Large Scale Mussel Restoration in the Susquehanna River:

Potential Benefits for Nutrient Reduction

(DRAFT)

I. Mussel Basics

Freshwater mussels are a diverse fauna found in lakes, streams, and rivers worldwide. Mussel size and age are highly variable among species; the largest mussels can reach 300 mm in length and individuals of some species live for more than 100 years. Freshwater mussels have a complex life-history because mussel larvae (glochidia) must temporarily parasitize a host fish to complete metamorphosis to the independent juvenile life stage (Kat 1984). After metamorphosis is complete, juveniles excyst from their hosts and fall to the substrate. Host specificity varies among mussel species. Adult mussels are sessile, so dispersal is dependent upon the movement of host fish while glochidia are attached.

The decline in range and abundance of North American mussel populations from historical levels has been well documented and attributed to anthropogenic impacts (Strayer et al. 2004, Haag 2012). The reproductive strategy of mussels makes their populations particularly vulnerable to habitat modification and fragmentation from dams (Vaughn and Taylor 1999, Watters 1999). If host fish cannot access habitat occupied by mussels, recruitment will cease (e.g., Kelner and Seitman 2000). Over time, these mussel populations lose their viability and become co-extirpated with their host fish regardless of the number of adult mussels present or quality of environmental conditions.

The Eastern Elliptio (*Elliptio complanata*) is the most abundant and widespread mussel species in the Mid-Atlantic region. The American Eel is the primary host fish for the glochidia of the Eastern Elliptio (Lellis et al. 2013). The dwindling Susquehanna River mussel populations are isolated and consist primarily of large (older) individuals. The lack of Eastern Elliptio recruitment in the Susquehanna River has been attributed to the exclusion of their host fish by large dams, such as the Conowingo Dam (Reese et al. 2014, Gailbraith et al. 2018).

II. Mussel Density in Rivers/Streams

Mussel distribution is inherently patchy due to the heterogeneous distribution of suitable habitat within streams. In areas of suitable habitat, mussels form dense aggregations that may comprise the predominant form of benthic biomass in a stream.

Examples of mussel density from the literature:

- Freshwater mussel harvest records from the early 1900s were used to estimate average (riverwide) densities of up to 10 mussels/m^2 and densities within mussel beds reaching 100 mussels/m^2 in large rivers Strayer (2014).

- A 1991 survey estimated mussel density in the freshwater portion of the Hudson River estuary (area = 140 km^2) to average 8 mussels/m^2 with *Elliptio complanata* densities averaging 4.9 mussels/m^2 (Strayer et al. 1994).

- Surveys conducted in 2008-2010 at 12 sites in the Susquehanna River Basin found mussel densities ranging from 0.02 mussels/m^2 to 6.9 mussels/m^2 (Galbraith et al. 2018).

- Dr. William A. Lellis at USGS estimated that the upper Delaware River supports about 2.2 million Eastern Elliptio mussels per mile. The higher abundance of this species in the upper Delaware River than the Susquehanna River is attributed to the lack of dams on the Delaware River (host fish migration has not been impeded).

- Dr. Danielle Kreeger reports eastern elliptio mussel densities in the Brandywine River of 83,000 per mile.

- A recent survey contracted by Exelon for the Susquehanna River downstream of Conowingo Dam report mussel densities ranging from 0.11 mussels/m^2 to 4.26 mussels/m^2 (Biodrawversity and Gomez and Sullivan Engineers, 2012).

III. Nutrient Processing by Mussels

Mussels are well-known for their ability to filter water. Mussels are filter-feeding organisms that remove particulate nutrients (seston) from the water column. Particle filtration by mussels range from 0.50 to 3.7 Liters per hour per mussel. The Eastern Elliptio is estimated to filter 16.5 gallons of water per mussel per day (24 hours). Through daily feeding activities, mussels improve water quality by reducing nutrient transport in riverine systems. Nutrients taken in by mussels are either stored in the tissue of the mussel (soft tissues and shell material), translocated from the water column to the substrate in the form of biodeposits (feces and pseudofeces), or returned to the water column as excreted (soluble) nutrients.

Assimilation of nutrients in mussel tissues

Mussel tissue is composed of 8-13% Nitrogen (N) and 1-4% Phosphorus (P).

Mussel shell is composed of 1-2% N and less than 1% P.
A single mussel is estimated to contain approximately 0.7 g N and 0.009 g P.

Examples of nutrient assimilation capacity in Susquehanna River tributaries:

- Charlotte Creek (area=2,124/m^2, density = 0.6 mussels/m^2)
    - Standing stock is 892 g N and 11 g P
    - Clearance rate of seston is 3,313 L/hr
- Aughwick Creek (area = 4,760/m^2, density = 2.8 mussels/m^2)
    - Standing stock is 9,330 g N and 120 g P
    - Clearance rate of seston is 34,653 L/hr
- Pine Creek (area = 9,656/m^2, density = 6.1 mussels/m^2)
    - Standing stock is 41,231 g N and 530 g P
    - Clearance rate of seston is 153,145 L/hr
    - Note: Pine Creek was a site for U.S. Fish and Wildlife Service experimental eel stocking in 2010-2013 (Minkkinen et al. 2014).

