-Ping et al. 2013 suggested that *F. coloradoensis* is much more widely distributed than previously thought and may not merit these rankings, at least on a range wide basis. They suggested that conservation measures should perhaps be focused on geographic subunits that may be at risk (Hsiu-Ping et al. 2013).

Figure 8. Empty shells of the prosobranch snail, *Fluminicola coloradoensis* found in several sections of the Jordan River and spring tributaries during the October 2014 survey. Scale lines are 1 mm.

A total of 21 individual *F. coloradoensis* were documented in the BLM/USU BugLab database from four sampling events in Jordan River/Salt Lake county (N = 20) and Utah county (N = 1) records in 2004, excluding the Jordan River Bluffdale Road Crossing misidentified lat/long site (Figure 9)(http://www.cnr.usu.edu/wmc/htm/data). There were 85 individuals collected in two sampling events at the misidentified Jordan River site, which true location needs to be verified. This large number of individuals could represent a valid population in the Jordan River if it was truly collected there and if it is still viable. BLM/USU BugLab samples were collected in 2004 and unprecedented urbanization has taken place since then at their reported locations (Figure 10 and Figure 11). Consequently, this population may no longer exist.

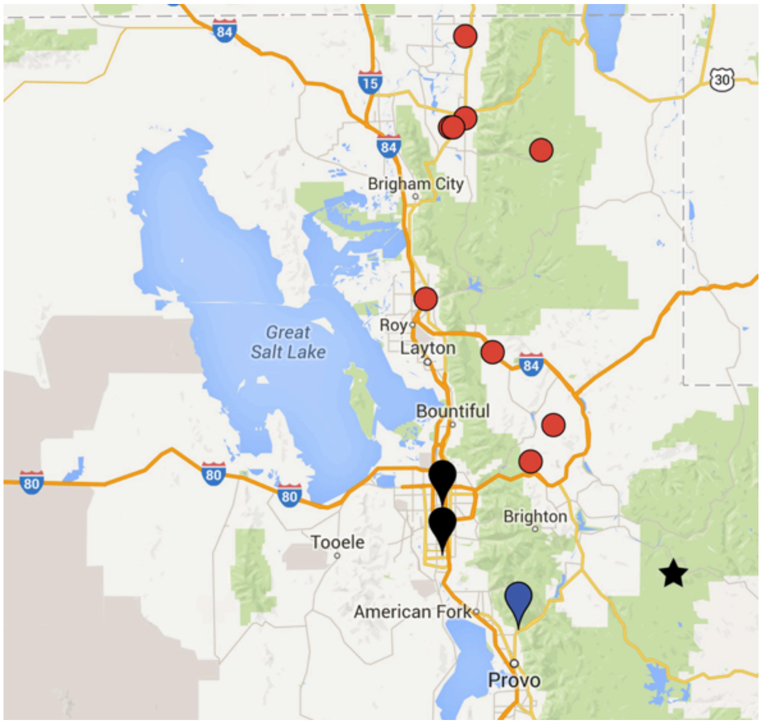

Figure 9 ***Fluminicola coloradoensis*** **in NW UT. Locations from WCMAFE BLM/USU Aquatic Monitoring Center, BugLab website (http://www.cnr.usu.edu/wmc/htm/data).** ***F. coloradoensis*** **symbol locations: Black teardrop = Jordan River/ Salt Lake County; blue teardrop = Utah county; black star = BugLab description was Jordan River at Bluffdale Road Crossing but lat/long coordinates located this site shown on the map; red circles = drainages other than Jordan River/Salt Lake and Utah counties. An additional location was from the Green River near the CO border but is not shown.**

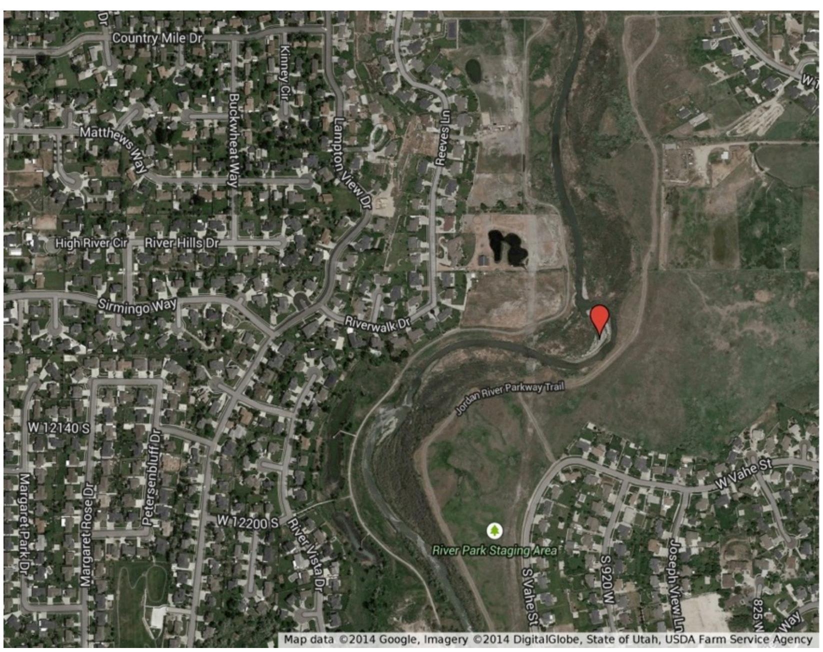

Figure 10. Location of ***Fluminicola coloradoensis*** **BLM/USU BugLab collection site in 2004. A total of nine individual were collected from combined qualitative and quantitative data.**

(http://www.cnr.usu.edu/wmc/htm/data). Unprecedented urbanization has occurred in this area since 2004 and may have caused their demise.

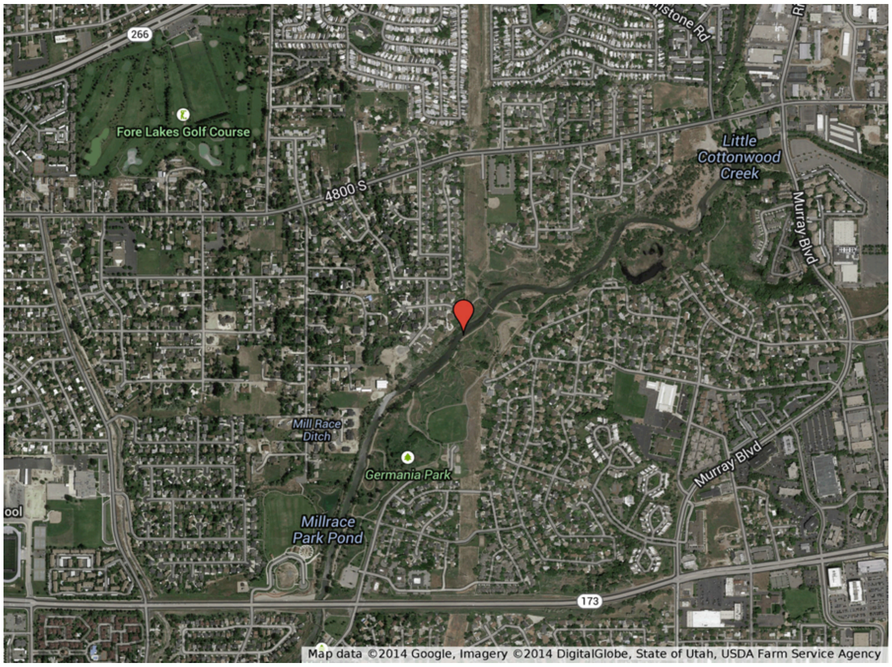

Figure 11. Location of *Fluminicola coloradoensis* BLM/USU BugLab collection site in 2004. A total of 11 individual shells were collected from qualitative data(http://www.cnr.usu.edu/wmc/htm/data).Unprecedented urbanization has occurred in this area since 2004 and may have contributed to their demise.

Pyrgulopsis, spring snails

Pyrgulopsis spp. (Figure 12) are known as 'springsnails' because they typically inhabit spring creeks, although some *Pyrgulopsis* spp. can also be found in rivers (ex. *P. robusta* and other unnamed *Pyrgulopsis* spp. in the Snake River, ID) and one species inhabits thermal springs (*P. bruneauensis* only found in the Bruneau River, ID). *Pyrgulopsis* spp. are one of the most diverse members of the endemic western North American aquatic biota and the largest number of species (at least 73) occur in the Great Basin (Figure 13)(Hershler et al., 2014). The Great Salt Lake drainage basin, particularly the Utah Lake drainage is one of the hotspots of *Pyrgulopsis* spp. distribution (Figure 13). However, their status is poorly known and many species are considered rare or extinct in UT (Bosworth and Oliver 2009). *Pyrgulopsis* spp. are rapidly becoming one of the most important indicators of groundwater and freshwater spring health because of their endemism and their conservation status (Hershler et al., 2014). These tiny gastropods are imperiled by threats ranging from groundwater pumping to livestock grazing (Hershler et al., 2014). BLM/USU identified *Pyrgulopsis* spp. and *P. pilsbryana* J. L. Baily and R. I. Baily, 1952 (common name: Bear Lake springsnail) in Salt Lake and Utah counties (Figure 14) and two individual *Pyrgulopsis* spp. collected from the Jordan River, in a 2002 qualitative sample (Figure

15). The pyrgs in the BLM/USU BugLab database could be more than one or two species due to difficulty in taxonomy.

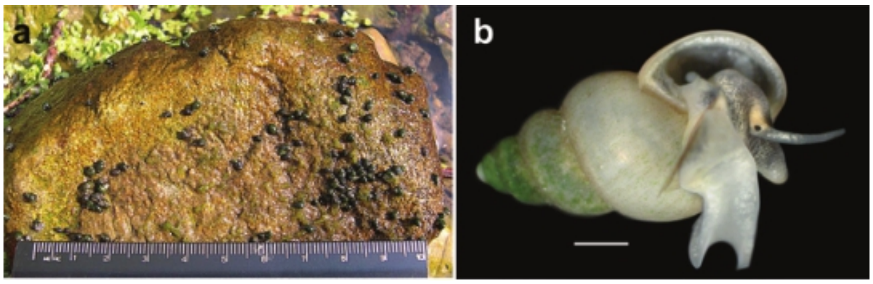

Figure 12. (a) *Pyrgulopsis* sp. on rock (East Fork Rock Creek, Idaho). Photograph: Daniel Gustafson. (b) *Pyrgulopsis robusta* (Snake River, Idaho). The scale bar represents 1 millimeter. Photograph: Robert Hershler. Both photos from Hershler et al., 2014.

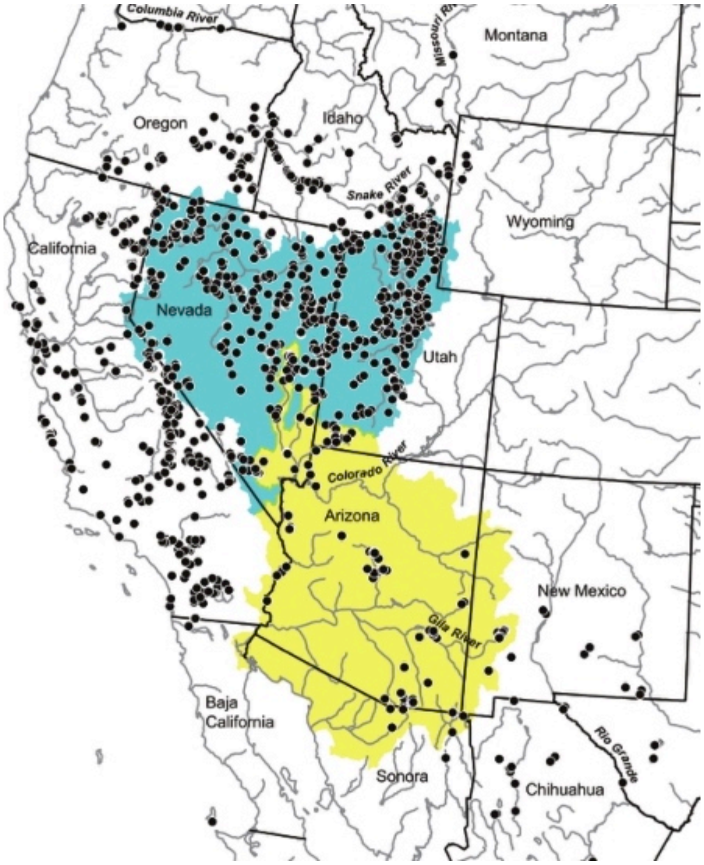

Figure 13. The distribution of *Pyrgulopsis*, based on records in the Smithsonian National Museum of Natural History and several other repositories. The Great Basin and lower Colorado River Basin are shaded in cyan and yellow, respectively. (Figure from Hershler et al. 2014)

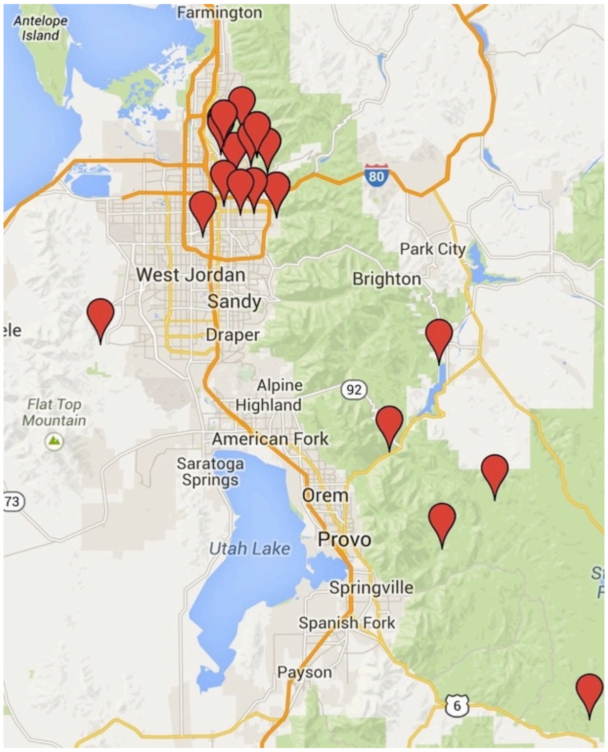

Figure 14. Reported locations of *Pyrgulopsis* spp. in Salt Lake and Utah counties from BLM/USU BugLab database (http://www.cnr.usu.edu/wmc/htm/data).

