LITERATURE REVIEW

Potential Role of Merrimack Station's Thermal Effluent on Asian Clams, Native Mussels, and Ecology of the Merrimack River

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1. Distribution of Asian clams in New Hampshire and New England

The Asian clam was introduced to North America sometime in the early 20th century and then spread throughout western, central, and eastern North America (Counts 1986, Strayer 1999). Cold water temperatures were thought to limit its northward range expansion (Mattice and Dye 1975); Asian clams were slow to invade New England and northern plains states. In New England, the Asian clam was once restricted to a portion of the Connecticut River downstream from the former Connecticut Yankee nuclear power plant in Haddam, Connecticut, where it was thought to rely on thermal effluent in an environment that was otherwise too cold for overwinter survival (Morgan *et al*. 2003). Biologists posited that the species' lower lethal temperature of ~35-37°F [2°C] would impede its spread farther into New England. However, its distribution has since greatly expanded throughout Connecticut, Rhode Island, Massachusetts, and more recently into Vermont (Lake Bomoseen) and southern New Hampshire. These occurrences are summarized below:

- **New Hampshire:** Merrimack River south of Bow. Cobbetts Pond (Windham) (NHDES Fact Sheet, 2012), Wash Pond (Hampstead) (NHFG website), Long Pond (Pelham) (NHDES 2013), Beaver Lake (Derry), Great Pond (Kingston). Due to the high-density of ponds in southern New Hampshire connected to ponds that are already infested, and the proximity of these waterbodies to the Merrimack River, it is very likely that Asian clams are more prevalent in southern New Hampshire than currently reported. Indeed, Amy Smagula (NHDES) indicated that Eversource has recently conducted Asian clam surveys in the Merrimack River and nearby waterbodies and has documented more populations in more waterbodies, though Eversource has not yet provided this list (as of November 2017).

- **Massachusetts:** Colwell *et al*. (2017) listed 28 waterbodies but there were some significant omissions for areas in both central (Connecticut River mainstem) and eastern Massachusetts. In the Massachusetts portion of the Merrimack watershed, it has been found in some ponds near the Merrimack River (Mascuppic Lake, Long Pond), in the entire Merrimack River to tidal areas (Lowell, Andover, Lawrence, Haverhill), and in several waterbodies in the Concord-Assabet-Sudbury watershed.

- **Rhode Island:** fairly widespread, locally abundant.

- **Connecticut:** widespread and locally abundant statewide; in lakes, ponds, rivers, and small streams.

- **Vermont:** Lake Bomoseen (recent).

- **Maine:** Not found yet.

Asian clams either acclimated/adapted to cooler waters of southern New England, or the thermal regime of regional waterbodies was trending warmer over the last 2-3 decades. Currently, Asian clams inhabit more than 100 waterbodies in New England, in large and small lakes, large rivers (e.g., Connecticut River, Housatonic River, Merrimack River), smaller rivers (e.g., Charles River, Farmington River, Sudbury River, Taunton River), and even small streams, especially lake-outlet streams. Maine is the only New England state where the Asian clam has not yet been found.

Asian clams were first reported within Merrimack Station's thermal plume in 2012 (Normandeau 2012); it had already been reported from other locations in the Merrimack River watershed by that time. Asian clams now appear to be widespread in the lower Merrimack River watershed in Massachusetts and New Hampshire, but the chronology of invasion is unknown. Neither New Hampshire nor Massachusetts (or other New England states) had an early detection or monitoring program that would have helped establish a chronology of invasion in the region.

