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Source: Western North American Naturalist, 79(1) : 72-84

Published By: Monte L. Bean Life Science Museum, Brigham Young University

URL: https://doi.org/10.3398/064.079.0108

Western North American Naturalist 79(1), © 2019, pp. 72–84

Apparent extinction of native mussels in Lower Mill Creek and Mid-Jordan River, Utah

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Abstract.—Native mussels likely occurred in Mill Creek and the Jordan River, Utah, in the past. However, human-induced impacts have virtually eliminated the possibility of their continued existence in these waters. We conducted an intensive native mussel survey upstream and downstream of a water reclamation facility discharge into Mill Creek and the Jordan River to determine its effects on mussel populations. The survey was conducted from September to October 2017 and resulted in approximately 7.6 m^3 of >4 mm-sized substrate particles being thoroughly examined at near 100% efficiency. We then used statistical models to estimate population densities as a function of probability of detection and search efficiencies based on this and other surveys. Regrettably, no live or recently dead native mussels were found. Given that our survey methods provided near perfect search efficiency, native mussel densities were estimated to be $<<0.03$ per m^2, which is much lower than what we consider to be a viable population density. Combined with multiple lines of evidence from other surveys, this low density strongly points toward the conclusion that native mussels are extinct in the survey area. Reasons for the demise of native mussels in Mill Creek and the Jordan River are numerous, and these factors need to be aggressively addressed if native mussels are to survive in the drainage.

Resumen.—Es probable que en el pasado habitaran mejillones nativos en el río Mill Creek y Jordan en Utah. Sin embargo, los impactos ocasionados por el hombre han eliminado prácticamente la posibilidad de su existencia en estas aguas. Llevamos a cabo un estudio intensivo de mejillones nativos, río abajo y río arriba en una instalación de descarga de agua reciclada en Mill Creek y en el río Jordan para determinar sus efectos en las poblaciones de mejillones. El estudio se llevó a cabo en septiembre y octubre del año 2017, en los cuales, se examinaron minuciosamente aproximadamente, 7.6 m^3 de partículas de sustrato de tamaño >4 mm, con una eficacia cercana al 100%. Posteriormente, utilizamos modelos estadísticos para estimar las densidades poblacionales en función de su probabilidad de detección y de la eficiencia de búsqueda, basada en este y en otros muestreos. Desafortunadamente, no encontramos mejillones nativos vivos o recientemente muertos. Debido a que, nuestros métodos de muestreo proporcionaron una eficacia de búsqueda casi perfecta, se estimó que la densidad de mejillones nativos es $<<0.03$ m^{-2}, mucho menor a lo que consideramos como una densidad poblacional viable, y cuando se combina con múltiples evidencias de otros muestreos, indica que los mejillones nativos están extintos en el área de estudio. Las razones de la desaparición de los mejillones nativos en los ríos Mill Creek y el Jordan son numerosas, y tales factores necesitan abordarse intensivamente para que los mejillones nativos puedan sobrevivir en el drenaje.

North America supports the richest diversity of freshwater mollusks (clams, mussels, and snails) on the planet, with at least 700 species of snails and 300 species of freshwater mussels (Johnson et al. 2013, FMCS 2015). Freshwater mollusks serve vital functions in freshwater ecosystems, are excellent indicators of water quality, and are increasingly recognized as important ecosystem providers (Huryn et al. 1995, Covich et al. 1999, Ostroumov 2005, Fulford et al. 2007, Brown and Lydeard 2010, Johnson et al. 2013). Unfortunately, freshwater mollusks are one of the most disproportionally imperiled groups on earth. Approximately 72% of North American freshwater mussel taxa are considered endangered, threatened, or species of concern (NatureServe 2014). This alarming decline is almost entirely due to human activities (Williams et al. 1993).

The greatest diversity of North America's freshwater mussels occurs in the southeastern USA, whereas in the western half of North America the mussel fauna is relatively depauperate. However, the area consisting of the

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Fig. 1. The Jordan River flows north from its origin at the outlet of Utah Lake to its confluence with the Great Salt Lake. Mill Creek flows west from its origin in the Wasatch Mountains to its confluence with Jordan River. Both water bodies flow through the highly urbanized Salt Lake City metropolitan area. Numerous canals and several other tributaries are also shown. The survey area was near the confluence of Mill Creek with Jordan River. The Central Valley Water Reclamation Facility (CVWRF) is located approximately 0.8 km upstream of the confluence of Mill Creek with Jordan River.

Great Basin, Snake River Basin, and Bonneville Basin, including the Great Salt Lake and Jordan River–Utah Lake drainages, is a freshwater molluscan hotspot (Hershler and Sada 2002, Hovingh 2004). There are at least 70 mollusk taxa reported from Utah (Oliver and Bosworth 1999), many of which are freshwater endemics to the Bonneville Basin, and the evolution and distribution of this unique diversity are strongly linked with the geological and geomorphic history of pluvial Lake Bonneville (Hershler and Sada 2002, Polhemus and Polhemus 2002, Mock et al. 2004) (Fig. 1).