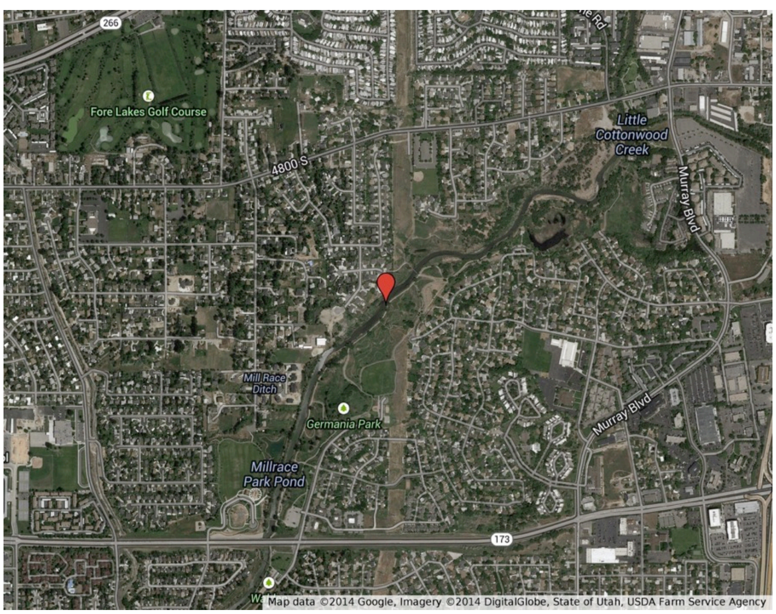

Figure 15. Location of two individual *Pyrgulopsis* spp. reported by BLM/USU BugLab in Jordan River, in a 2002 qualitative sample. (http://www.cnr.usu.edu/wmc/htm/data).

Unprecedented urbanization has occurred in this area since 2002 and may have contributed to their demise.

Other prosobranchs
Two additional uncommon prosobranch snails also occur in UT, *Tryonia porrecta* (Mighels, 1845)(Common Name: Desert tryonia) and *Colligyrus greggi* (Pilsbry, 1935)(Common Name: Rocky Mountain dusky snail) but were not reported in the Jordan River drainage in the WCMAFE BLM/USU Aquatic Monitoring Center, BugLab database (http://www.cnr.usu.edu/wmc/htm/data)(Figure 16).

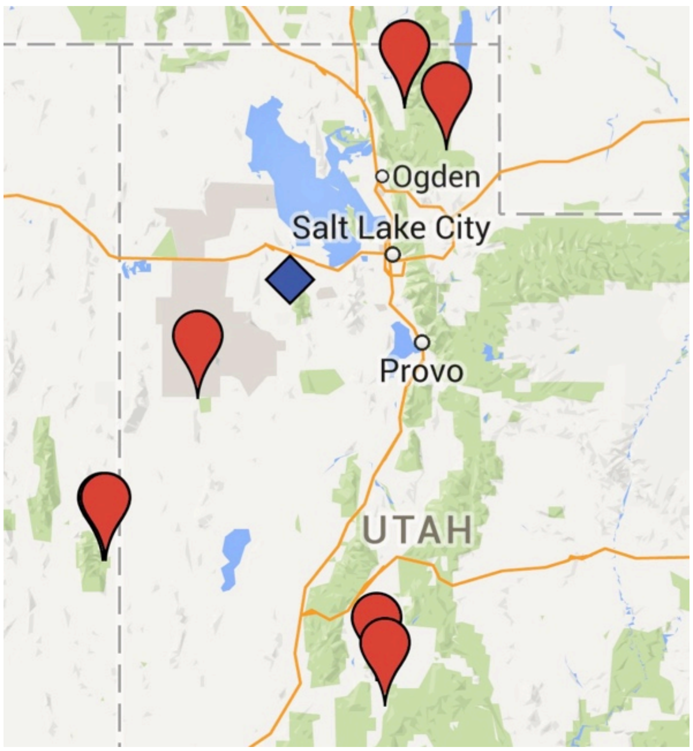

Figure 16. *Colligyrus* greggi. (red ballons) and *Tryonia* sp. (blue diamond) locations reported from WCMAFE BLM/USU Aquatic Monitoring Center, BugLab website (http://www.cnr.usu.edu/wmc/htm/data).

Valvata, valve snails
Valvata is a genus of very small freshwater snails with an operculum, in the family Valvatidae, the valve snails. They are non-pulmonates and are heterobranchs meaning "different gilled snails" (as opposed to prosobranchs which means "gills in front of heart"). There are likely two taxa that can or have occurred in the Jordan River drainage, *V. humeralis* and *V. utahensis*. Hovingh (2004) considers *V. humeralis* in UT to be *V. californica* based on shell morphology, however this taxon will be identified as *V. humeralis* in this report.

Valvata humeralis Say 1829
Common Name: Glossy *Valvata*
Valvata humeralis is widely distributed in Western North America (but see Hovingh 2004)

including the Colorado River, the upper Rio Grande, the Columbia-Snake River, the California Pacific Coast drainages, and the Great Basin. Its habitats range from large lakes to small ponds, marshes, streams, and springs (Hovingh 2004). This species historically occurred in: Box Elder, Cache, Juab, Kane, Rich, Sevier, Summit, Tooele, Utah, and Wasatch watersheds in UT, NatureServe suggests that *V. humeralis* may possibly have been extirpated in all of these counties (http://explorer.natureserve.org), however Hovingh (2004) and BLM/USU BugLab reported live populations in UT (Figure 17) but none from Salt Lake or Utah counties. This discrepancy highlights the difficulty in assessing populations of tiny hard to find and identify snails.

Valvata utahensis Call 1884
Common Name: Utah round mouth snail, desert snail
Valvata utahensis was federally delisted because it has been found in a wider range of habitats and locations in the Snake River, ID. It is distinguished from *V. humeralis* based on the much taller shell spire and prominent carinae (as opposed to a flatter, noncarinate shell in *V. humeralis*) (Miller et al., 2006)(see Figure 37). *Valvata utahensis* historically occurred in a wide variety of habitats including: creeks, high gradient medium sized rivers, moderate gradient, springs and spring brooks. It also can occur in shallow and deep lakes (NatureServe Explorer, Hovingh 2004). It can occur in a wide range of benthic habitats including submergent aquatic plants on fine silt substrate, pebbles, and cobbles (USFWS, 1992; Lysne and Koetsier 2006). *Valvata utahensis* was extirpated from Utah Lake and Call (1884) was apparently the only person to collect shells of this species with opercula (i.e. live specimens)(Chamberlin and Jones 1929, Hovingh 2004). NatureServe reported *V. utahensis* historically in the Bear Lake and Utah Lake HUC8 watersheds. (http://explorer.natureserve.org) but consider this species to be extinct in UT (Figure 17). Live V. *utahensis* are known only to occur in the Snake River, ID (Hovingh 2004).

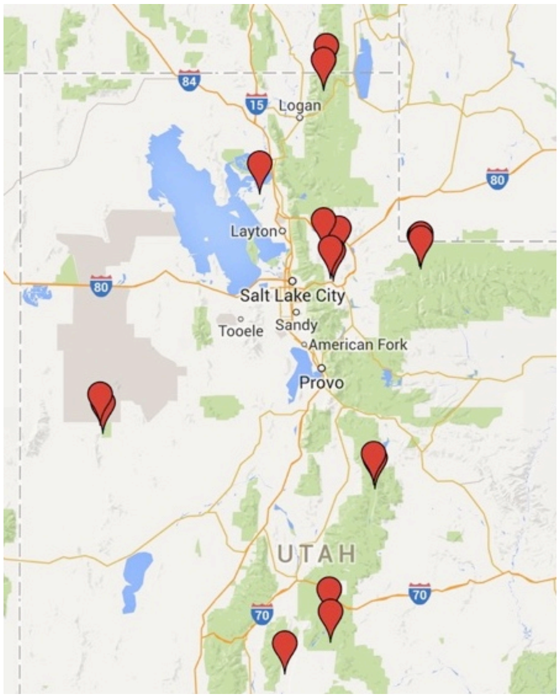

Figure 17. *Valvata* spp. in UT locations reported from WCMAFE BLM/USU Aquatic Monitoring Center, BugLab website (http://www.cnr.usu.edu/wmc/htm/data). No *Valvata* spp. were reported in the BLM/USU BugLab database for Salt Lake and Utah counties and *Valvata* spp. and *Valvata humeralis* were the only two *Valvata* taxa reported.

Table 2. Status of native Unionid mussels and non-pulmonate snails that could occur in Jordan River and which were the focus of this survey.

Taxon	NatureServe Status[1]			UT- DNR[2]	IUCN[3]	AFS[4]
	Global	National	Utah			
Unionid mussels						
Gonidea angulata	3	3	NA	NA	NE	Und.
Anodonta californiensis	3Q	3Q	1Q	NA	LC	Und.
Margaritifera falcata	4, 5	4, 5	1, H	NA	NE	Und.
Non-pulmonate snails						
Colligyrus greggi	4	4	1	R, I, RE	LC	CS
Fluminicola coloradoensis	2, 3	2, 3	2, 3	R, I, RE	NE	T
Pyrgulopsis pilsbryana	2	2	1	R, I, RE	NT	T
Pyrgulopsis spp.	NA	NA	NA	NA	NA	NA
Tryonia porrecta	3	2	2	R, I, RE	LC	CS
Valvata humeralis	5Q	5	H	R, I, RE	LC	CS
Valvata utahensis	1, 2	1, 2	X	R, I, RE	VU	E

[1]Nature Serve Status Codes:

1. Critically imperiled - At very high risk of extinction or elimination due to extreme rarity, very steep declines, or other factors.
2: Imperiled-At high risk of extinction due to very restricted range, very few populations (often 20 or fewer), steep declines, or other factors.
3: Vulnerable-At moderate risk of extinction due to a restricted range, relatively few populations (often 80 or fewer), recent and widespread declines, or other factors.
4. Apparently Secure-Uncommon but not rare; some cause for long-term concern due to declines or other factors.
5. Secure-Common; widespread and abundant.
Q. Questionable taxonomy-Taxonomic distinctiveness at the current level is questionable; resolution of this uncertainty may result in change from a species to a subspecies or hybrid, or the inclusion of this taxon in another taxon
X. Presumed Extinct -Not located despite intensive searches and virtually no likelihood of rediscovery.
H. Possibly Extinct -Missing; known from only historical occurrences but still some hope of rediscovery.
NA. Not reported to occur in UT.

[2]UT DNR: Utah Department of Natural Resources, Oliver and Bosworth (1999) Utah Status Report Codes:

R. Rare
I. Imperiled
RE. Recently extinct or extirpated

[3]IUCN: Red List Category Codes:

LC. Least concern
NT. Near threatened
NE. Not evaluated

[4]AFS = American Fisheries Society Codes

E. Endangered: A species that is in imminent danger of extinction.
T. Threatened: A species that is imminently likely to become endangered throughout all or a significant portion of its range.

V. Vulnerable: A species that is imminently likely to become threatened throughout all or a significant portion of its range; equivalent to “Special Concern” as designated by Deacon et al. (1979) and Williams et al. (1989).
CS. Currently Stable: Species populations not currently at risk.
Und. Undetermined.

Invasive mollusks

Non-native, invasive mollusks can be extremely abundant in the Jordan River, particularly the prosobranch New Zealand mudsnails (NZMS)(*Potamopyrgus antipodarum*) and the Asiatic clam, *Corbicula fluminea*. At high densities these two invasives can completely alter nutrient cycling (spiraling), particularly ammonia (Appendix 24).

JORDAN RIVER MOLLUSK SURVEY, 2014

JUSTIFICATION AND OBJECTIVES

In addition to augmenting the limited information on the status of Utah’s freshwater mollusks, the U.S. Environmental Protection Agency (USEPA) recently recommended changes in ambient water quality criteria for ammonia in freshwaters (USEPA 2013). These recommendations were primarily based on toxicity test results conducted on freshwater mollusks (mussels, clams, and snails): specifically several Eastern USA freshwater mussel species in the family Unionidae and also non-pulmonate, gill bearing- snails, whose taxonomic relatives also occur in western USA freshwaters. Because these taxa may not occur in a region or potentially impacted area, EPA also developed a recalculation procedure to develop site specific water quality criteria ‘to better reflect the organisms that occur at a specific site” (EPA 2013b: *Revised Deletion Process for the Site-Specific Recalculation Procedure for Aquatic Life Criteria)*. “The Recalculation Procedure is intended to allow site-specific criteria that appropriately differ from national criteria recommendations (i.e., ammonia concentrations that are higher or lower than national recommendations) where there are demonstrated differences in sensitivity between the aquatic species that occur at the site and those that were used to derive the national criteria recommendations.” (USEPA 2013). If Unionidae mussels and prosobranch snails are determined to be absent from a site then states and tribes may decide to adopt site-specific criteria based either on the alternative criteria values provided in Appendix N of the 2013 national ammonia criteria recommendations, or on their own criteria values resulting from application of the Recalculation Procedure.