2. Thermal tolerance of Asian clams

Asian clams exist within a thermal range of approximately 65°F [36°C], from a lower lethal temperature of ~35°F [2°C] to an upper lethal temperature of ~100°F [38°C] (Mattice and Dye 1975, McMahon 1991). They are also highly sensitive to low dissolved oxygen. Optimal temperature for growth is near 71-75°F [22-24°C], and optimal temperature for reproduction is near 59°F [15°C]. Asian clams can adapt to warm temperatures; Falfushynska *et al*. (2016) found that Asian clams living within a cooling water discharge had higher lethal temperature thresholds than Asian clams from pristine (unheated) areas. As a subtropical species, it was considered poorly adapted to colder thermal regimes of temperate regions, and most of the first reports of Asian clams in temperate regions were from localized, thermally polluted areas such as near power plants with cooling water discharges (French and Schlosser 1991, Morgan *et al*. 2003, Simard *et al*. 2012). Large-scale mortality events have been documented due to both cold stress (Sickel 1986, Werner and Rothhaupt 2008) and heat stress (McDowell *et al*. 2017), with the latter also usually associated with low levels of dissolved oxygen.

In recent years in both Europe and North America, Asian clams have been found to occur in areas farther north, and in colder thermal regimes, than was predicted based on their lower lethal temperature, leading researchers to investigate acclimation and adaptation to cooler temperatures (Muller and Baur 2011, Cvetanovska 2014). In a laboratory experiment, Muller and Baur (2011) found that in water of 32°F [0°C], Asian clam survival decreased from 100% to 17.5% with increasing exposure from four to nine weeks. The largest individuals were more likely to survive longer durations at cold temperatures. Cvetanovska (2014) found that a significant portion of Asian clam individuals, especially larger clams, survived two months at 32.9-33.8°F [0.5-1.0°C] and that survivorship was enhanced by prior acclimation to low temperatures. When acclimated to 50°F [10°C], clams from northern populations showed greater survivorship than those from southern populations. She concluded that physiological plasticity and acclimation history accounted for variation in cold tolerance across populations. Adaptation to survival at low temperatures, combined with milder winters due to climate change (Weitere *et al*. 2009, McDowell *et al*. 2014), could permit Asian clams to continue expanding its invasive range farther north in Europe and North America.

3. Role of Merrimack Station's thermal discharge in sustaining an Asian clam population in the Merrimack River

Merrimack Station provided a warm and stable thermal environment; ensured locally high Asian clam growth rate, abundance, and overwinter survival and therefore a more stable source population; and provided an opportunity for Asian clams to acclimate and adapt to cooler waters. As reported in Normandeau (2012), Asian clams were concentrated in areas of Hooksett Pool within the Station's thermal plume. Of the 18 samples taken at or downstream of Merrimack Station's discharge, Asian clams were the dominant taxon in 14 of them, and ranged in relative abundance from 58 to 94 percent (Normandeau 2012). Qualitative sampling by NHDES (2013) and EPA (2014) revealed both higher densities of Asian clams and larger individuals near the mouth of the discharge canal, compared to those collected farther downstream in Hooksett Pool, and in Amoskeag Pool below the Hooksett Dam. Neither NHDES nor EPA found Asian clams upstream from Merrimack Station in 2013 or 2014, suggesting an unsuitable thermal regime upstream from Merrimack Station, and also suggesting that the strong source population of Asian clams downstream from Merrimack Station exists solely because of thermal pollution.

CWA § 316(a) variance-based temperature limits must assure the protection and propagation of the balanced indigenous population of organisms, while New Hampshire water quality standards impose similar requirements for the protection of local aquatic life. Merrimack Station's role in sustaining a source population of Asian clams within its thermal plume violates these criteria.

4. Potential spread of Asian clams to other parts of the river and other regional waterbodies

If we assume that Asian clams first gained a foothold in the Merrimack River in thermally impacted areas (either below Merrimack Station or elsewhere in the lower river), then the "potential" for this to facilitate regional invasion is already playing out. Based on currently available data, and a new dataset that has not been released by Eversource, Asian clams have already invaded the lower Merrimack River watershed in New Hampshire and Massachusetts, including ~60 miles of the mainstem Merrimack River and more than 10 lakes and ponds (not including the lakes and rivers in the Concord-Sudbury-Assabet watershed). Survey data are limited, and it is very likely that Asian clams are even more widespread. There is a large number of impoundments and natural lakes in the region that are hydrologically connected, and Asian clams may quickly spread through these watersheds. For example, Asian clams occur in Wash Pond in Hampstead (NH), in the upper Spicket River watershed, and it is likely that other ponds in the same watershed may soon be invaded (if not already), such as Island Pond, Taylor Reservoir, Arlington Mill Reservoir, and several miles of the Spicket River. Similarly, Asian clams occur in Great Pond in Kingston (NH), in the upper Powwow River watershed, and there are several ponds in the watershed that could soon be invaded such as Long Pond, Powwow Pond, Country Pond, Tuxbury Pond, Lake Attitash, and Gardner Lake.