Two species of native mussels, the Floater, *Anodonta* sp. (Family: Unionidae) and the Western Pearlshell, *Margaritifera falcata* (Family: Margaritiferidae), probably occurred in the Jordan River, Utah, and its tributaries, including Mill Creek (Richards 2017, UDWQ 2017b). Taxonomy of *Anodonta* sp. is presently being reevaluated (Mock et al. 2004). Unfortunately, severely degraded conditions along with secondary host-dependent, dispersal-limited population dynamics and absence of past monitoring and legal protection have jeopardized the mussels' continued existence in these waters and waters throughout the west (USEPA 2013a, Richards 2017). There are no historical records of *M. falcata* occurring in Mill Creek or the Jordan River, and there is only one historical record, from 1942, of *Anodonta* sp. potentially occurring at a single location in the Jordan River (UDWQ 2017b), although *M. falcata* (formerly *Margaritana margaritifera*) was collected from Big Cottonwood Creek, a tributary of the Jordan River, a few miles upstream of Mill Creek in the 1880s (Natural History Museum of Utah, Salt Lake City specimens examined).

Prior to this study, Richards (2017) conducted the most extensive native mussel surveys in the Jordan River drainage to date, but did not find any live or recently dead native mussels in Mill Creek or the Jordan River. However, Richards (2017) did find several highly weathered *Anodonta* sp. shell fragments, indicating that this species could have occurred in these or nearby waters in the past. Even though Richards (2017) concluded that native mussels were likely absent in Mill Creek and the Jordan River, absolute determination of absence is not possible without an unfeasibly complete and thorough examination of the entire creek and river beds (USEPA 2013a, 2013b, Richards 2017). Alternatively, probability of detection and survey efficiency statistical models in conjunction with knowledge of native mussel ecology and population dynamics can be employed to help validate a presence or absence conclusion (Smith 2006, Richards 2017, Richards and Miller 2017, UDWQ 2017a).

The United States Environmental Protection Agency (USEPA) recently recommended methods for surveying mussels (USEPA 2013b), and the Utah Division of Water Quality (UDWQ 2017a) developed mussel probability of detection (POD) standards for Utah waters. USEPA and UDWQ recommendations came in response to new USEPA ammonia criteria based on mussel sensitivities from published toxicity tests (USEPA 2013a). The POD criteria developed by UDWQ were based on survey search efficiencies and seemingly based on biological meaningful densities in order to determine presence or absence of native mollusks on a site-specific basis using Smith et al. (2001) and Smith (2006) statistical models. Search efficiency (SE) is also termed detectability, which is the probability of detecting an individual mussel in the survey area (Smith 2006).

We adapted USEPA-recommended methods to conduct an intensive and intrusive survey of native mussels in sections of Mill Creek and the mid-Jordan River upstream and downstream of a water treatment facility to determine whether native mussels occurred in this area and if so, whether their densities were affected by the facility's "zone of influence" (Richards and Miller 2017). We then calculated several PODs, SEs, and density estimates following Smith et al. (2001) and Smith (2006), and we compared our results with POD criteria developed by UDWQ. In addition, we produced a multiple-lines-of-evidence analysis based on results from our mussel surveys conducted over the past several years and from available historic survey data collected by other qualified researchers.

STUDY AREA

The Jordan River drainage is in north central Utah and drains an area of over 9842 km^2 (Fig. 1). Elevations range from 3637 m in the Wasatch Range to 1280 m where the Jordan River enters the Great Salt Lake. Average precipitation ranges from 31 $cm \cdot year^{-1}$ in the lower valleys to over 127 $cm \cdot year^{-1}$ in the higher elevations. Much of the precipitation occurs as snow, which contributes to the rivers as snowmelt during spring and summer. The Jordan River flows north from Utah Lake for about 82 km through the most populous, industrialized, and urbanized area of Utah, including Salt Lake City, before entering the Great Salt Lake. Major tributaries to the Jordan River include Big Cottonwood, Little Cottonwood, Red Butte, Mill, Parleys, and City Creeks. However, most of these tributaries were diverted and heavily modified by Mormon settlers in the Salt Lake Valley, starting in the mid-1800s (Bancroft 1889, Alexander 2003), and most remain disconnected from the Jordan River.

Mill Creek originates in the Wasatch Mountains and then flows through the City of South Salt Lake where it joins the Jordan River (Fig. 1). After leaving the Wasatch Mountains and United States Forest Service lands, where it is relatively unimpaired, most Mill Creek waters are captured and diverted for municipal use by the citizens of Salt Lake City. Remaining waters in Mill Creek are then supplemented and often dominated by waters transported directly from highly eutrophic Utah Lake via the Jordan and Salt Lake Canals. After water quality has been compromised by Utah Lake water, Lower Mill Creek flows through a heavily urbanized, residential, and industrial landscape before joining the Jordan River. By all standards, the sections of Mill Creek and the Jordan River that we surveyed are in poor condition, are poorly managed, and are of eroded integrity (Richards and Miller 2017).

The Central Valley Water Reclamation Facility (CVWRF) at 800 West Central Valley Road (3190 South) in Salt Lake City, Utah, is the largest treatment facility in the greater Salt Lake City area and was built to treat 75 million gallons of wastewater per day, serving over half a million people in Salt Lake County. CVWRF discharges treated water directly into Mill Creek approximately 400 m upstream of its confluence with the Jordan River. Discharge from the facility is required to meet state and federal water quality standards, including new ammonia criteria that were primarily based on native mussel presence or absence (USEPA 2013a, 2013b, UDWQ 2017a). An ammonia "zone of influence" was designated by UDWQ to extend from CVWRF discharge downstream in Mill Creek and the Jordan River to about the bridge crossing at 900 South, approximately 3.5 km (Richards and Miller 2017).