It therefore becomes imperative to determine the presence/absence of mollusk taxa and in particular, Unionidae mussels and non-pulmonate snails in tributaries of the Jordan River and the main stem of the Jordan River, to determine if recalculation of EPA’s ammonia criteria is warranted. Mollusk presence/absence surveys are particularly important in areas potentially affected by the water treatment facilities along the Jordan River. Mollusk taxa should be identified at the species level because each species will have unique tolerance values to ammonia and mean values based on genera or family level taxonomy may not represent values of local species. For example, EPA ammonia species mean acute values (SMAV) for mussel species in the family Unionidae ranged from 23.12 mg TAN/L to 109 mg TAN/L (Appendix 22). This represents a 471% difference in SMAV in just the eastern U.S. unionid species used to develop EPA criteria. Within the Unionidae genus *Lampsilis*, SMAV values ranged from 26.03 mg TAN/L to 69.97 mg TAN/L (Appendix 22), a 270% difference in values. Thus each species will have it's own unique ammonia tolerance value and species found in the western U.S. may have tolerance values far different than those used by EPA.

The objectives of this survey are to determine presence and estimate the probability of occurrence/absence of Unionoida mussels and non-prosobranch snails in the Jordan River and nearby tributaries. In addition, reasons for their present distribution and population status will be discussed. Results of this mollusk survey can also be used by regulators to consider whether a site-specific recalculation of ammonia criteria is appropriate.

METHODS

First Tier Mollusk Surveys: Literature Review, and Reconnaissance and Qualitative Surveys

Literature Review

All relevant databases and literature concerning historic and recent mollusk distributions in watersheds of the Great Salt Lake focusing on the Jordan River drainage were searched. These included: UT Department of Natural Resources reports, the WCMAFE BLM/USU Aquatic Monitoring Center, BugLab website (http://www.cnr.usu.edu/wmc/htm/data), NatureServe Explorer (http://explorer.natureserve.org), The Xerces Society (xerces.org), American Malacological Society, Freshwater Mollusk Conservation Society (molluskconservation.org) and pertinent peer reviewed and gray literature.

Survey locations

Nine sites were surveyed for native mussels on the Jordan River, including sites upstream and downstream of water treatment facilities, for a total river length distance of about 7.5 miles (Table 3 and Figure 18-21) in April 2014. Mill Pond and Spring Creek, which empty into the NE corner of Utah Lake in Utah County, were also surveyed based on reports of historic *Anodonta* sp. shells occurring there by Dr. Larry Gray and others.

Table 3. Mussel survey site latitude and longitude coordinates and river length surveyed.

Site 1	Latitude	Longitude	Distance (miles)
Upstream	40°27'37.85"N	111°55'56.28"W	
Downstream	40°28'23.15"N	111°55'57.25"W	0.9
Site 2			
Upstream	40°32'57.44"N	111°54'55.95"W	
Downstream	40°33'54.58"N	111°54'32.04"W	1.47
Site 3			

Upstream	40°34’34.65”N	111°55’7.42”W	
Downstream	40°34’59.87”N	111°55’2.67”W	0.6
Site 4			
Upstream	40°35’16.58”N	111°54’45.54”W	
Downstream	40°35’28.92”N	111°54’45.01”W	0.25
Site 5			
Upstream	40°36’55.37”N	111°55’14.97”W	
Downstream	40°37’24.85”N	111°55’15.05”W	0.6
Site 6			
Upstream	40°41’9.73”N	111°55’15.27”W	
Downstream	40°41’57.37”N	111°55’27.51”W	1.3
Site 7			
Upstream	40°42’25.89”N	111°54’26.10”W	
Downstream	40°42’35.93”N	111°55’25.34”	0.9
Site 8			
Upstream	40°43’42.31”N	111°55’29.92”W	
Downstream	40°44’4.41”N	111°55’23.76”W	0.4
Site 9			
Upstream	40°50’5.48”N	111°56’39.88”W	
Downstream	40°50’54.21”N	111°57’13.63”W	1.1

Figure 18. Sample location in The “Narrows” section of Jordan River. Sampling occurred between the blue pins on the map.

Figure 19. Site 2. Sampling occurred between the blue pins on the map.

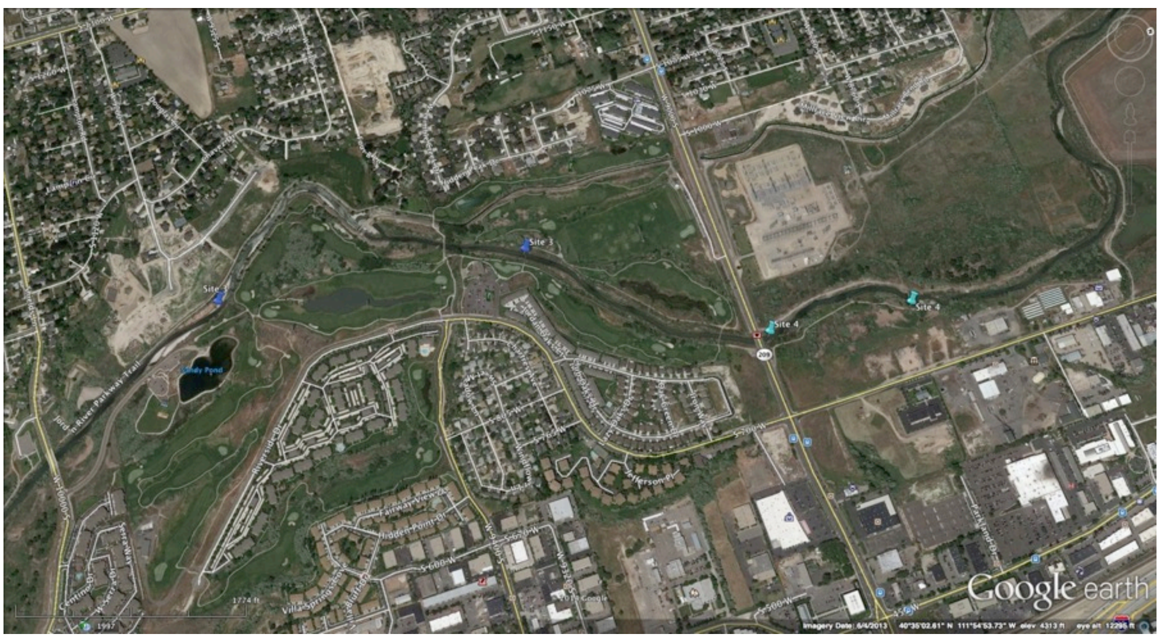

Figure 20. Mussel survey sites 3 and 4. Sampling occurred between the blue pins on the map.

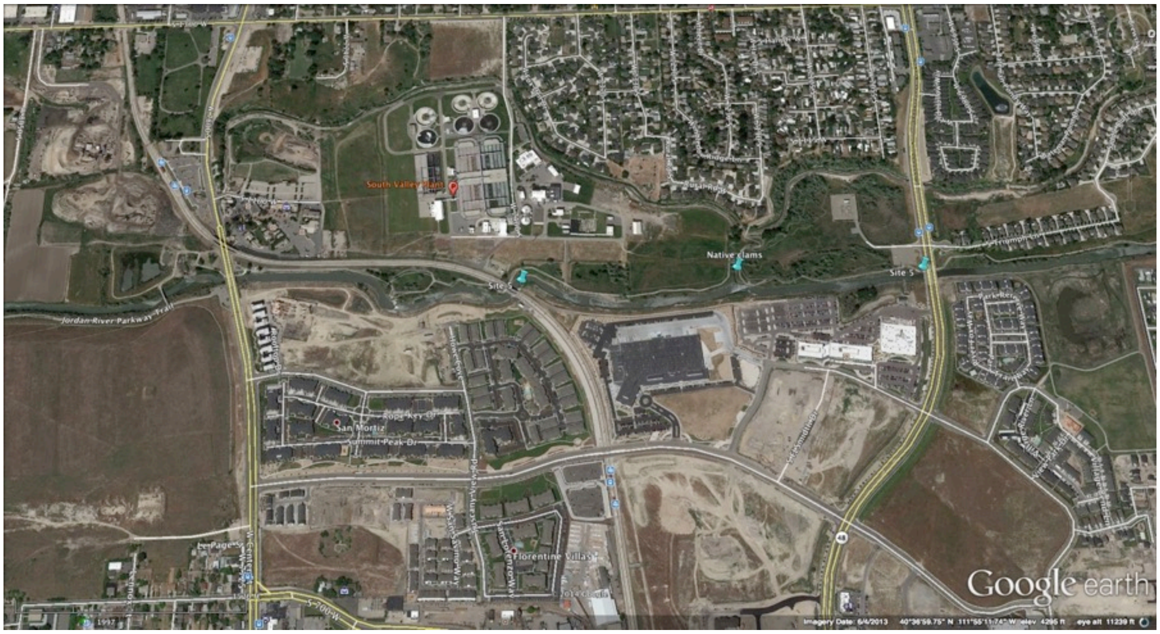

Figure 21. Mussel survey site 5 with tributary marked where native clams were common. Sampling occurred between the blue pins on the map.

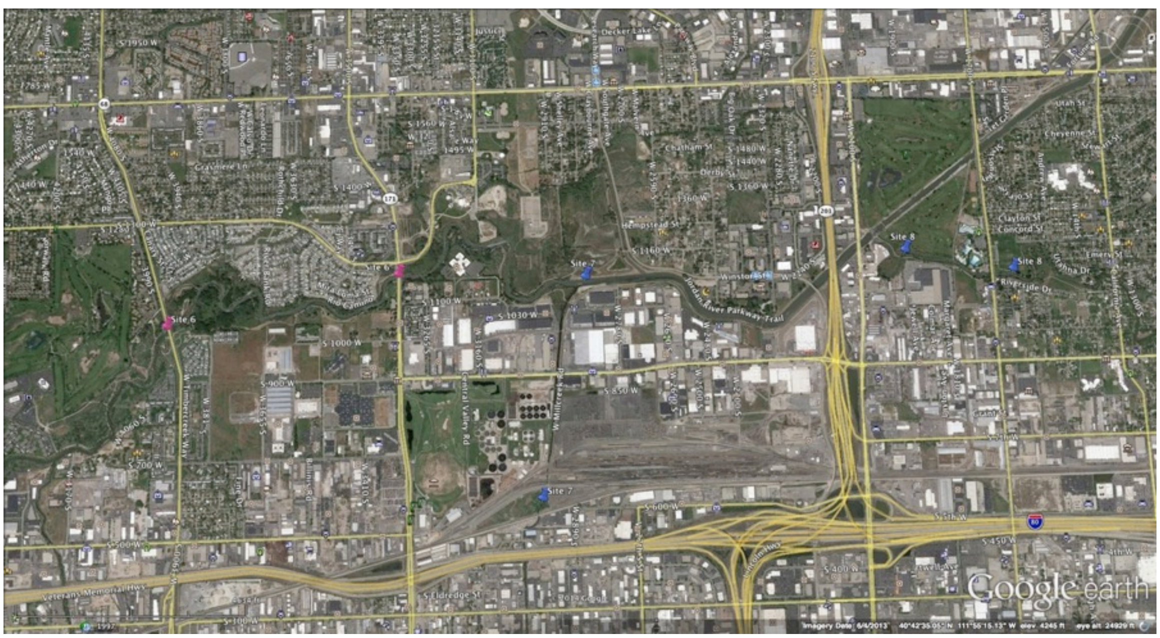

Figure 22. Mussel survey sites 6, 7, and 8. Site 7 was Mill Creek and small portion of Jordan River. Sampling occurred between the blue pins on the map.

Figure 23. Mussel survey site 9. Legacy Nature Preserve. Sampling occurred between the blue pins on the map.

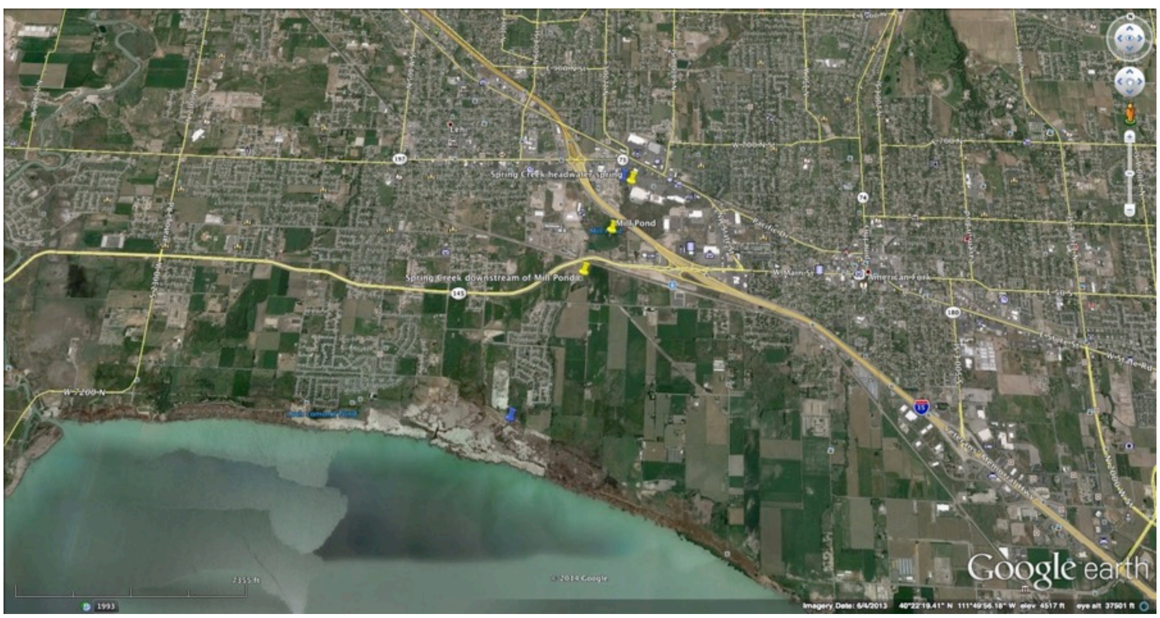

Figure 24. Mill Pond and Spring Creek, Utah County. Unionid mussel surveys were conducted between blue pins; yellow pin at headwater spring is in a Wal-Mart parking lot and under a dumpster; yellow pin at Spring Creek downstream of Mill Pond is where the most *Anodonta californiensis* shells were found in the 2014 survey.