To date, unless there are such data in the Eversource report, Asian clams have not been found upstream from the thermal plume of Merrimack Station in the Merrimack River or in any lakes or ponds in Merrimack, Hillsborough (west of the Merrimack River), Belknap, Strafford, or northern Rockingham counties, or points farther north in New Hampshire. The presence of source populations in the Merrimack River and ponds in eastern Hillsborough and southern Rockingham County puts the entire region at risk of further invasion. The physical (especially the thermal regime) and chemical suitability of waterbodies in southern and central New Hampshire, or southern Maine, for Asian clams is not known.

5. Potential effects of Asian clams on the Merrimack River's native mussel fauna and ecology

Scientists agree that Asian clams have had detrimental effects on freshwater ecosystems and native freshwater mussels (Strayer 1999, Sousa *et al*. 2008, 2014). The precise mechanisms and relative importance of the myriad interactions between Asian clams and native bivalves remain poorly understood, and evidence for collapse of native mussel populations due to the introduction of Asian clams is lacking (Strayer 1999). This remains an active area of freshwater research, as Asian clams remain one of the most pervasive and ecologically important aquatic invasive species. Native freshwater mussels are among the most endangered faunal groups in the world (Strayer *et al*. 2004, Lopes-Lima 2017), and the decline and loss of native bivalves has enormous implications for ecosystem health (Vaughn and Hakenkamp 2001, Vaughn 2017). There are several possible negative effects of Asian clams on native freshwater bivalves (Strayer 1999, Sousa *et al*. 2008, 2014):

- Competition for space; Asian clams may displace native species or reduce their available habitat due to their presence and bioturbation, especially in dense populations.

- Competition for food; Asian clams compete against native species for both benthic and planktonic food resources, thereby affecting the survival, growth, and condition of native species.

- Direct consumption; Asian clams may ingest sperm, glochidia and newly metamorphosed juveniles of native mussels, thereby reducing mussel fertilization and recruitment.

- Asian clams are vectors of parasites and pathogens.

- Asian clams often undergo mass mortality events, especially in response to challenging environmental conditions, and this can affect native benthic species by depressing dissolved oxygen and releasing high (toxic) concentrations of ammonia.

- Asian clams bioaccumulate and bioamplify contaminants.

- Asian clams have the potential to alter nutrient cycling and trophic pathways in aquatic ecosystems.

Based on the large body of peer-reviewed scientific literature, there is a wide range of potential effects of Asian clams on the Merrimack River and its native mussel species. In the Merrimack River, adverse effects of Asian clams should be most acute where population densities are highest; to date, this appears to be in areas of the Hooksett Pool within Merrimack Station's thermal plume. Although there is little specific data on the effect of this large source population of Asian clams on native mussels and the local ecosystem, there is certainly strong potential for adverse effects. Two state-listed native mussel species *may* occur in the Merrimack River near Merrimack Station: the Endangered brook floater (*Alasmidonta varicosa*), and the

Special Concern eastern pondmussel (*Ligumia nasuta*). Six other species might also occur near the Station: eastern elliptio (*Elliptio complanata*), eastern lampmussel (*Lampsilis radiata*), triangle floater (*Alasmidonta undulata*), creeper (*Strophitus undulatus*), alewife floater (*Anodonta implicata*), and eastern floater (*Pyganodon cataracta*).