METHODS

We conducted intrusive excavation surveys as suggested by UDWQ (2017a) and USEPA (2013b) using 2 methods: (1) shovel-netting for wadeable sections of the area, and (2) suction dredging for deeper, nonwadeable sections of the area. The survey was conducted between 16 September 2017 and 24 October 2017 (Appendixes 1 and 2 include dates, Universal Transverse Mercator [UTM] coordinates, survey method, area [m^2], substrate types, and depths [cm] for the Jordan River and Mill Creek, respectively).

Wadeable Sections

We used a flat-bottom shovel with a 10-cm depth line marked across the blade to survey wadeable sections of the survey area. One surveyor demarcated a 0.5-m^2 area of substrate using the known width of the shovel blade and then sank the shovel down to a penetrable depth (up to 10 cm) and scooped all sediment in the 0.5-m^2 area into a heavy-framed 1-mm-mesh benthic net held by a second surveyor standing directly downstream of the first surveyor. Net contents were then taken on shore and sieved through 4-mm-mesh sieves into large plastic trays and closely examined for mollusks (bivalves and gastropods). We used a grid layout and randomly selected grids for sampling. We collected 132 shovel/net substrate samples (0.5 m^2 each) at 79 locations for a total of 66 m^2 (approximately 6.6 m^3) (Appendixes 1, 2).

Nonwadeable Sections

We used a shoreline-based suction dredge sampler fitted with a handheld 7.62-cm-diameter suction hose to sample nonwadeable sections of the survey area on several occasions. We attached a 22.23-cm-wide by 20.32-cm-tall (3.79-L) aluminum large-mouth funnel to the end of the hose (end diameter of the funnel = 387.77 cm^2). One surveyor pushed the funnel into the soft-bottomed substrate to a depth up to 10 cm while wading and while the suction pump was running. The funnel was pushed into substrate 13 times in adjacent locations to cover a 0.5-m^2 area while suction contents were being pumped into a 189.27-L barrel on shore. The pump was powerful enough to collect sediments up to large gravel size (and presumably large mussels). To ensure that enough sediment was collected, a line was drawn along the outside of the 189.27-L barrel to mark a volume of 0.05 m^3 (0.5 m^2 × 0.1 m substrate depth), and dredging continued until sediments filled the barrel to that line. Sediments were gravel size or smaller at all but one site; therefore, by measuring content volume in the barrel we estimated that we sampled at least a 0.5-m^2 area. The substrate at one of the deeper sites was mostly medium to large cobbles; consequently, we dredged approximately a 4.0-m^2 area to ensure adequate coverage. A total of approximately 9.7 m^2 of substrate was sampled from 7 locations in deeper-water habitats using the suction dredge method (Appendixes 1, 2). All suction dredge locations within the deeper-water sites were randomly chosen, similar to methods used in the wadeable sections.

Statistical Models

We used the Smith (2006) quantitative mussel survey formula (eq. 4, p. 703)

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

where POD = probability of detecting at least one individual mussel; β = search efficiency (SE), α = search area = 75.7 m^2, and μ = density (m^{-2}), to develop a probability of detection (POD) model as a function of density at a search efficiency between 0.75 and 1.00. We then compared our model results with UDWQ (2017a) criteria that recommend surveying enough area with 100% search efficiency and 90% POD at their predetermined biologically meaningful density of 0.1 m^{-2}. We also modeled these relationships from other data sources as multiple lines of evidence for presence/absence determination. Other sources included Richards (2017) survey data, the Bureau of Land Management/Utah State University MAPIT database, and the UDWQ (2017a) report.

RESULTS

No live or recently dead native mussels (*Anodonta* sp. or *M. falcata*) were found in the survey area, despite our intensive survey efforts. Therefore, we could not evaluate the effects of CVWRF on native mussel populations within the study area because none were found either upstream or downstream of the facility. Only one tiny, well-weathered *Anodonta* fragment was found in Mill Creek. It is unknown whether this shell fragment represented an individual that once lived in the survey area or one that was deposited via past high-flow events from an upstream source, including Utah Lake, a former *Anodonta* stronghold (UDNR 2007).

Probabilities of Detection (POD), Search Efficiencies (SEs), and Density Estimates

Using the Smith (2006) equation, we determined that estimated mussel densities only had to be ≥ 0.04 m^{-2} at an unrealistically low search efficiency of 0.75 for our survey to obtain a UDWQ-recommended POD of 0.90 (Fig. 2). However, excavation methods (e.g., shovel-nets, suction dredges) are considered the most effective sampling methods for detecting mussels (USEPA 2013b), and when sieved materials are thoroughly examined, survey results closely approach 100% search efficiency. Thus, we assumed that our search efficiency was ≥ 0.99, which equated to a density estimate of 0.03 m^{-2} at POD = 0.90 (Fig. 2). In other words, we should have observed at least one mussel if they occurred in the survey area at densities ≥ 0.03 m^{-2}. At UDWQ's recommended biologically meaningful density of 0.1 m^{-2}, our estimated POD was 1.00, even at the unrealistically low search efficiency of 0.75 (Fig. 2). That is, even if after close examination we missed observing 1 out of 4 mussels in our viewing trays, we still would have found mussels if they occurred at density levels ≥ 0.1 m^{-2}.