Survey methods

Native Unionoida mussels

A combination of reconnaissance and qualitative mollusk surveys was conducted. Reconnaissance surveys were cursory visual searches in the most promising habitats and gave us a preliminary understanding of mollusk presence or absence in the Jordan River drainage. Reconnaissance surveys were conducted to help determine if additional more comprehensive qualitative surveys were warranted. Valid reconnaissance surveys depended on *a priori* knowledge of expected mussel distribution and habitat requirements. For example, *Margaritifera falcata* tend to be immediately upstream or downstream of riffles, while in the low gradient sections of the Jordan River, *M. falcata* and *Anodonta* sp. mussels would most likely be present in areas with sufficient flows necessary for filtering. There was no evidence of native unionid mussel presence during reconnaissance surveys; therefore we conducted qualitative surveys. Dr. David Richards trained surveyors for approximately four hours on Mill Pond and Spring Creek, Utah County, an area where Anodonta shells were previously reported (see qualifications in Appendix 26). Several *Anodonta* shells were recovered during this training session. The surveyors continued training for four hours at Site 1 on the Jordan River the following day. For the qualitative surveys, three to four mussel surveyors using aquascopes (Figure 25), kick nets (Figure 26), and shoreline examination (Figure 27) surveyed approximately 7.5 miles of the Jordan River from April 1, 2014 to April 11, 2014 for a total of about 270 surveyor hours. April was chosen because visibility in the Jordan River typically is best and mollusks would likely be closer to the surface of the sediment than in winter. Visibility was typically between 2 to 3 feet. Surveyors using aquascopes could view depths to about 4 feet therefore, habitats with depths > 4 feet were not closely examined. Habitats with silt/clay sediments > 2 to 3 feet thick were also not examined. Therefore, an estimated 70% of the Jordan River substrate in the 7.5 miles was viewed for an estimated total of 58,000 to 76,000 m^2. Surveyors using aquascopes traversed the river bottom from side to side and then moved several meters upstream in most of the sections looking for mussel shell fragments or whole live or dead mussels. Habitats examined included: riffles, runs, pools, and back eddies with substrate ranging from boulders/large cobbles to fine silt and clay. Empty invasive Asian clams, *Corbicula fluminea* shells and live *Corbicula* were clearly visible using aquascopes and most live *Corbicula* were seen to be actively filtering, therefore native mussels were also assumed to be detectable on the substrate surface using the aquascopes. However, as a precaution, kick net 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 sampling allowed surveyors to collect sediments and mollusks to depths of up to several inches. Shorelines were carefully examined for empty shells on sandbars, muskrat middens, and other areas of the shoreline.

Figure 25. One of the commercial aquascope types used in the mussel survey.

Figure 26. Mollusk surveyor using kick net

Figure 27. Mollusk surveyor searching shoreline and gravel bar.

Non-pulmonate snails

Snails were surveyed using 0.5 mm mesh kick nets and by examining cobbles in early October 2014 for ten days with two to three surveyors at the same locations as the unionid mussel surveys. Three spring tributaries of the Jordan River; an unnamed spring seep system on the west bank of Surplus/State/South Jordan canal at the "Narrows", Midas/Butterfield Creeks confluence with Jordan River, and Bingham Creek at the Jordan Valley Water Conservation District and its confluence with the Jordan River were also sampled (Figure 28 and Figure 29). Nets were dragged upstream through the substrate to depths of about 2-5 cm while simultaneously vigorously kicking substrate upstream of the net, which allowed loosened material to flow into the net. Most samples contained numerous heavy live Corbicula clams, sand, gravel, or cobbles, which assured that the kick methods were able to efficiently collect live snails or empty shells. When nets were about ¼ full, sample contents were placed into large shallow trays ½ filled with water and allowed to stand for approximately 15 minutes to allow snails to become active and more visible and in many cases to attach to the sides and bottoms of the trays. Slightly stirred water was slowly poured out of trays to remove detritus (but not empty shells) up to several times depending on the amount of detritus. All live snails and empty snail shells were hand picked from contents at the site. Hand lens were often used to locate very small snails or determine that they were not tiny pebbles or sand particles. Empty shells were placed in small sample jars dry, live snails were placed in jars with river water sprinkled with menthol crystals and relaxed for 24 hrs in a refrigerator or on ice in a cooler. Relaxed snails were then stored in 70% EtOH final solution. The EtOH preserved samples may be used for future genetic taxonomic verification. Taxonomic identification and verification at minimum to family level was conducted in the field by the author however, many were identifiable to species or genus level. Voucher specimens are housed at OreoHelix Consulting, Moab, UT and are available for use and taxonomic verification. Any evidence of unionid mussels was also noted. However, no live or empty shells of mussels were observed during the snail survey in October 2014.

Figure 28. Bingham Creek.

Figure 29. Springs on west side of Jordan River at "Narrows" (40°27'56.19"N; 111°56'1.87"W)

Figure 30. Two Bingham Creek sample locations: JRWCD land (40°36'17.17"N; 111°55'14.68"W) and where Bingham Creek enters the Jordan River (40°36'4.84"N; 111°55'41.67"

RESULTS

Unionoida mussels

No live native unionid mussels were found after the intensive ten-day survey of 7.5 miles of the Jordan River in April 2014 or during the ten day, non-pulmonate snail survey in October 2014. However, live invasive Asiatic clam, *Corbicula fluminea* occurred in every site and often in very high abundance. Shells of native fingernail clams (Family Sphaeriidae) were observed at the majority of sites including tributaries and live native clams were often observed. The observation of native fingernail clams supports the assumption that native Unionoida mussels would have also been encountered in the survey.

One small weathered shell fragment (about 2 cm long x 0.5 cm wide) of *Anodonta* sp. was found in Jordan River at Site 2 and many fragments and two whole *Anodonta* sp. shells in Spring Creek downstream of Mill Pond, Utah County but none that were alive or appeared to be recently dead (i.e. no muscle tissue present). The only complete matching pairs (both left and right halves) of *Anodonta* sp. shells that we found were in Spring Creek buried under sand and a thick layer of *Corbicula* shells. Two of the *Anodonta* sp. shells were from one large and one empty shell was from a smaller *Anodonta* sp. (Figure 31).

Figure 31. Complete *Anodonta* sp. shell from Mill Pond, Utah County, April 2014. No body tissue was present and the time since death is unknown.

Substrate throughout most of the Jordan River was mostly sand, silt, clay, and organic matter, with occasional gravel/cobble riffles. The narrows' section of the Jordan River included large boulders and appeared to be the most likely section for finding *M. falcata*. Mill Pond, Utah County had mostly sand, silt, and clay substrate whereas, Spring Creek, Utah County, also had gravel and small cobbles where Anodonta shells were collected. Mill Creek upstream of Central Valley Treatment Facilities effluent had mostly hardpan, tightly embedded gravels with some sand/silt, clay. Mill Creek downstream of effluent was mostly sand/silt/clay/OM.

Corbicula fluminea occurred throughout the Jordan River at every site we sampled including Mill Pond but was not seen in the upstream Mill Creek site (7). *Corbicula* often occurred at extremely high abundance, if empty shells were included in the estimate. *Corbicula* sp. was extremely abundant in the canal that flowed along the west side the Jordan River near the "Narrows" (Site 1). Because this was a presence/absence survey, mollusk densities were not estimated. *Corbicula* appeared to be most abundant in sand/gravel sediments between the anoxic layer that occurred a few centimeters deep (e.g.black ooze with smell of sulfur) and the surface of the substrate and often under a thin layer of filamentous algae (*Cladophora* sp.) where it was present. Sand/gravel substrates are preferred by *Corbicula* habitat (see Appendix 24). The largest *Corbicula* shell observed by the author was collected at Mill Pond and measured about 6 cm in max diameter (Figure 32).

Figure 32. Atypically large *Corbicula* shells for Jordan River, UT drainage. These large *Corbicula* are approaching the average size of *Anodonta* at sexual maturity. This large shelled *Corbicula* also illustrates ideal habitat conditions for this invasive species in many areas of the Jordan River drainage.

Non-pulmonate snails

No live non-pulmonate snails were found in the main stem Jordan River, except for the invasive New Zealand mudsnail, *Potamopyrgus antipodarum*. Empty shells of *Fluminicola coloradoensis, Pyrgulopsis sp., Valvata humeralis,* and *V. utahensis* shells were found in the main stem but their age and origin are unknown (Figure 33– 33). Mollusk shells can remain intact for >100 years. It is likely that empty shells found in the Jordan River samples were either deposited from tributaries where extant populations exist or from relatively recently extirpated (≥ 10-20 years) main stem Jordan River populations. Live *F. coloradoensis* and *Pyrgulopsis* spp. were reported in the Jordan River and surrounding areas as recently as 2004 (BLM/USU BugLab data). If live *F. coloradoensis* and *Pyrgulopsis* spp. were found in the Jordan River in BLM/USU BugLab surveys then additional intensive surveys should be conducted as soon as possible in those locations to help verify their status in the Jordan River.

Live *Fluminicola coloradoensis and Pyrgulopsis* spp. were found in the spring fed tributaries of the Jordan River and on occasion were relatively abundant. These tributaries were: an unnamed series of springs along the west side of the Narrows and the South Jordan Canal (Figure 29), Bingham Creek, and others. The largest spring creek, Bingham Creek, flows through the Jordan

Valley Water Conservation District (Figure 38) and had the highest abundances of *F. coloradoensis* in the survey. Upstream and downstream of JVWCD property, Bingham Creek is heavily impaired by construction and urbanization and downstream it becomes mixed with degraded canal return water before it enters the Jordan River (Figure 39 and Figure 40). It is surprising that native non-pulmonates survive in downstream sections of Bingham Creek.

Figure 33. Empty shells of the prosobranch snail, *Fluminicola coloradoensis* from the Jordan River.

Figure 34. Empty shells of the prosobranch snail, *Fluminicola coloradoensis* from the Jordan River. Scale lines are 1 mm.

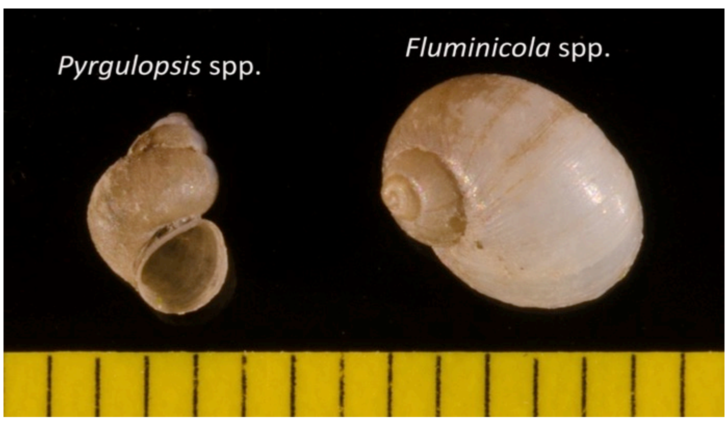

Figure 35. Empty shells of the prosobranch snails, *Pyrgulopsis* spp., and *Fluminicola coloradoensis* and heterobranch *Valvata* spp. from the Jordan River. Scale lines are 1 mm.

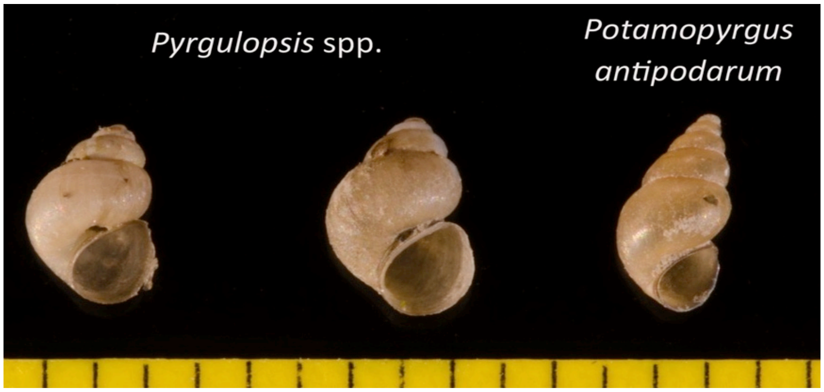

Figure 36. Two empty shells of the prosobranch snail, *Pyrgulopsis* spp., and the invasive New Zealand mudsnail, *Potamopyrgus antipodarum* from the Jordan River. Scale lines are 1 mm. Many snail taxa are somewhat difficult to distinguish using shell morphology and often require a malacological expert in the field.

Figure 37. Empty shells of two species of the heterobranch snail, *Valvata humeralis* (smooth shell) and *V. utahensis* (ridged shell) found in the Jordan River and its spring tributaries. Scale lines are 1 mm.