6. Thermal tolerance of native mussel species

Freshwater mussel species tolerate a broad range of water temperatures; some of the most species-rich and abundant mussel communities in New England occur in waterbodies whose thermal regime includes extreme low temperatures in the winter and summertime temperatures upwards of 85°F [30°C] (Nedeau 2008). The freshwater mussel species native to New England are adapted to regional climate and the thermal regime of the waterbodies they occupy. As noted by one author, "*acclimatization to environmental conditions occurs over time, so normal temperatures in an animal's natural habitat are rarely harmful*" (Pandolfo *et al*. 2010). Water temperature is critically important to aspects of their life cycles, behavior, and physiology; warm temperatures may interfere with all of these things, resulting in effects such as sublethal stress, mortality, and decreased fertilization and recruitment (Pandolfo *et al*. 2010).

However, there is only a limited understanding of species-specific thermal tolerance (upper or lower), sublethal responses [i.e., thermal stress] of different life stages, importance of seasonal cycles (i.e., thermal regime), the role of acclimation or adaptation, interaction with related factors such as dissolved oxygen availability, and effects of altered thermal regimes on fish communities that would, in turn, affect mussel species that rely on fish for reproduction and dispersal. Any human-caused changes to the thermal regime of waterbodies create the potential for wide-ranging effects on individuals, populations, and communities, both for mussels and their host fish (Caissie 2006).

Very generally, sublethal (stress) responses of the most sensitive life stages of freshwater mussels (glochidia and juveniles) begin to be observed near 75°F [24°C], more acute stress responses and mortality occur across most taxa as temperatures approach and exceed ~85°F [30°C], and high mortality of all life stages is expected at higher temperatures (see brief overview of key studies, below). Glochidia and juveniles are typically more sensitive to temperature than adult mussels (Pandolfo *et al*. 2010). Most species and life stages can tolerate higher temperatures if first acclimated to warmer temperatures (Galbraith *et al*. 2012, Martin 2016).

<u>Key Studies</u>

Ganser *et al*. (2013): Tested juvenile *Lampsilis abrupta*, *Lampsilis siliquoidea*, and *Megalonaias nervosa*. 28-day LT50s (lethal temperature affecting 50% of the population) ranged from 25.3 to 30.3°C across the three species tested. Heart rate declined with higher temperatures for 2 of 3 species.

Archambault *et al*. (2013): 96-hr LT50 34.4°C and 34.7°C for 22°C and 27°C acclimation temperatures, respectively. Elevated water temperatures reduced burrowing and byssus production in juveniles. Spikes in stress enzymes suggest a sublethal response at lower temperatures than the LT50.

Archambault *et al*. (2014): *Lampsilis abrupta* and *Lampsilis radiata*. 96-hr LT50s ranged from 29.9 to 35.6°C, with a grand mean of 32.8°C. Increased temperatures significantly reduced burrowing behavior and byssus production.

Galbraith *et al*. (2012): Evaluated the critical thermal maximum (CTM) of *Alasmidonta varicosa*, *Elliptio complanata*, and *Strophitus undulatus* acclimated to two temperatures (15 and 25°C) and exposed to two aeration treatments. Responses varied by species, but mussels acclimated to 25°C generally had a higher CTM than mussels acclimated to 15°C. CTM for all three species in the range from 39.1 to 42.7°C, with some variation by species, acclimation temperature, and aeration.

Martin (2016): MS Thesis. LT50s for juveniles less than 3 weeks old were within 2-3°C higher or lower compared to juveniles 1-2 years older. LT50s for peak temperature in summer-acclimated mussels were 33.2, 39.1, and 38.9°C for Western pearlshell, Fatmucket, and Washboard juveniles less than 3 weeks old compared to LT50s of 36.1 and 40.8°C for Fatmucket and Washboard 1-2 years of age. Winter acclimated Washboard had LT50s 2-4°C lower than summer acclimated animals.

Pandolfo *et al*. (2010): Glochidia of 8 species of mussels were tested: *Lampsilis siliquoidea*, *Potamilus alatus*, *Ligumia recta*, *Ellipsaria lineolata*, *Lasmigona complanata*, *Megalonaias nervosa*, *Alasmidonta varicosa*, and *Villosa delumbis*. Seven of these species also were tested as juveniles. Survival trends were monitored while mussels held at 3 acclimation temperatures (17, 22, and 27°C) were exposed to a range of common and extreme water temperatures (20–42°C). Looked at both LT50 and LT05; LT05 represents temperatures that are high enough to cause sublethal effects.