Multiple Lines of Evidence from Other Native Mussel Surveys

This survey produced no live or recently dead native mussels, and our POD, SEs, and density estimate models suggested that native mussels were absent from the survey area. However, concluding absence (extinction) of Utah's native mussels from an area where they should occur based on a single survey does not seem wise. The following analyses from other mussel surveys on Mill Creek and Jordan River provided multiple lines of evidence that further helped determine whether native mussels were present or absent in the survey area.

THE RICHARDS (2017) UTAH LAKE–JORDAN RIVER DRAINAGE MUSSEL SURVEY—Richards (2017) conducted extensive visual and limited excavation surveys in Mill Creek, the Jordan River, and other locations within the Utah Lake–Jordan River drainage in 2015 and 2016. Analysis of the Richards (2017) unpublished data for the Jordan River and Lower Mill Creek produced probability of detection (POD) and search efficiency relationships as a function of density that also support an absence conclusion. As an example, mussel densities only needed to be at a biologically unsustainable density of 0.001 visible mussels m^{-2}, even at an extremely low search efficiency of 0.07 (i.e., only 7 out of 100 mussels needed to be observed on the substrate surface) in Mill Creek when data were modeled at POD = 0.90 (Fig. 3). Similarly, mussel densities in the Jordan River only had to be at a density of 0.0005 m^{-2} to have a POD = 0.90, again with an extremely low search efficiency of 0.08 (i.e., 8 out of 100 observed) (Fig. 4). At a UDWQ-suggested biologically meaningful density = 0.1 m^{-2} and POD = 0.90, search efficiencies based on Richards' (2017) data only needed to be 1 visible mussel out of 1000 in Mill Creek and 4 visible mussels out of 10,000 in the Jordan River (Figs. 3, 4). These very low search efficiency requirements are well below what other mussel experts report for the proportion of mussel populations visible on the substrate surface. For example, USEPA (2013) reported that 50% of a mussel community was present at the substrate surface, and Smith (2006) reported that 30% to 50% of 2 species of the family Unionidae (river mussels) were visible on the substrate surface. These results are further evidence that native mussels are absent or may occur at extremely low, unsustainable densities in the survey area.

USU–BLM MAPIT DATABASE.—The MAPIT database (Mapping Application for Freshwater Invertebrate Taxa; http://wmc6.bluezone.usu.edu), developed by the Bureau of Land Management and Utah State University's National

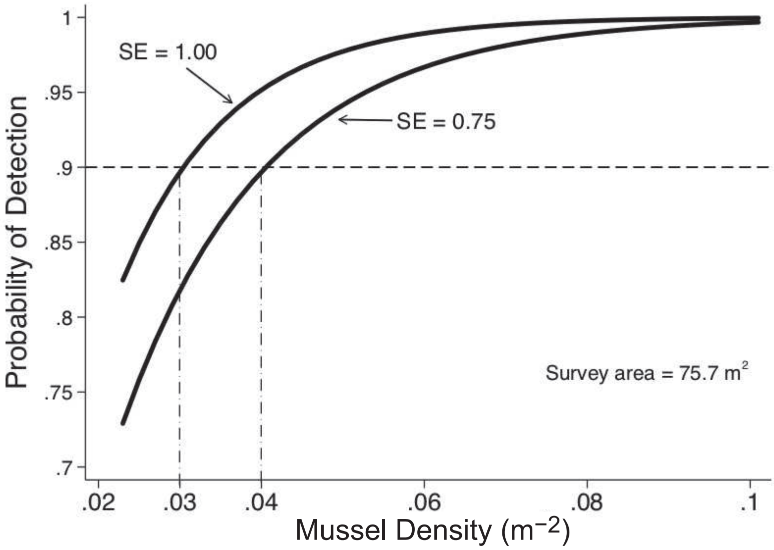
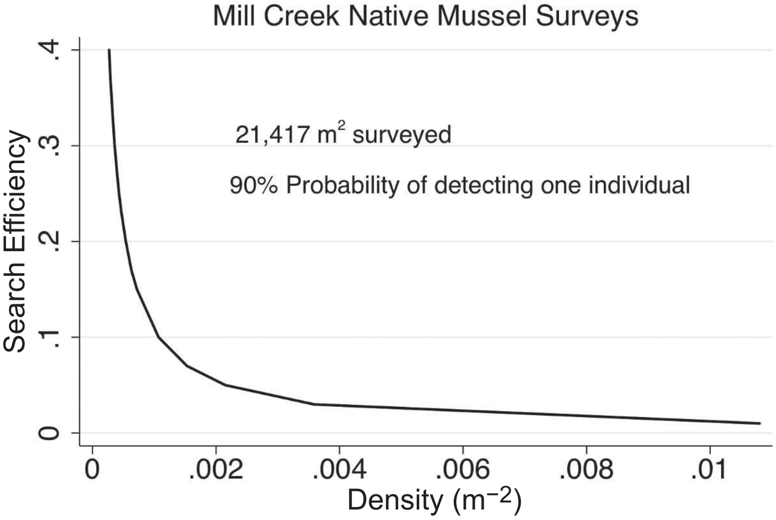
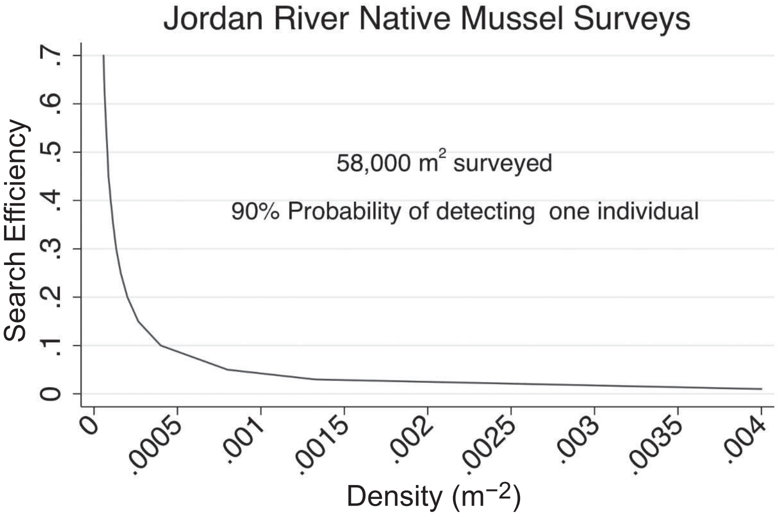