Figure 38. Bingham Creek upstream of construction site on the Jordan Valley Water Conservation District property, October 2014. These are typical attainable, stable, conditions of relatively healthy spring creeks in the Jordan River drainage.

Figure 39. All too common construction that continues to impact spring creek tributaries of the Jordan River, UT. This location at the Jordan Valley Water Conservation District property was photographed October 2014.

Figure 40. Bingham Creek downstream of several construction sites and after canal return flows as it enters the Jordan River, October 2014. These are typical conditions of the spring creeks during construction and after heavy rains in the Jordan River drainage.

Pulmonate Snails

Although not the focus of this report, several pulmonate snail taxa shells were found in the springs and the Jordan River including, two Physid taxa, two Lymnaeid taxa, and several Planorbidae taxa. Taxonomic identification of pulmonate snails continues. Two live pulmonate taxa were found in the springs and Jordan River; *Physa* sp. and a planorbid taxon. These two live taxa were collected within shoreline vegetation or slow backwater channels, their preferred habitat.

Invasive species

New Zealand mudsnails (NZMS)(Figure 41 and Figure 36) and Asiatic clams occurred in almost all kick samples and at all sites. *Corbicula* sp. was extremely abundant at the downstream site near 1700 South (Figure 42). NZMS were extremely abundant at the JVWCD spring creek site and estimated to be at densities far greater than 100,000/m^2 (Figure 41).

Figure 41. Live invasive NZMS and native physid snails from a quick dip net scoop in aquatic vegetation and estimated at >> 100,000/m^2 in Bingham Spring Creek as it flows through the Jordan Valley Water Conservation District property.

Figure 42. Clamming on the Jordan River at 1700 South. This photo illustrates *Corbicula* sp. at extreme high densities collected from approximately a 1 m^2 sized area. Their body sizes are much smaller than the largest sized *Corbicula* found in Mill Pond and Spring Creek, Utah County suggesting that the substrate in the Jordan River, at least in this location, is less stable than in habitats where larger individuals were found but that food resources were likely not limiting.

DISCUSSION

The Great Basin, including Great Salt Lake tributaries such as the Jordan River and Utah Lake, were historically native freshwater mollusk diversity 'hotspots' and are part of Utah's unique biotic heritage. However, it now appears that native Unionoida mussels and non-pulmonate snails may no longer occur in the Jordan River (based on this survey and the literature) and possibly Utah Lake (based on available literature), or they occur at such extremely low densities and in isolated locations so as to be almost non-detectable. Isolated populations of non-pulmonate snails may occur in sections of the Jordan River in very limited areas where spring creeks and other tributaries enter the Jordan River or spring upwelling occurs for a few short meters downstream in the river. As discussed throughout the report, conditions other than ammonia likely contribute to their absence.

The absence (non-detection) of live Unionoida mussels and non-pulmonate snails in this survey is consistent with the Utah DWQ designation of many sections (management units) of the Jordan River downstream of the "Narrows" as a warm water, non-game fisheries (many of the focal taxa surveyed prefer cold water) and it is unlikely that these taxa can survive under present conditions. Many of the empty native mussel and non-pulmonate snail shells examined in the Jordan River are likely from tributary flushing and depositing in the benthos or possibly from extinct populations. More pollution tolerant, warm water, pulmonate snails (e.g. *Physa* sp.) occur throughout the Jordan River, typically in the slower, shoreline, vegetated sections.

Spring seeps and creeks that enter the Jordan River are now critical habitat for remaining non-pulmonate snail taxa; *Fluminicola coloradoensis*, *Pyrgulopsis* spp., and *Valvata* spp. They may also be the last best available habitat for any future reintroduction programs. Unfortunately, these spring creeks also now act as nurseries and prime habitat for the invasive NZMS (*P. antipodarum)* and often *Corbicula*. Spring seeps and creeks in the Jordan River system are in urgent need of special protection and management and ammonia criteria based on native taxa that occur there should be developed specifically for these habitats.

Mollusk presence/absence

Mollusk presence can be defined in numerous ways (EPA 2013). Mollusk presence in this survey was defined as existence of live mollusks, recently dead mollusk shells, unweathered shells, and/or valid presence data from recent surveys. Defining mollusk absence however, was not as clear-cut. Observed mollusk absence could have been due to many factors including: mollusks were extremely rare or uncommon, not visually observing mollusks when using aquascopes or other sampling methods (i.e. sampling error), or mollusks were truly absent. The combination of reconnaissance and qualitative surveys using an experienced field malacologist encompassed enough area and duration to demonstrate a reasonable probability of target mollusk absence, particularly in the site-specific survey locations. A reasonable probability estimation for Unionoida in the Jordan River would be approximately < 1 individual for 270 hours of visual examination or about < 1 individual/ 50,000 m^2. Because concluding true absence of target mollusks is not possible without examining the entire substrate of the Jordan River (or Utah Lake), the development of eDNA sampling methods as an additional line of evidence will strongly improve a conclusion of target mollusk absence (see Appendix 25. DNA Barcoding). Additional discussion of Unionoida and non-pulmonate snail status in the Jordan River drainage follows.

Metapopulation viability, the extinction vortex, and the extinction debt

Populations of the two Unionoida taxa that may have been resident, native to the Jordan River drainage, *Anodonta californiensis/nuttalliana* and *Margaritifera falcata* were likely continuous or metapopulations prior to Ancient Lake Bonneville's recession. Unionoida populations later became metapopulations as continuously connected freshwater suitable habitats decreased and became more isolated, starting with the recession of Lake Bonneville, approximately 11,000 to 14,500 years ago (Mock et al. 2004) and as a result of human economic activities. These two taxa likely no longer persist as metapopulations, which require some limited dispersal between populations, but now exist as isolated populations. 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 as a consequence of demographic stochasticity. However, limited connectivity can provide for recolonization of the extinct populations: thus metapopulations have less extinction risk than completely isolated populations (Hanski 1999). Both of the two native Unionoida taxa in UT now occur as isolated fragmented populations due to the natural recession of Lake Bonneville and negative environmental conditions exacerbated by modern humans. There is likely no dispersal between remaining populations of either taxon within the Jordan River drainage (e.g. unsuitable Utah Lake conditions) or within the Bear River drainage or between the two drainages (e.g. Great Salt Lake salinity barrier). 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). For example, Richards et al. (2009) conducted a metapopulation viability analysis and quantitative risk assessment on a federally listed threatened hydrobiid snail that showed that colonies (populations) were more likely to go extinct in isolated spring habitats than in habitats in springs and sections of the Snake River which had limited dispersal via connectivity (i.e. metapopulations), even though the isolated spring habitats had less environmental stochasticity than Snake River habitats. Unlike hydrobiid snails, Unionoida mussels are dependent on fish hosts for larvae dispersal (e.g. parasitic glochidia). Unionoida resident to Utah likely depended on past large populations of native fish hosts (e.g. cutthroat trout) for their dispersal. Fish populations that are currently present in the Jordan River, native or introduced, are but a small fraction of past populations and may not provide enough individual hosts for glochidia dispersal. 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. 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 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.

Isolated Unionoida populations in UT 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). 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 water quality management agencies. Because isolated Unionoida populations in the Jordan River drainage are at such low densities, it is likely 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). This may be particularly true for the long-lived native mussel, *Margaritifera falcata* colonies that survive outside of the Jordan River drainage that may only harbor adults. Successful reproduction of *M. falcata* in some populations may not have occurred in over 50 years. Most Unionoida populations, and to a lesser extent, non- pulmonate snail populations in Utah may simply no longer be viable without massive management intervention and monetary expenditures.

Unionoida and Non- Pulmonate Snail 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 waters”. The continued survival and viability of Unionoida and non-pulmonate snails in Utah is directly linked to these three interacting elements of integrity: physical, chemical, and biological.

The **physical integrity** of the Jordan River has been severely compromised. Human induced factors that have compromised the physical integrity of the Jordan River include, but are not limited to:

- Dewatering
- Non natural flow regime

- Channelization
- Sedimentation
- Urbanization
- Dredging
- Flood event scouring as a result of channelization
- Loss of floodplain connection (e.g. flood dynamics are not the same as when Jordan River was allowed to inundate flood plain. Floodplains also dissipate flood scour energy/intensity).
- Global climate change. Expected increased temperatures, decreased precipitation, and increased and unpredictable/ extreme storm events that likely will have deleterious but unquantifiable effects on physical integrity

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

The **chemical integrity** of the Jordan River has also been severely compromised. Factors that have compromised the chemical integrity of the Jordan River include, but are not limited to:

- Low dissolved oxygen, particularly under winter ice
- Point and non-point sources of pollutants
- Increased salinity (evaporative loss in Utah Lake exceeding input)
- Nutrients
- High summer temperatures
- The chemical integrity of Utah Lake
- Global climate change. Expected increased temperatures, decreased precipitation, and increased and unpredictable/ extreme storm events that likely will have deleterious but unquantifiable effects on chemical integrity

As with the physical factors, until remedied, chemical factors preclude the viability of Unionoida and non-pulmonate snails in the Jordan River. 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 saturated than colder water, particularly during rare occasions when 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 about 10 ft. Shallow water heats up faster than deeper water and is less able to hold DO. This is in contrast to historic 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. More importantly, winter ice cover can reduce DO in Utah Lake to very low levels.

The **biological integrity** of the Jordan River has also been severely compromised. Factors that have compromised the biological integrity of the Jordan River include, but are not limited to:

- Invasive species
- 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))
- Loss of population interactions (e.g. metapopulation dynamics, isolated populations)
- Loss or change in genetic diversity
- Unknown changes in species interactions resulting from loss of biodiversity and species interactions
- Effects of demographic and environmental stochasticity on small, isolated populations
- Global climate change. Expected increased temperatures, decreased precipitation, and increased and unpredictable/ extreme storm events that likely will have deleterious but unquantifiable effects on biological integrity

As with the physical and chemical factors and until remedied, these biological factors reduce the viability of Unionoida and non-pulmonate snails in the Jordan River.

Additional reasons for the non-detection of native Unionoida mussels and non-prosobranch snails in the Jordan River likely include a combination of the following:

- High sediment loads, particularly clay.
- Intensive and extensive urbanization, industrialization, and agriculture impacts, including dewatering and channelization of Jordan River.
- Water quality impairment (see Appendix 23a and 23b).
- High densities of the invasive *Corbicula* clam limited available native bivalve habitat (for other impacts of *Corbicula* see Appendix 24).
- Absence of native fish hosts for native larval mussel glochidia. Very low fish abundances of any species other than carp in Jordan River compared to historic abundances of native fish species.
- High flows (e.g. 2011) in the exceedingly channelized Jordan River may have covered any remaining mussel habitat and may have removed mussel shells.

- Rapidly recolonizing *Corbicula* can quickly become established in remaining suitable habitats after recent high flows and can preclude any reestablishment by any remaining native mussels. Native mussels require an abundance of fish hosts to reproduce whereas, *Corbicula* does not.
- Historically there was a trout hatchery on Mill Pond, Utah County and native mussels may have been associated with these activities. Spring Creek, which flows into and out of Mill Pond, also could have had thriving populations of unintentionally introduced native mussels when its flows were stable, water quality and habitat were less impaired, and a hatchery existed.
- Two of the most highly invasive mollusk taxa now dominate the benthic assemblage in the Jordan River and probably Utah Lake: NZMS and *Corbicula*. These taxa are likely altering the nitrogen cycle in this system, including ammonia (see Appendix 24). For example, Hall et al. (2006) showed that NZMS production could far outweigh that of native taxa with production estimates among the highest ever reported in the literature for a single species of freshwater macroinvertebrate. NZMS can also dominate carbon and nitrogen cycling, where they can consume up to 75% of gross primary production and excrete two-thirds of total ecosystem ammonium demand (Hall et al. 2003). Welker and Walz (1998) and Vaughn et al. (unpublished data) have found that the volume of water filtered by freshwater bivalves (e.g. *Corbicula*) within dense beds can equal or exceed daily stream discharge. In fact, Strayer et al. (1999) and Dame (1996) have suggested that **any** assemblage of bivalves may significantly influence phytoplankton concentrations when filtration rates are large relative to food supply.

Note: EPA and UDWQ use what is known as “G factors” and “resident” vs. “non-resident” criteria to help determine the status and likelihood of reoccurrence of taxa and habitat conditions that may preclude that likelihood. An attempt was made to address these criteria and can be found in Appendix 23a and 23b, however, these criteria are not necessarily useful for the taxa surveyed in this report and are somewhat vague in their meaning and consequently their interpretation.

CONCLUSION

Most Unionoida mussels and non-pulmonate snail populations are under threat or are in serious decline in Utah’s freshwaters. Unionoida taxa, primarily *Anodonta californiensis/nuttalliana* and *Margaritifera falcata* are likely absent from the Jordan River and viable populations in the Jordan River drainage may not persist into the foreseeable future. Native non-pulmonate snails are also becoming scarce in the Jordan River drainage and spring -stream tributary habitats may be the last refugia for these species in the Jordan River if they are able to continue to coexist with the already present invasive New Zealand mudsnails and Asian clams. Additional surveys are urgently needed and comprehensive metapopulation viability analyses should be conducted for all of these taxa and particularly for *A. californiensis/nuttalliana*. The multitude of physical, chemical, and biological impairments discussed in this report and by others combine to prevent re- establishment of Unionoida taxa into the Jordan River. Proposed efforts to further reduce ammonia concentrations in the Jordan River will likely have no net benefit until these other more deleterious factors are remedied.