- Glochidia Tests (24-hr): Mean LT50 was 31.6°C, with a range from 21.4 to 42.7°C. Mean LT05 was 25.0°C, with a range from 15.6 to 30.3°C.

- Juvenile Tests (96-hr): Mean LT50 was 34.7°C, with a range from 32.5 to 38.8°C. Mean LT05 was 29.4°C, with a range from 23.7 to 34.1°C.

Based on comparisons of LT50s, thermal tolerances differed among species for glochidia, but not for juveniles. Acclimation temperature did not affect thermal tolerance for either life stage. On average, the difference between the LT50 and the LT05 of juveniles within a given species was only 5.3°C, and the difference was only 10.6°C for glochidia of a given species. Over this relatively narrow span of temperatures, mortality could theoretically increase from 5 to 50 percent.

Dimock and Wright (1993) (cited in Pandolfo *et al*. 2010): Reported a 96-h LT50 of 31.5°C for 1-wk-old juvenile *Utterbackia imbecillis* and 33°C for 1-wk-old *Pyganodon cataracta*.

Ganser *et al*. (2015): Reviewed abstract only. Studied physiological response of four species to elevated water temperatures (20, 25, 30 and 35°C). *Amblema plicata*, *Elliptio complanata, Fusconaia flava* and *Lampsilis cardium*. Oxygen consumption rates were directly affected by temperature in *E. complanata* and *L. cardium*, and indirectly affected by temperature in *A. plicata* and *F. flava*. Rates of O_2 consumption were generally positively correlated with water temperature. Ammonium excretion rates varied significantly with temperature in *E. complanata* and generally increased with temperature. The amount of O_2 consumed relative to nitrogen excreted (O:N ratio), varied significantly with temperature in *A. plicata*, *E. complanata* and *F. flava*. Data suggest that elevated temperatures can alter metabolic rates in native mussels and may decrease the amount of energy that is available for key biological processes, such as survival, growth and reproduction.

7. Potential effects of a thermal discharge on native mussels in the Merrimack River

The occurrence, distribution, abundance, and habitat of native mussel species in the areas of the Merrimack River upstream and downstream from Merrimack Station is either not known or not adequately reported. This precludes an adequate risk assessment for the effects of the thermal discharge on native mussel species. Without more complete data, it is reasonable to assume that eight native mussel species could occur in this area. Two state-listed native mussel species may occur in the Merrimack River near Merrimack Station: the Endangered brook floater (*Alasmidonta varicosa*), and the Special Concern eastern pondmussel (*Ligumia nasuta*). Six other species might also occur near the Station: eastern elliptio (*Elliptio complanata*), eastern lampmussel (*Lampsilis radiata*), triangle floater (*Alasmidonta undulata*), creeper (*Strophitus undulatus*), alewife floater (*Anodonta implicata*), and eastern floater (*Pyganodon cataracta*).

Based on available temperature data, the thermal effluent is warm enough to cause mortality or sublethal (stress) for some life stages of freshwater mussels living within the thermal plume, to cause sensitive fish species (some of which may be important hosts for native mussels) to avoid the thermal plume, and to alter the river's thermal regime by eliminating the wintertime cold period and potentially disrupting natural cues for dormancy, breeding, and spawning. However, the magnitude of these effects remains unknown due to lack of data.

Available temperature data are inadequate for understanding (1) natural condition (upstream monitoring), (2) thermal regime (year-round continuous monitoring) within and outside (upstream and downstream) of the thermal plume, (3) the full spatial extent of the thermal plume under a variety of conditions (seasonal, at different river flows, etc), (4) how the spatial extent of the thermal plume relates to the distribution of mussels and mussel habitat, (5) data on other water quality parameters, such as dissolved oxygen, that could interact with temperature to affect mussels.

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