Fig. 2. Relationship between probability of detection (POD) and mussel density (m^{-2}) at search efficiencies (SEs) between 0.75 and 1.00 in our Mill Creek and mid-Jordan River survey area (75.7 m^2). Even at a very poor search efficiency of 0.75, densities only needed to be 0.04 m^{-2} for a UDWQ-recommended POD of 0.90 (dashed and dotted lines). However, we assumed that our search efficiency was ≥0.99, which equates to a density estimate of 0.03 m^{-2} at UDWQ-recommended POD = 0.90 (dashed and dotted lines). At UDWQ-recommended biologically meaningful density = 0.1 m^{-2}, our estimated POD was 1.00, even if we had a very poor search efficiency of 0.75. Model based on Smith (2006).



Search efficiency at 0.1/m^2 and 90% POD = 0.00107

Fig. 3. Ninety percent probabilities of detecting at least one individual native mussel (e.g., *Anodonta* sp.) during the Mill Creek survey at various search efficiencies and corresponding densities, given the Richards (2017) survey of 21,417 m^2. As an example, Richards' (2017) data had a 90% probability of detecting at least one individual if densities were 0.001 m^{-2} with a search efficiency of approximately 0.07 (7%). Estimates are based on mussel distributions from Smith (2006). The formula for the graph is $0.90 = 1 - e^{-\beta\alpha\mu}$, where 0.90 is a 90% probability of detecting at least one individual mussel, β = search efficiency, α = search area = 21,417 m^2, and μ = density (m^{-2}).



Search efficiency at 0.1/m^2 and 90% POD = 0.00038

Fig. 4. Ninety percent probabilities of detecting at least one individual native mussel (e.g., *Anodonta* sp.) in the Jordan River at various search efficiencies and corresponding densities, given that Richards (2017) sampled 58,000 m^2 of river. As an example, there was a 90% probability of detecting at least one individual if densities were 0.0005/m^2 and a search efficiency of approximately 0.078 (approximately 8%). Estimates are based on mussel distributions from Smith (2006). The formula for the graph is $0.90 = 1 - e^{-\beta\alpha\mu}$, where 0.90 is a 90% probability of detecting at least one individual mussel, β = search efficiency, α = search area = 58,000 m^2, and μ = density (m^{-2}).

Aquatic Monitoring Center, has an extensive set of benthic invertebrate survey data compiled from several water quality management agencies, including EMAP–West, NAQWA, USU/BLM–BUGLAB, and UDWQ. We queried this database for the presence of native mussels from samples collected in the Jordan River and Mill Creek and then calculated the total survey areas (m^2) sampled. The MAPIT database produced 80 Mill Creek macroinvertebrate data sets for a total of 65.97 m^2 sampled with no native mussels reported. MAPIT also produced 55 Jordan River macroinvertebrate data sets for a total of 40.38 m^2 sampled, but again no native mussels were reported. Most of the water quality monitoring programs, including USU/BLM–BUGLAB and UDWQ, employ standardized benthic invertebrate sampling methods. These methods typically involve the use of Hess or Surber samplers that do not target native mussel collection. However, their protocols direct surveyors to specifically include mussels "when encountered," and other bivalves such as *Corbicula* sp. and Sphaeriidae were reported in their MAPIT data sets. Therefore, we consider these data sets to be valid supportive information for determining presence/absence. Subsequently, we developed useful and reliable POD, SE, and density models from the 2 MAPIT data sets (Figs. 5, 6). As an example from the models (Figs. 5, 6), mussel densities needed to be ≥ 0.11 m^{-2} for mussels in the Jordan River and ≥ 0.07 m^{-2} for mussels in Mill Creek, at a UDWQ-recommended POD = 0.90, to be detected at a very low SE of 0.50. We could not determine search efficiencies for methods used in the MAPIT data but assume that they are at least 0.50. These MAPIT-based models also support our survey findings that live or recently dead native mussels in Mill Creek and the Jordan River are likely absent.