RECOMMENDATIONS

The following surveys and analyses are recommended to determine the distribution and status of Unionoida and non-pulmonate snails in the Jordan River drainage:

- Expand the mollusk survey area and revisit Jordan River sites at least every 3 years
- Coordinate, share, and annually update private, government, and non-profit data on mollusk distributions and status.
- Survey the location that the BLM/USU BugLab reported as having live *Fluminicola* and *Pyrgulopsis* in 2004. Snail population abundances can fluctuate yearly and may naturally have greater abundances in the future and therefore may be more detectable.
- Increase mollusk, particularly native mussel, survey efforts in Utah Lake and tributaries. These could be the only remaining potential sources of recolonization in the Jordan River.
- Develop and add eDNA sampling methods to the program. Genetic biomarkers for *Anodonta* and *Margaritifera* eDNA are expected to be developed and in use, summer 2015.
- Resurvey known locations of *Anodonta* populations in the Jordan River drainage and conduct qualitative surveys to estimate abundances and size classes for each population.
- Conduct metapopulation viability analyses and quantitative risk assessments for Unionoida and non-pulmonate snails in Jordan River drainage.
- Conduct acute and chronic ammonia toxicity tests on Utah's native mussels.
- Conduct detailed distribution, life history, and ecological studies of invasive New Zealand mudsnails and Asian clams in the Jordan River drainage. Determine their impacts on water quality including nutrient cycling and ammonia.
- Immediate and increased protection of remaining Unionoida populations and their habitat in the Jordan River drainage.
- Immediate and increased protection of spring tributaries of the Jordan to help insure that native non-pulmonate snail populations do not travel down the path towards extinction in UT that *Anodonta* appears to be following.
- Educate Utah citizens regarding their unique natural heritage of native mollusks, which is rapidly being lost, and encourage active participation in mollusk recovery.

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LITERATURE CITED AND SELECT REFERENCES

Abell, R. 2002. Conservation biology for the biodiversity crisis: a freshwater follow-up. Conservation Biology 16:1435–1437.

Abell, R., D. M. Olsen, E. Dinerstein, P. T. Hurley, J. T. Diggs, W. Eichbaum, S. Walters, W. Wettengel, T. Allnutt, C. J. Loucks, and P. Hedao. 2000. Freshwater ecoregions of North America: a conservation assessment. Island Press, Washington, D.C.

Albrecht, C., K. Kuhn, and B. Streit. 2007. A molecular phylogeny of Planorboidea (Gastropoda, Pulmonata): insights from enhanced taxon sampling. Zoologica Scripta 36:27–39.

Alcocer, J., and F. W. Bernal-Brooks. 2010. Limnology in Mexico. Hydrobiologia 644:15–68.

Alcocer, J., E. Escobar, and A. Lugo. 2000. Water use (and abuse) and its effects on the crater lakes of Valle de Santiago, Mexico. Lakes & Reservoirs: Research and Management 2000:145–149.

Barnosky, A. D., N. Matzke, S. Tomiya, G. O. U. Wogan, B. Swartz, T. B. Quental, C. Marshall, J. L. McGuire, E. L. Lindsey, K. C.

Maguire, B. Mersey, and E. A. Ferrer. 2011. Has the Earth's sixth mass extinction already arrived? Nature 471:51–57.

Beissinger, S. R. 1990. Alternative foods of a diet specialist, the snail kite. The Auk 107(2):237–333.

Besser, J. M., D. L. Hardesty, I. E. Greer, and C. G. Ingersoll. 2009. Sensitivity of freshwater snails to aquatic contaminants: survival and growth of endangered snail species and surrogates in 28- day exposure to copper, ammonia, and pentachlorophenol. Administrative report CERC-8335-FY07-20-10, submitted to U.S. Environmental Protection Agency, Office of Research and Development, Duluth, Minnesota.

Bogan, A. E. 2006. Conservation and extinction of the freshwater mol- luscan fauna of North America. Pages 373–383 *in* C. F. Sturm, T. A. Pearce, and A. Valdés, editors. The mollusks: a guide to their study, collection, and preservation. American Malacological Society, Universal-Publishers, Boca Raton, Florida.

Bogan, A. E., J. M. Pierson, and P. Hartfield. 1995. Decline in the freshwater gastropod fauna in the Mobile Bay Basin. Pages 249– 252 *in* E. T. LaRoe, G. S. Farris, C. E. Puckett, P. D. Doran, and M. J. Mac, editors. Our living resources, a report to the

Nation on the distribution, abundance and health of U.S. plants, animals, and ecosystems. U.S. Department of Interior, National Biological Survey, Washington, D.C.

Boschung, H. T., and R. L. Mayden. 2004. Fishes of Alabama. Smith- sonian Press, Washington, D.C.

Bouchet, P., and J. P. Rocroi. 2005. Classification and nomenclator of gastropod families. With classification by J. Frýda, B. Hausdorf, W. Ponder, A. Valdés, and A. Warén. Malacologia 47:1–397.

Bourne, G. R. 1993. Differential snail-size predation by snail kites and limpkins. Oikos 68:217–223.

Brasher, A. M. 1997. Life history characteristics of the native Hawaiian stream snail *Neritina granosa* (Hihiwai). Cooperative National Park Resources Studies Unit, University of Hawaiì at Manoa, Manoa, Honolulu, Hawaii, Technical Report 114.

Brown, K. M., and P. D. Johnson. 2004. Comparative conservation ecology and pleurocerid and pulmonate gastropods of the United States. American Malacological Bulletin 19:57–62.

Brown, K. M., B. Lang, and K. E. Perez. 2008. The conservation ecol- ogy of North American pleurocerid and hydrobiid gastropods. Journal of the NorthAmerican Benthological Society 27:484–495.

Brown, K. M., and C. E. Lydeard. 2010. Mollusca: Gastropoda. Pages 277–307 *in* J. H. Thorpe and A. P. Covich, editors. Ecology and classification of freshwater invertebrates of North America. Elsevier.

Brown, K. M., D. Varza, and T. D. Richardson. 1989. Life histories and population dynamics of two subtropical snails (Prosobranchia: Viviparidae). Journal of the North American Benthological Society 8:222–228.

Burch, J. B. 1989. North American freshwater snails. Malacological Publications, Hamburg, Michigan.

Burkhead, N. M. 2012a. Extinction rates in North American freshwater fishes. Available: http://fl.biology.usgs.gov/extinct_fishes/index. html. (March 2013).

Burkhead, N. M. 2012b. Extinction rates in North American freshwater fishes, 1900 to 2010. BioScience 62:798–808.

Cagle, F. R. 1952. The status of turtles *Graptemys pulchra* Baur and *Graptemys barbouri* Carr and Marchand, with notes on their natu- ral history. Copeia 1952:223–234.

Clarke, A. H. 1976. Endangered freshwater mollusks of northwestern North America. Bulletin of the American Malacological Union 1: 18–19.

Contreras-Balderas, S., G. Ruiz-Campos, J. J. Schmitter-Soto, E. Díaz-Pardo, T. Contreras-McBeath, M. Medina-Soto, L. Zam- brano-González, A. Varela-Romero, R. Mendoza-Alfaro, C. Ramírez-Martínez, M. A. Leija-Tristán, P. Almada-Villela, D. A.
Hendrickson, and J. Lyons. 2008. Freshwater fishes and water status in México: a country-wide appraisal. Aquatic Ecosystem Health & Management 11:246–256.

Correa, A. C., J. S. Escobar, P. Durand, F. Renaud, P. David, P. Jarne, J. P. Pointier, and S. Hurtrez-Boussès. 2010. Bridging gaps in the molecular phylogeny of the Lymnaeidae (Gastropoda: Pulmo- nata), vectors of *Fascioliasis*. BMC Evolutionary Biology 10:381.
Available: http://www.biomedcentral.com/1471-2148/10/381. (April 2011).

Covich, A. P., M. A. Palmer, and T. A. Crowl. 1999. The role of ben- thic invertebrate species in freshwater ecosystems. BioScience 49:119–127.

Crummett, L. T., and M. L. Wayne. 2009. Comparing fecundity in parthenogenic versus sexual populations of the freshwater snail *Campeloma limum*: is there a two-fold cost of sex? Invertebrate Biology 128:1–8.

Dame RF. 1996. Ecology of Marine Bivalves: An Ecosystem Approach. Boca Raton (FL): CRC Press.

Davis, C. C. 1961. A study of the hatching process in aquatic inverte- brates. I. The hatching process in *Amnicola limosa* (Gastropoda: Prosobranchia). Transactions of the American Microscopical So- ciety 80:227–234.

Deacon, J. E., G. Kobetich, J. D. Williams, and S. Contreras. 1979. Fishes of North America endangered, threatened, or of special concern. Fisheries 4:29–44.

DeVries, D. R. 2005. Evaluating changes in the *Tulotoma magnifica* populations in the Coosa River and its tributaries during 1992 through 2004. Final Report to U.S. Fish and Wildlife Service, Jackson, Mississippi.

DeWitt, R. M. 1954. Reproductive capacity in a pulmonate snail(*Physa gyrina* Say). The American Naturalist 88:159–164.

Dillon, R. T. 2011. Robust shell phenotype is a local response to stream size in the genus *Pleurocera* (Rafineque, 1818). Malacologia 53:265–277.

Dillon, R. T., and J. D. Robinson. 2009. The snails the dinosaurs saw: are the pleurocerid populations of the older Appalachians a relict of the Paleozoic? Journal of the North American Benthological Society 28:1–11.

Dillon, R. T., J. D. Robinson, and A. R. Wethington. 2007. Empirical estimates of reproductive isolation between the freshwater pul- monates *Physa acuta*, *P. pomilia*, and *P. hendersoni*. Malacologia 49:283–292.

Dillon, R. T., A. R. Wethington, and C. E. Lydeard. 2011. The evolu- tion of reproductive isolation in a simultaneous hermaphrodite, the freshwater snail *Physa*. BMC Evolutionary Biology 11:144. Available: http://www.biomedcentral.com/1471-2148/11/144. (May 2011).

Dinger, E. C., A. E. Cohen, D. A. Hendrickson, and J. C. Marks. 2005. Aquatic invertebrates of Cuatro Ciénegas, Coahuila, México: natives and exotics. Southwestern Naturalist 50:237–246.

Downing, J. A., P. Van Meter, and D. A. Woolnough. 2010. Suspects and evidence: a review of the causes of extirpation and decline of freshwater mussels. Animal Biodiversity and Conservation 33:151–185.

Dundee, D. S. 1957. Aspects of the biology of *Pomatiopsis lapidaria*. Museum of Zoology, University of Michigan, Ann Arbor, Michi- gan, Occasional Paper 100: 1–37.

Ehrlich, P. R., and R. M. Pringle. 2008. Where does biodiversity go from here? A grim business-as-usual forecast and a hopeful port- folio of partial solutions. Proceedings National Academy of Sci- ences 105(Suppl.1):11579–11586.

Estoy, G. F., Jr., Y. Yusa, T. Wada, H. Sakurai, and K. Tsuchida. 2002. Effects of food availability and age on the reproductive effort of the apple snail, *Pomacea canaliculata* (Lamark) (Gastropoda: Ampullariidae). Japanese Journal of Applied Entomology and Zoology 37:543–550.

Etnier, D. A., and W. C. Starnes. 1994. The fishes of Tennessee. The University of Tennessee Press, Knoxville.

Fagen, W. F. and E. E. Holmes. 2006. Quantifying the extinction vortex. Ecology Letters. 9: 51-60.

Ford, D. K., and D. Moll. 2004. Sexual and seasonal variation in forag- ing patterns in the stinkpot, *Sternotherus odoratus*, in southwest- ern Missouri. Journal of Herpetology 38(2):296–301.

Freshwater Mollusk Conservation Society (FMCS). 2013. Freshwater gastropod home page. Available: http://molluskconservation.org/ Snails_Ftpage.html. (May 2013).

Grabarkiewicz, J., and W. Davis. 2008. An introduction to fresh- water mussels as biological indicators. U.S. Environmental Protection Agency, Office of Environmental Information, EPA- 260-R-08-015, Washington, D.C.

Graf, D. L. 2001. The cleansing of the Augean stables, or a lexicon of the nominal species of the Pleuroceridae (Gastropoda: Proso- branchia) of Recent North America, North of Mexico. Walkerana 12:1–124.

Haag, W. R., and M. L. Warren, Jr. 2006. Seasonal feeding specializa- tion on snails by river darters (*Percina shumardi*) with a review of snail feeding by other dater species. Copeia 2006:604–612.

Hall, R. O., J. F. Tank, and M. F. Dybdahl. 2003. Exotic snails dominate nitrogen and carbon cycling in a highly productive stream. Front. Ecol. Environ. 1(8): 407–411.

Hanski, I. 1999. Metapopulation ecology. Oxford [Oxfordshire]: Oxford University Press.

Harrold, M. N., and R. P. Guralnick. 2008. A field guide to the freshwa- ter mollusks of Colorado. Colorado Division of Wildlife, Denver, Colorado.

Hawkins, C. P., and J. K. Furnish. 1987. Are snails important competitors in stream ecosystems? Oikos 49:209–220.

Hayes, D. M., R. L. Minton, and K. M. Perez. 2007. *Elimia comalensis* (Gastropoda: Pleuroceridae) from the Edwards Plateau, Texas: unrecognized endemics or native exotic. American Midland Natu- ralist 158:97–112.

Heinz Center Report. 2002. The state of the Nation's ecosystems: mea- suring the lands, waters, and living resources of the United States. Cambridge University Press, Cambridge, UK.

Hershler, R. 2001. Systematics of the North and Central American aquatic snail genus *Tryonia* (Rissooidea: Hydrobiidae). Smithso- nian Contributions to Zoology 612. Smithsonian Institution Press, Washington, D.C.