UDWQ HISTORIC MUSSEL SPECIFIC SURVEYS.—UDWQ (2017b) recently completed a report based on a literature review of historical mussel presence/absence locations in Utah. They found no records of *M. falcata* in Mill Creek or the Jordan River and no *Anodonta* records from lower Mill Creek or the mid-Jordan River in our survey area. However, UDWQ (2017b) did report one *Anodonta* data point from the Jordan River dated 1942. It appears that this record was collected from an old Jordan River channel that is no

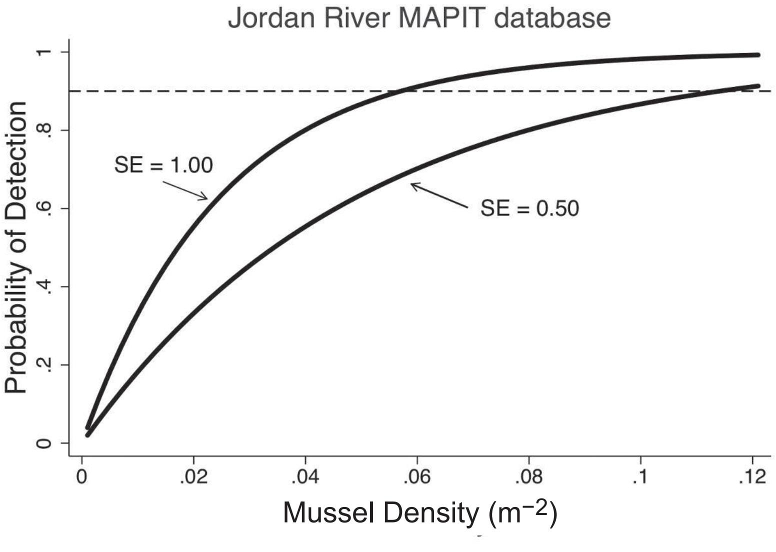


Fig. 5. Bureau of Land Management/Utah State University MAPIT data set for Jordan River. $N = 55$ sample events, 40.38 m^2 sampled.

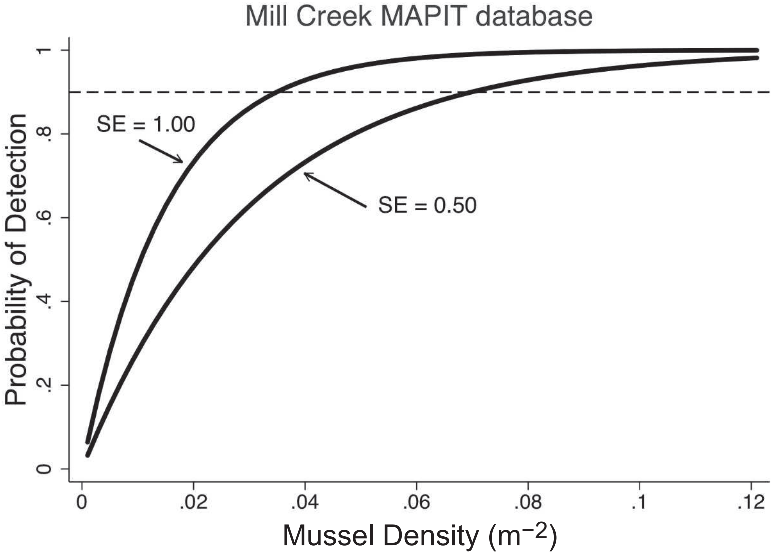


Fig. 6. Bureau of Land Management/Utah State University MAPIT data set for Mill Creek. $N = 80$ sample events, 65.97 m^2 sampled.

longer occupied by the present Jordan River channel, or it is possible that the latitude/longitude coordinates were not reported correctly. The UDWQ (2017b) historical data review is consistent with our survey findings that native mussels are absent from the survey area and likely the entire lower Mill Creek and Jordan River, although we caution that very few mussel-specific surveys other than those presented here and by Richards (2017) have been conducted in Utah waters.

DISCUSSION

The combined analyses presented here provide a strong multiple-lines-of-evidence conclusion that native mussels in Mill Creek and the Jordan River are likely absent. This apparent extinction of native mussels in our survey area and their continued demise throughout the Utah Lake–Jordan River drainage as reported by Richards (2017) are of great ecological and societal concern. Reasons for their rapid decline in Utah and throughout the United States are numerous and cumulative, and are discussed at length by Richards (2017) and others (Strayer 1999, 2013, Johnson et al. 2013). It does not appear that the Central Valley Water Reclamation Facility discharge was responsible for the apparent extinction of native mussels in the survey area, nor that native mussels will return in the foreseeable future (Richards 2017, Richards and Miller 2017).

If per chance native mussels do survive undetected in the Jordan River or Mill Creek, they do so at what we suggest are critically low, unsustainable densities. Both native mussel taxa, *Anodonta* sp. and *M. falcata,* require secondary fish hosts to reproduce. Consequently, suitable fish host densities and mussel densities both need to be sufficiently great for mussel viability (i.e., biologically meaningful densities) (Strayer 2013, Richards 2017), but neither appears to be sufficient in the Jordan River or Mill Creek (Richards 2017). As far as we know, biologically meaningful densities for either mussel taxon have not been adequately evaluated or equivocally determined. For example, a mussel density of 0.1 m^{-2} could be sufficient if fish host density were extremely high but would be considered unsustainable if fish host densities were low or if there were no connectivity between populations (i.e., isolated populations vs. metapopulations). The POD models developed by Smith (2006) were based on several distribution assumptions that, although necessary for model development, are not always representative of mussel population distributions. As an example, the Smith (2006) models were based on Poisson probability distributions, which implies that mussels at very low densities have a spatially random distribution (Smith 2006). We suggest that mussel density distributions are often not spatially random but are often highly spatially autocorrelated, especially when populations become small and isolated. That is, it is more likely to encounter a mussel where other mussels occur. We are also advocates of the axiom that “nothing in the universe is random,” although things may appear to be random in the absence of useful information. However, assuming that the Smith (2006) models provide reasonable statistical relationships between POD, SE, and mussel density and that the models are extremely useful for understanding mussel population viability, biologically meaningful densities still need to be determined. Smith (2006) stated, “The determination of a biologically meaningful threshold should involve multiple considerations including legal mandates, life history, population viability, and comparisons of densities throughout a local watershed, region, or range.” These factors clearly need to be addressed before biologically meaningful densities can be determined for native mussels in the Jordan River drainage. Much of this information is available. For example, Richards (2017) discussed life histories and population viability dynamics (including metapopulation viability dynamics) at length and provided density estimates of native mussels throughout much of the drainage. Sadly, the prognosis is not good. Native mussel populations appear to be in steep decline throughout the region, and only a few small, isolated populations of *Anodonta* still exist in the Utah Lake–Jordan River drainage. The Western Pearlshell mussel, *Margaritifera falcata,* may no longer exist.