Hershler, R. and T. J. Frest. 1996. A review of the North American freshwater snail genus *Fluminicola* (Hydrobiidae). Smithsonian Contributions to Zoology 583:1–41.

Hershler, R., and H. P. Liu. 2008. Phylogenetic relationships of assimi- neid gastropods of the Death Valley–lower Colorado River region: relicts of a late Neogene marine incursion? Journal of Biogeog- raphy 35:1816–1825.

Hershler, R., and H. P. Liu. 2012. A new species of springsnail (*Pyrgulopsis*) from the Owyhee River basin, Nevada. Western North American Naturalist 72(1):21–31.

Hershler, R., H. P. Liu, T. J. Frest, and E. J. Johannes. 2007a. Exten- sive diversification of pebblesnails (Lithoglyphidae: *Flumnicola*) in the upper Sacramento River basin, northwestern USA. Zoologi- cal Journal of the Linnean Society 149:371–422.

Hershler, R., H. P. Liu, and B. K. Lang. 2007b. Genetic and morpho- logic variation of the Pecos assiminea, an endangered mollusk of the Rio Grande region, United States and Mexico (Caenogas- tropoda: Rissooidea: Assimineidae). Hydrobiologia 579:317–335.

Hershler, R., M. Mulvey, and H. P. Liu. 2005. Genetic variation in the desert springsnail (*Tryonia porrecta*): implications for reproduc- tive mode and dispersal. Molecular Ecology 14:1755–1765.

Hershler, R., J. M. Pierson, and R. S. Krotzer. 1990. Rediscovery of *Tulotoma magnifica* (Conrad) (Gastropoda: Viviparidae). Pro- ceedings of the Biological Society of Washington 103:815–824.

Hershler, R., and W. Ponder. 1998. A review of morphological charac- ters of hydrobioid snails. Smithsonian Contributions to Zoology 600. Smithsonian Institution Press, Washington, D.C.

Holznagel, W. E., and C. E. Lydeard. 2000. A molecular phylogeny of North American Pleuroceridae (Gastropoda: Cerithioidea) based on mitochondrial 16S rDNA sequences. Journal of Molluscan Studies 66:233–257.

Hovingh, P. 2004. Intermountain freshwater mollusks, USA (*Margaritifera, Anodonta, Gonidea, Valvata, Ferrissia*): Geography, conservation, and fish management implications. Monographs of the Western North American Naturalist 2, pp. 109–135.

Hsiu-Ping Liu, Jessica Walsh, and Robert Hershler. 2013. Taxonomic clarification and phylogeography of *Fluminicola coloradensis* Morrison, a widely ranging western North American pebblesnail. Monographs of the Western North American Naturalist 6, pp. 87–110.

Hubendick, B. 1978. Systematics and comparative morphology of the Basommatophora. Academic Press, London, UK.

Huryn, A. E., A. C. Benke, and G. M. Ward. 1995. Direct and indirect effect of geology on the distribution, biomass, and production of the freshwater snail *Elimia*. Journal of the North American Ben- thological Society 14:519–534.

IUCN. (International Union for Conservation of Nature). 2001. Red List categories and criteria version 3.1. Available: http://www. iucnredlist.org/technical-documents/categories-and-criteria/2001- categories-criteria. (May 2012).

2012. The IUCN Red List of threatened species. Version 2012.2. Available: http://www.iucnredlist.org. (November 2012).

Jelks, H. H., S. J. Walsh, N. M. Burkhead, S. Contreras-Balderas, E. Diaz-Pardo, D. A. Hendrickson, J. Lyons, N. E. Mandrak, F. Mc- Cormick, J. S. Nelson, S. P. Platania, B. A. Porter, C. B. Renaud, J. J. Schmitter-Soto, E. B. Taylor, and M. L. Warren. 2008. Conservation status of imperiled North American freshwater and diadromous fishes. Fisheries 33:372–407.

Gilpin ME, Soulé ME (1986). "Minimum Viable Populations: Processes of Species Extinction". In M. E. Soulé. Conservation Biology: The Science of Scarcity and Diversity. Sinauer, Sunderland, Mass. pp. 19–34.

Gabriel, W. M. Lynch, and R. Burger (1993). Muller's Ratchet and mutational meltdowns. Evolution 47:1744-1757.

Lynch, M, R. Burger, D. Butcher, and W. Gabriel (1993). The mutational meltdown in asexual populations. J. Hered. 84:339-344.

Lynch, M. and W. Gabriel (1990). Mutation load and the survival of small populations. Evolution 44:1725-1737.

Jenkins, R. E. 1994. Harelip sucker: *Moxostoma lacerum* (Jordan and Brayton). Pages 519–523 *in* R. E. Jenkins and N. M. Burkhead, editors. The freshwater fauna of Virginia. American Fisheries So- ciety, Bethesda, Maryland.

Jenkins, R. E., and N. M. Burkhead. 1994. The freshwater fishes of Virginia. The American Fisheries Society, Bethesda, Maryland.

Johnson, P. D., and K. M. Brown. 1997. The role of current and light in explaining the habitat distribution of the lotic snail *Elimia semi- carinata* (Say). Journal of the North American Benthological So- ciety 16:545–561.

Johnson, P.D, A. E. Bogan, K. M. Brown, N. M. Burkhead, J. R. Cordeiro, J. T. Garner, P.D. Hartfield, D. A. W. Lepitzki, G. L. Mackie, E. Pip, T. A. Tarpley, J. S. Tiemann, N. V. Whelan, and E. E. Strong. 2013. American Fisheries Society List of Freshwater Gastropods from Canada and the United States. Available: http://fl.biology.usgs.gov/afs_snail/index.html. (June 2013).

Johnson, S. C. 1992. Spontaneous and hybrid origins of parthenogenesis in *Campeloma decisum* (freshwater prosobranch snail). He- redity 68:253–261.

Johnson, P, D, ,Arthur E. Bogan ,Kenneth M. Brown ,Noel M. Burkhead ,James R. Cordeiro , Jeffrey T. Garner, Paul D. Hartfield ,Dwayne A.W. Lepitzki, Gerry L. Mackie, Eva Pip ,Thomas A. Tarpley, Jeremy S. Tiemann ,Nathan V.Whelan and Ellen E. Strong (2013) Conservation Status of Freshwater Gastropods of Canada and the United States,Fisheries,38:6,247-282,DOI:10.1080/03632415.2013.785396

Karr, J. R. 1999. Defining and measuring river health. Freshwater Biology. 41: 221-234.

Katoh, M., and D. W. Foltz. 1994. Genetic subdivision and morpho- logical variation in a freshwater snail species complex formerly referred to as *Viviparus georgianus* (Lea 1834). Biological Journal of the Linnean Society 53:73–95.

Kesler, D. H. 1981. Periphyton grazing by *Amnicola limosa*: an enclosure–exclosure experiment. Journal of Freshwater Ecology 1:51–59.

Kurata, K., and E. Kikuchi. 1999. Comparisons of life-history traits and sexual dimorphism between *Assiminea japonica* and *Angust- assiminea castanea* (Gastropoda: Assimineidae). Journal of Molluscan Studies 66:177–196.

Kuussaari, M.; Bommarco, R.; Heikkinen, R. K.; Helm, A.; Krauss, J.; Lindborg, R.; Öckinger, E.; Pärtel, M.; Pino, J.; Rodà, F.; Stefanescu, C.; Teder, T.; Zobel, M.; Steffan-Dewenter, I. (2009). "Extinction debt: a challenge for biodiversity conservation". Trends in Ecology & Evolution 24 (10): 564

Lee, J. S., and J. D. Ackerman. 2001. COSEWIC status report on the Rocky Mountain capshell *Acroloxus coloradensis* in Canada. *In* COSEWIC assessment and status report on the Rocky Mountain capshell *Acroloxus coloradensis* in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa, Ontario.

Lepitzki, D. A. W. 2013. Recovery of the Banff Springs Physa. United States Geological Service. American Fisheries Society. Available: http://fl.biology.usgs.gov/afs_snail/banff_springs_physa.html. (June 2013).

Lefever, G. and W C. Curtis. 1912. Studies on the reproduction and artificial propagation of fresh-water mussels. Bulletin of the Bureau of Fisheries. Volume 30. Washington, D.C.

Lydeard, C. E., R. H. Cowie, W. F. Ponder, A. E. Bogan, P. Bouchet, S. A. Clark, K. S. Cummings, T. J. Frest, O. Gargominy, D. G. Her- bert, R. Hershler, K. E. Perez, B. Roth, M. Seddon, E. E. Strong, and F. G. Thompson. 2004. The global decline of nonmarine mollusks. BioScience 54:321–330.

Lysne, S. J., and P. Koetsier. 2006. The life history of the Utah (Desert) *Valvata*, *Valvata utahensis*, in the Snake River, Idaho. Journal of Freshwater Ecology 21:285–291.

Lysne, S. J., K. E. Perez, K. M. Brown, R. L. Minton, and J. D. Sides. 2008. A review of freshwater gastropod conservation: challenges and opportunities. Journal of the North American Benthological Society 27:463–470.

Lysne, S. and P. Koetsier. 2006. Experimental studies on habitat preference and tolerances of three species of snails from the Snake River of southern Idaho, U.S.A. American Malacological Bulletin, 21(1/2): 77-85

Lysne, S. and P. Koetsier. 2006. Growth rate and thermal tolerance of two endangered Snake River snails. Western North American Naturalist, 66(2): 230-238.

Master, L. L., B. A. Stein, L. S. Kutner, and G. A. Hammererson. 2000. Vanishing assets: Conservation status of U.S. species. Pages 93– 118 *in* B. A. Stein, L. S. Kutner, and J. S. Adams, editors. Precious heritage, the status of biodiversity in the United States. Oxford University Press, New York.

MacArthur, R. H. and E. O. Wilson. 1967. The theory of island biogeography. Princeton University Press. 224 pp.

McMahon, R. F. 2002. Evolutionary and physiological adaptations of aquatic invasive animals: r selection versus resistance. Can. J. Fish. Aquat. Sci. 59: 1235–1244.

Miller, M.P, D.E. Weigel, K.E. Mock, and B. Roth. 2006. Evidence for an outcrossing reproductive strategy in the hermaphroditic heterobranch gastropod *Valvata utahensis* (Valvatidae), with notes on the genetic differentiation of *V. utahensis* and *V. humeralis*. Journal of Molluscan Studies, 72: 397-403.

Miller, M.P., D.E. Weigel, and K.E. Mock. 2006. Patterns of genetic structure in the endangered aquatic gastropod *Valvata utahensis* (Mollusca: Valvatidae) at small and large spatial scales. Freshwater Biology, 51: 2362-2375.

Master, L. L., D. Faber-Langendoen, R. Bittman, G. A. Hammerson, B. Heidel, J. Nichols, L. Ramsay, and A. Tomaino. 2009. Nature- Serve conservation status assessments: factors for assessing extinction risk. NatureServe, Arlington, Virginia.

Mettee, M. F., P. E. O'Neil, and J. M. Pierson. 1996. Fishes of Ala- bama and the Mobile River basin. Oxmoor House, Birmingham, Alabama.

Miller, R. R., J. D. Williams, and J. E. Williams. 1989. Extinctions of North American fishes during the past century. Fisheries 14:22– 30, 32–38.

Minton, R. L., and C. Lydeard. 2003. Phylogeny, taxonomy, genetics and global heritage ranks of an imperiled, freshwater genus *Litha- sia* (Pleuroceridae). Molecular Ecology 12:75–87.

Minton, R. L., A. P. Norwood, and D. M. Hayes. 2008. Quantifying phenotypic gradients in freshwater snails: a case study in *Lithasia* (Gastropoda: Pleuroceridae). *Hydrobiologia* 605:173–182.

Mladenka, G. C., and G. W. Minshall. 2001. Variation in the life history and abundance of three populations of Bruneau hot springsnails (*Pyrgulopsis bruneauensis*). Western North American Naturalist 61:204–212.

Mock, K. E., J. C. Brim-Box, M. P. Miller, M. E. Downing, and W. R. Hoeh. 2004. Genetic diversity and divergence among freshwater mussel(Anodonta) populations in the Bonneville Basin of Utah. Molecular Ecology. 13: 1085-1098.

Morales, J. B. and A. K. Ward. 2000. Snail grazers affect the fate of labile dissolved organic C in streams. J. N. Benthol. Soc. 19(4): 659-669.

Musick, J. A., M. M. Harbin, S. A. Berkeley, G. H. Burgess, A. M. Eklund, L. Findley, R. G. Gilmore, J. T. Golden, D. S. Ha, G. R. Huntsman, J. C. McGovern, S. J. Parker, S. G. Poss, E. Sala, T. W. Schmidt, G. R. Sedberry, H. Weeks, and S. G. Wright. 2000. Marine, estuarine, and diadromous fish stocks at risk of extinc- tion in North America (exclusive of Pacific salmonids). Fisheries 25:6–30.

NatureServe. 2013. A network connecting science with conservation. Available: http://www.natureserve.org/. (May 2012).

NatureServe. 2014. NatureServe Explorer: An online encyclopedia of life [web application]. Version 7.1. NatureServe, Arlington, Virginia. Available http://explorer.natureserve.org

Neely, D. A., A. E. Hunter, and R. L. Mayden. 2003. Threatened fishes of the world: *Etheostoma sellare* (Radcliffe and Welsh) 1913 (Percidae). Environmental Biology of Fishes 67:340.

Neves, R. J., A. E. Bogan, J. D. Williams, S. A. Ahlstedt, and P. D. Hartfield. 1997. Status of aquatic mollusks in the southeastern United States: a downward spiral of diversity. Pages 43–85 *in* G. W. Benz and D. E. Collins, editors. Aquatic fauna in peril: the southeastern perspective. Southeast Aquatic Research Institute, Special Publication 1, Chattanooga, Tennessee.

Neves, R. J., and M. C. Odum. 1989. Muskrat predation on endangered freshwater mussels in Virginia. Journal of Wildlife Management 53:934–941.

Newell, R. I. E. 2004. Ecosystem influences of natural and cultivated populations of suspension-feeding bivalve molluscs: A review. Journal of Shellfish Research. Vol. 23. No. 1. pp 51-61.

Noss, R. F. 2000. High-risk ecosystems as foci for considering biodiversity and ecological integrity in ecological risk assessments. Environmental Science and Policy 3:321–332.

Ó Foighil, D., J. Li, T. Lee, P. Johnson, R. Evans, and J. Burch. 2011. Conservation genetics of a critically endangered limpet genus and the rediscovery of an extinct species. PLoS ONE 6(5):e20496.

Oliver, G. V. and W. R. Bosworth, III. 1999. State of Utah Department of Natural Resources, "Rare, Imperiled, and Recently Extinct or Extirpated Mollusks of Utah: A Literature Review" (1999). All U.S. Government Documents (Utah Regional Depository). Paper 531. http://digitalcommons.usu.edu/govdocs/531.

O'Neil, P. E., and T. E. Shepard. 2000. Water-quality assessment of the lower Cahaba River watershed, Alabama. Geological Survey of Alabama, Bulletin 167. Tuscaloosa, Alabama.

Pereira, H. M., P. W. Leadley, V. Proença, R. Alkemade, J. P. W. Scharlemann, J. F. Fernandez-Manjarrés, M. B. Araújo, P. Balvanera, R. American Benthological Society 29:344–358.

Ricciardi J. NS F. G. Rasmussen. 1995. Predicting the intensity and impact of Dreisserza infestation on native unionid bivalves from Drrissrna field densitv. Canadian Journal of Fisheries and Aquatic Sciences 52: 1449-1461.

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.

Strong, E. E. 2005. A morphological reanalysis of *Pleurocera acuta* Rafinesque, 1831, and *Elimia livescens* (Menke, 1830) (Gastrop- oda: Cerithioidea: Pleuroceridae). The Nautilus 119:119–132. Strong, E. E., and T. E. Frest. 2007. On the anatomy and systematics of *Juga* from western North America (Gastropoda: Cerithioidea: Pleuroceridae). The Nautilus 121:43–65.

Strayer, D. L. 1999. Effects of alien species on freshwater mollusks in North America. J. N. Am. Benthol. Soc. 18(1): 74-98.

Strong, E. E., O. Gargominy, W. F. Ponder, and P. Bouchet. 2008. Global diversity of gastropods (Gastropoda; Mollusca) in freshwater. Hydrobiologia 595:149–166.

Strong, E. E., and F. Köhler. 2009. Morphological and molecular analysis of *'Melania' jacqueti* Dautzenberg and Fischer, 1906: from anonymous orphan to critical basal offshoot of the Semisulcospiridae (Gastropoda: Cerithioidea). Zoologica Scripta 38:483–502.

Taylor, C. A., G. A. Schuster, J. E. Cooper, R. J. DiStefano, A. G. Eversole, P. Hamr, H. H. Hobbs, III, H. W. Robinson, C. E. Skelton, and R. F. Thomas. 2007. A reassessment of the conservation status crayfishes of the United States and Canada after 10+ years of in- creased awareness. Fisheries 32:372–389.

Taylor, C.A., M. L. Warren, Jr., J. F. Patrick, Jr., H. H. Hobbs, II, R. F. Jezerinac, W. L. Pflieger, and H. W. Robison. 1996. Conserva- tion status of crayfishes of the United States and Canada. Fisheries 21(4):25–38.

Taylor, D. W. 1987. Freshwater mollusks from New Mexico and vicinity. New Mexico Bureau of Mines and Mineral Resources Bulletin 116:1–50.

Taylor, D. W. 2003. Introduction to Physidae (Gastropoda: Hygrophila); biogeography, classification, morphology. Revista de Biología Tropical 51(Suppl.)1:1–287.

Turgeon, D. D., J. F. Quinn, Jr., A. E. Bogan, E. V. Coan, F. G. Hoch- berg, W. G. Lyons, P. M. Mikkelsen, R. J. Neves, C. F. E. Roper, G. Rosenburg, B. Roth, A. Scheltema, F. G. Thompson, M. Vecchione, and J. D. Williams. 1998. Common and scientific names of aquatic invertebrates from the Unites States and Canada: mollusks, 2nd edition. American Fisheries Society, Special Publication 26. American Fisheries Society, Bethesda, Maryland.

U.S. Fish and Wildlife Service (USFWS). 1992. Endangered and Threatened Wildlife and Plants; Determination of Endangered Status or Threatened Status for Five Aquatic Snails in South Central Idaho. Final Rule. Federal Register. 57(240):59244-56

U.S. Fish and Wildlife Service (USFWS). 2010. Endangered and threatened wildlife and plants; removal of the Utah (desert) *Valvata* snail from the federal list of endangered and threatened wildlife. Federal Register 75(164):52272-5228

USDA FOREST SERVICE AND USDI BUREAU OF LAND MANAGEMENT. 2001. Record of decision for amendments to the Survey and Manage, protection buffer, and other mitigation measures standards and guidelines in Forest Service and Bureau of Land Management planning documents within the range of the Northern Spotted Owl. USDA Forest Service and USDI Bureau of Land Management, Portland, OR; [cited 22 August 2012]. 160 pp. Available from:

http://www.blm.gov/or/plans/surveyandmanage/files/ rd-rod_s_and_g-2001-01.pdf

USEPA 2013. Aquatic Life Ambient Water Quality Criteria For Ammonia – Freshwater 2013. EPA-822-R-13-001

Valiente-Banuet, A. et al. 2015. Beyond species loss: the extinction of ecological interactions in a changing world.

USFWS (U.S. Fish and Wildlife Service). 2000. Recovery plan for Mobile River basin aquatic ecosystem. U.S. Fish and Wildlife Service, Southeast Region, Atlanta, Georgia.

———. 2010. Proposed reclassification of the tulotoma snail from endangered to threatened. Federal Register 75(119):35424–35431. June 22, 2010.

Vaughn, C. C. and C. C. Hakenkamp. 2001. The functional role of burrowing bivalves in freshwater ecosystems. Freshwater Biology. 46, 1431-1446

van der Schalie, H. 1959. Transect distribution of eggs of *Pomatiopsis lapidaria* Say, an amphibious prosobranch snail. Transactions of the American Microscopical Society 78:409–420.

van der Schalie, H., and D. S. Dundee. 1956. The morphology of *Po- matiopsis cincinnatiensis* (Lea), an amphibious prosobranch snail. Museum of Zoology, University of Michigan, Ann Arbor, Michi- gan, Occasional Paper 579.

Vaughn, C. E. 2010. Biodiversity losses and ecosystem function in freshwaters: emerging conclusions and research directions. Bio- Science 60:25–35.

Vitousek, P. M., H. A. Mooney, J. Lubchenco, and J. M. Melillo.1997. Human domination of Earth's ecosystems. Science 277:494–499.

Walther, A. C., J. B. Burch, and D. Ó. Foighil. 2010. Molecular phylogenetic revision of the freshwater limpet genus *Ferrissia* (Planor- bidae: Ancylidae) in North America yields two species: *Ferrissia* (Ferrissia) rivularis and Ferrissia (Kincaidilla) fragilis. Malaco- logia 53:25–45.

Walther, A. C., T. Lee, J. B. Burch, and D. Ó. Foighil. 2006. E pluribus unum: a phylogenetic and phylogeographic reassessment of *Laevapex* (Pulmonata: Ancylidae), a North American genus of freshwater limpets. Molecular Phylogenetics and Evolution 40:501–516.

Wethington, A. R., and C. Lydeard. 2007. A molecular phylogeny of Physidae (Gastropoda: Basommatophora) based on mitochondrial DNA sequences. Journal of Molluscan Studies 73:241–257.

Wethington, A. R., J. Wise, and R. T. Dillon. 2009. Genetic and mor- phological characterization of the Physidae of South Carolina (Gastropoda: Pulmonata: Basommatophora), with description of a new species. The Nautilus 123(4):282–292.

Whelan, N. V., P. D. Johnson, and P. M. Harris. 2012a. Presence or absence of carinae in closely related populations of *Leptoxis ampla* (Anthony, 1855) (Gastropoda: Cerithioidea: Pleuroceridae) is not the result of ecophenotypic plasticity. Journal of Molluscan Stud- ies 78:231–233.

Whelan, N. V., P. D. Johnson, and P. M. Harris. 2012b. Rediscovery of the *Leptoxis compacta* (Anthony, 1854) (Gastropoda: Cerithioidea: Pleuroceridae). PLoS ONE 7(8):e42499.

Wilke, T., G. M. Davis, A. Falniowski, F. Giusti, M. Bodon, and M. Szarowska. 2001. Molecular systematics of Hydrobiidae (Mollusca: Gastropoda: Rissooidea): testing monophyly and phylo- genetic relationships. Proceedings of the Academy of Natural Sciences, Philadelphia 151:1–21.

Williams, J. D., M. L. Warren, Jr., K. S. Cummings, J. L. Harris, and R. J. Neves. 1993. Conservation status of freshwater mussels of the United States and Canada. Fisheries 18:6–22.

Williams, J. E., J. E. Johnson, D. A. Hendrickson, S. Contreras-Bal-deras, J. D. Williams, M. Navarro-Mendoza, D. E. McAllister, and J. E. Deacon. 1989. Fishes of North America endangered, threatened, or of special concern: 1989. Fisheries 14:2–20.

APPENDICES

Appendix 1. Photos of Mollusk Survey Sites.

Appendix 1. Jordan River "Narrows" section. Furthest upstream site surveyed on Jordan River.

Appendix 2. Side channels of Jordan River were also surveyed.

Appendix 3. 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.

Appendix 4. Typical channelization of Jordan River. Channelization and associated dredging is not conducive to native unionid mussel population viability.

Appendix 5. Mill Creek upstream of CVWTF and Jordan River.

Appendix 6. Many downstream sections of the Jordan River have substrates of mostly silt, sand, clay, and organic matter.

Appendix 7. Muskrat midden of invasive clam, *Corbicula fluminea*. No native unionids were found in this midden.

Appendix 8. Jordan River bank stabilization rip rap.

Appendix 9. Mollusk surveyor examining Jordan River substrate.

Appendix 10. Typical upstream section of Jordan River. Mostly gravel and sand substrate. Very good *Corbicula* habitat.

Appendix 11. Mollusk surveyor positioning aquascope for visualizing substrate and mollusks.

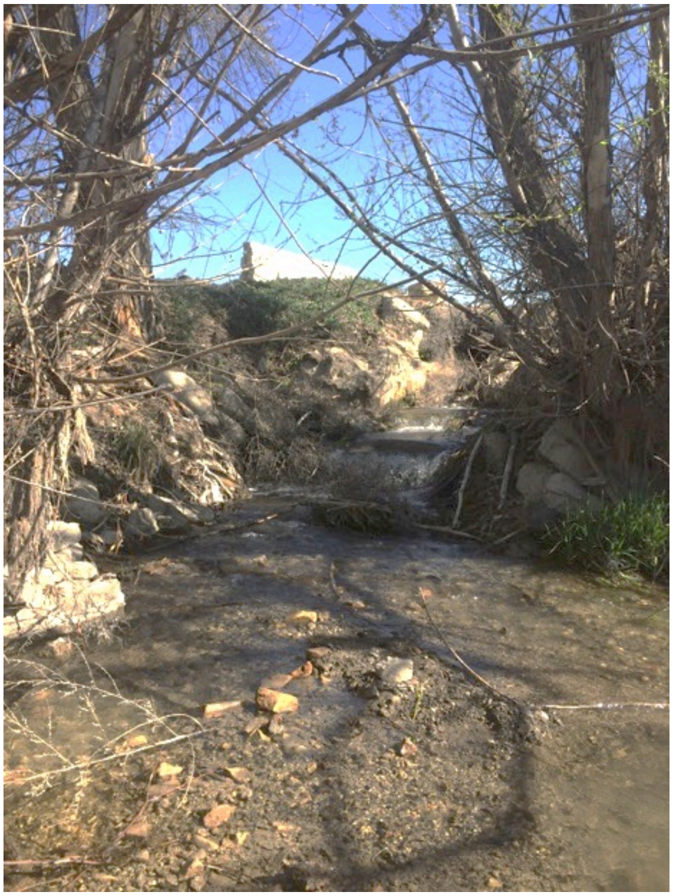
Appendix 12. Common Jordan River habitat. Side bars were visually examined for mollusk shells.

Appendix 13. Large Jordan River sidebar that was extensively examined for mollusk shells (mostly *Corbicula* shells were found).

Appendix 14. Mollusk surveyor preparing to use aquascope along channelized section of Jordan River.

Appendix 15. 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.

Appendix 16. Mill Pond, Utah County.



Appendix 17. Outlet of Mill Pond, Utah County.

Appendix 18. Spring Creek, upstream of Mill Pond, Utah County.

Appendix 19. Spring Creek downstream of Mill Pond where *Anodonta* shells were collected amidst the hundreds of *Corbicula*.

Appendix 20. Complete *Anodonta* shell found in Spring Creek, Utah County. No other complete *Anodonta* shells were collected and this may be the last of the population. Further surveys at this site are strongly recommended.