Even though native mussels in all likelihood are absent from lower Mill Creek and the mid-Jordan River, the invasive clam *Corbicula fluminea* thrives. Although not the focus of this survey, we have accumulated the most data to date on *Corbicula* densities in relation to habitat conditions in Mill Creek and the Jordan River (Richards and Miller 2017). We estimated that *Corbicula* densities can sometimes exceed 12,000 m^{-2} as live individuals and >16,000 m^{-2} as live and empty shells in ideal Jordan River habitat. Ideal habitat for *Corbicula* appears to be runs with moderate flow and mostly small- to medium-sized gravels of sufficient depth to allow the clams to secure themselves. It is well known that *Corbicula* is a very strong competitor and predator on native mussels and is likely a major contributor to the continued demise of native mussels in our survey area and other invaded locations (Phelps 1994, Strayer 1999, Strayer 2013, Richards 2017).

Our mussel survey methods also weren't designed as fish surveys, although we have conducted fish surveys in the past. We did not observe many potential fish hosts during our mussel survey. We captured only 2 individuals, one small burbot (*Lota lota*) and one fathead minnow (*Pimephales promelas*), in the survey and only rarely saw other fish swimming by, mostly common carp (*Cyprinus carpio*). Richards (2017) discussed at length how secondary fish host densities must be high enough for successful glochidium (larval mussel) attachment and juvenile recruitment, including fish host densities in Mill Creek and the Jordan River. We suggest that Mill Creek and the Jordan River no longer have high enough densities of fish hosts for mussel viability.

Finally, Mill Creek and the Jordan River have been physically degraded for many decades. Both water bodies have been channelized and diverted and no longer function as natural systems (Richards and Miller 2017). Most sections of these waters in the survey area continue to be dredged on a regular basis, eliminating whole age classes of extant native mussel populations, making recruitment almost nonexistent, and sending population viability spiraling to zero in these locations, even without the other factors that negatively influence their populations.

Conclusion

Results of this native mussel survey combined with other surveys provide multiple lines of evidence that show that native mussels in lower Mill Creek and the mid-Jordan River are likely extinct or are so extremely rare and cryptic that as far as is known, no live individuals have ever been documented in Mill Creek nor have any been documented in the Jordan River since 1942. Reasons for their rapid decline, decreased population viability, and potential complete demise throughout the Jordan River drainage are numerous, and immediate steps need to be taken if they are to survive in remaining occupied habitats.

Acknowledgments

We extend thanks to our mussel survey technicians W.D. Robinson and Frank Fluckinger and to the Wasatch Front Water Quality Council for funding this important research.

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Received 8 March 2018
Revised 7 May 2018
Accepted 6 June 2018

Appendix 1. Jordan River 2017 site data. Locations are given in relation to the confluence with Mill Creek. All shovel sample areas equal 0.5 m^2, whereas all suction dredge sample areas were between 0.5 and 4.0 m^2. Samples were collected between 23 September 2017 and 23 October 2017. Substrate codes: CPOM = coarse particulate organic matter, FPOM = fine particulate organic matter, OM = organic matter, and SAV = submerged aquatic vegetation.

UTM 12T			Depth (cm)
Easting (m)	Northing (m)	Substrate	
1a. Downstream of Mill Creek confluence (impacted sites); method = shovel			
422033.54	4509629.59	Cobble/gravel/sand	60
422039	4509711.02	CPOM/garbage/OM/pea gravel	62
422003	4509839	*Corbicula*/peagravel	55
421949	4509831	*Corbicula*/peagravel	62
421956.91	4509950.37	*Corbicula*/peagravel/CPOM	50–80
422031.98	4509980.84	clay/gravel	50–80
422057.83	4510004.51	OM/silt/sand/*Corbicula*	50–70
422120.14	4510254.91	silt/sand/CPOM	50–90
422074	4510333.88	CPOM/silt/sand	70–100
422445.97	4510750.23	CPOM/silt/anaerobic	40–100
422480.56	4510716.21	OM/silt/sand	70–100
422453.14	4510645.01	peagravel/silt	70–120
422231.91	4510739.51	CPOM/silt	50–90
422210.96	4510756.82	CPOM/silt/fine sand	70–110
422223	4510790.25	silt/CPOM/fines	70–110
422235.72	4510806	silt/CPOM/fines	70–100
422246.02	4510923.75	silt/CPOM/fines	65–100
422319.9	4511415.2	deep OM/CPOM/garbage	60–100
422393.17	4511375.5	sand/CPOM/cobble	65
422280.64	4511422.33	OM/silt/clay/garbage	35
422222.28	4511382.05	OM/silt/clay/garbage	50
421964.7	4507219.29	sand/gravel	10
421963.81	4507324.34	silt/sand/gravel	34
421946.32	4507474.33	OM/silt/sand/gravel	82
422156.14	4507695.2	silt/sand/gravel	90
422016.53	4507623.26	silt/sand/gravel	117
422276	4508124.34	OM/silt/sand	110
421936.27	4508567.51	cobble/gravel/*Corbicula*	60
421805.52	4508909.21	sand/peagravel/*Corbicula*	95
421870.73	4509030.97	CPOM/silt/sand/peagravel/*Corbicula*	75
421924.25	4509240.47	roots/CPOM/FPOM/silt	100
422357	4511306	silt/CPOM	90–120
422306	4511288	silt/CPOM/FPOM/clay	60–120
422259	4511255	silt/CPOM/FPOM/clay	70–120
422142	4511074	FPOM/clay/silt	90–140
422249	4510953	silt/CPOM/FPOM/clay	70–120
422211	4510743	CPOM/FPOM/silt/muck/sand	90–130
422209	4510747	CPOM/FPOM/silt/muck/sand	100–130
422207	4510750	muck	70–120
1b. Downstream of Mill Creek confluence (impacted sites); method = suction dredge			
422259.92	4508110.23	cobbles/sand/silt/garbage/CPOM	90–130
422246.65	4508078.02	cobbles/sand/silt/garbage/CPOM	90–140
1c. Upstream of Mill Creek confluence (control sites); method = shovel			
421879.36	4505831.52	peagravel/gravel	30–40
421886.68	4505935.81	gravel/clay	50–80
421730.66	4506092.01	gravel/SAV/sand	40–80
422847	4503923	large gravel/peagravel/sand	50–100
422817	4503986	peagravel/gravel/small cobble/sand	50–120
421939	4500685	small cobble/gavel/sand/silt/ SAV	40–90
421947	4500715	large gravel/peagravel/hard pan	30–60

Appendix 2. Mill Creek 2017 site data. Locations are given in relation to the Central Valley Water Reclamation Facility (CVWRF). All shovel sample areas equal 0.5 m^2, whereas all suction dredge sample areas were between 0.5 and 4.0 m^2. Samples were collected between 18 September 2017 and 21 September 2017. Substrate codes: CPOM = coarse particulate organic matter, FPOM = fine particulate organic matter, OM = organic matter, and SAV = submerged aquatic vegetation.

UTM 12T			
Easting (m)	Northing (m)	Substrate	Depth (cm)
2a. Upstream of CVWRF (control sites); method = shovel			
422656.00	4506771.71	CPOM/FPOM/clay	70
422676.10	4506768.19	CPOM/FPOM/clay	60
422704.00	4506764.00	clay	60
422726.00	4506761.00	SAV/silt/sand/CPOM/FPOM	75
422772.00	4506757.00	silt/SAV/CPOM/FPOM	60
422805.00	4506756.00	sand/silt/OM/trash/slag	60
422826.00	4506753.00	CPOM/sand/SAV	60
422861.00	4506747.00	hard clay/SAV	60
422877.00	4506745.00	hard clay	60–70
422925.00	4506741.00	hard clay/silt	60–70
422948.00	4506736.00	tree branches/CPOM	50–70
422978.00	4506733.00	sand/silt/clay	65
423604.92	4506540.01	gravel	65
423533.48	4506541.77	gravel	50
423402.69	4506634.96	sand/gravel	60
423377.19	4506643.72	silt/sand/veg/roots	60–70
423548.12	4506539.82	roots/silt/sand/CPOM	60–70
423579.90	4506539.59	gravel	60
2b. Downstream of CVWRF (impacted sites); method = shovel			
422074.00	4506876.00	silt/sand/clay	125
422064.00	4506881.00	silt/sand/clay	110
422059.00	4506885.00	silt/sand	90
422006.00	4506930.00	gravel/sand/silt	90
422001.00	4506934.00	sand/gravel/trash	100
422135.00	4506847.00	gravel/sand/silt/FPOM	90–100
422162.00	4506836.00	gravel/sand/silt/FPOM	90–100
422170.00	4506834.00	gravel/sand/silt/FPOM	90–100
422178.00	4506833.00	gravel/sand/silt/FPOM	90–100
422220.00	4506823.00	gravel/sand/silt/FPOM	90–100
422301.00	4506815.00	gravel/sand/cobble	90–100
422425.00	4506800.00	gravel/sand/cobble	90–100
422431.00	4506799.00	gravel/sand/cobble	90–100
422481.00	4506791.00	gravel/sand/cobble	90–100
422500.00	4506791.00	gravel/sand/cobble	90–100
2c. Downstream of CVWRF (impacted sites); method = suction dredge			
422005.00	4506933.00	FPOM/silt/sand/gravel	120
422003.00	4506928.00	FPOM/silt/sand/gravel	130
421993.00	4506940.00	FPOM/silt/sand/gravel	130
421992.00	4506946.00	FPOM/silt/sand/gravel	100
421989.00	4506949.00	FPOM/silt/sand/gravel	125