Retention of nutrients in biodeposits

Biodeposition rates:

- *Margaritifera falcata* - 14 mg/hr per mussel (Howard and Cuffey 2006)
- *Lasmigona complanata* - 59 mg/hr per mussel (Hoellein et al. 2017)
- *Pyganodon grandis* - 128 mg/hr per mussel (Hoellein et al. 2017)

Strayer (2014) estimated the biodeposition rates for the 1% of the Hudson River Estuary with the densest freshwater mussel populations; these mussels were capable of retaining 440 pounds of nitrogen per day (80.3 tons annually) and 110 pounds of phosphorus per day (20.1 tons annually).

Kreeger (2005) estimated the effect of freshwater mussels on water clarity in the Brandywine River. It was estimated that mussels (density = 83,000 mussels per river mile) removed 4.3 metric tons (9,700 pounds) of TSS per river mile annually, or 7% of the suspended solids passing through the system.

Holistic estimate of nutrient reduction/retention

A study estimated total mussel mediated denitrification for the East Branch of the DuPage River near Chicago (Hoellein et al. 2017). Average mussel density was 0.97 mussels/m^2 (approximately 23,000 mussels/mile). The study calculated a denitrification rate of 0.0897 grams N/m^2/day. Annual mussel-enhanced reduction of nitrogen was 44,968 pounds (~1,730 pounds N per mile) in the DuPage River.

- Scaling the results from the DuPage River would result in 251,901 pounds of N removed per year per river mile in the Susquehanna River.

IV. Restoration Goals

Increasing the size and biomass of mussel populations through a combination of augmentation, reintroduction, and re-establishing the host-affiliate relationship could improve water quality through enhanced nutrient reduction due to filtration, retention, and biodeposition by mussels. While Eastern Elliptio would be the primary target due to its predominance of the community, other mussel species that are reliant on migratory fish hosts or reside in other habitats of the basin could also be targeted for population augmentation to increase biomass and filtration capacity.

The average mussel density found in the 2010-2012 surveys of the Susquehanna River downstream of Conowingo Dam averaged 2.6 mussels/m^2 (Biodrawversity and Gomez and Sullivan Engineers, 2012). Similarly, a moderate sized mussel bed (Aughwick Creek) for tributaries to the Susquehanna River has a density of 2.8 mussels/m^2. This conservative restoration goal would result in approximately 3.5 million mussels per river mile downstream of Conowingo Dam (see calculations in Appendix).

Target population sizes for various river widths and mussel densities (# mussels/river mile)

Average river width	5 mussels/m^2	2.5 mussels/m^2	1 mussel/m^2
0.5 mile (805 m)	6.5 million	3.2 million	1.3 million
0.25 mile (402 m)	3.2 million	1.6 million	647 thousand
0.1 mile (161 m)	1.3 million	648 thousand	259 thousand
Tributaries (15 m)	121 thousand	60 thousand	24 thousand

Potential mussel mediated nutrient retention in the Susquehanna River

# mussels/ river mile	# miles restored	Annual Biodeposition Rates (pounds)			Standing Stock (pounds)	
		TSS	Nitrogen	Phosphorus	Nitrogen	Phosphorus
25 thousand	1	10,250 - 13,750	30 - 38	10 - 15	39	0.5
	10	102,500 - 137,500	300 - 375	100 - 150	386	5
	25	256,250 - 343,750-	750 - 950	250 - 375	965	13
100 thousand	1	41,000 - 55,000	120 - 150	40 - 60	154	2
	10	410,000 - 550,000	1,200 - 1,500	400 - 600	1,543	20
	25	1.0 - 1.4 million	3,000 - 3,750	1,000 - 1,500	3,858	50
500 thousand	1	205,000 - 275,000	600 - 750	200 - 300	772	10
	10	2.1 - 2.8 million	6,000 - 7,500	2,000 - 3,000	7,716	99
	25	6.3 - 6.9 million	15,000 - 18,750	5,000 - 7,500	19,290	248
1 million	1	410,000 - 550,000	1,200 - 1,500	400 - 600	1,543	20
	10	4.1 - 5.5 million	12,000 - 15,000	4,000 - 6,000	15,432	198
	25	10.3 - 13.8 million	30,000 - 37,500	10,000 - 15,000	38,580	495
3 million	1	1.2 - 1.7 million	3,600 - 4,500	1,200 - 1,800	4,630	60
	10	12 - 17 million	36,000 - 45,000	12,000 - 18,000	46,297	595
	25	30 - 43 million	90,000 - 1.1 million	30,000 - 45,000	115,743	1,488

V. Uncertainties

Associated benefits

- Calculations do not account for natural recruitment within restored populations
- Mussels provide other ecosystem services; however, there are currently no methods to quantify their benefits
    - Mussels stabilize the streambed and provide structure that helps trap sediment and other particulate nutrients within the mussel bed.
    - Mussels may promote denitrification in the sediment, resulting in additional nutrient reduction within the system.
    - Mussels have been shown to increase the biomass and diversity of other aquatic macroinvertebrates, which in turn assimilate and process nutrients.

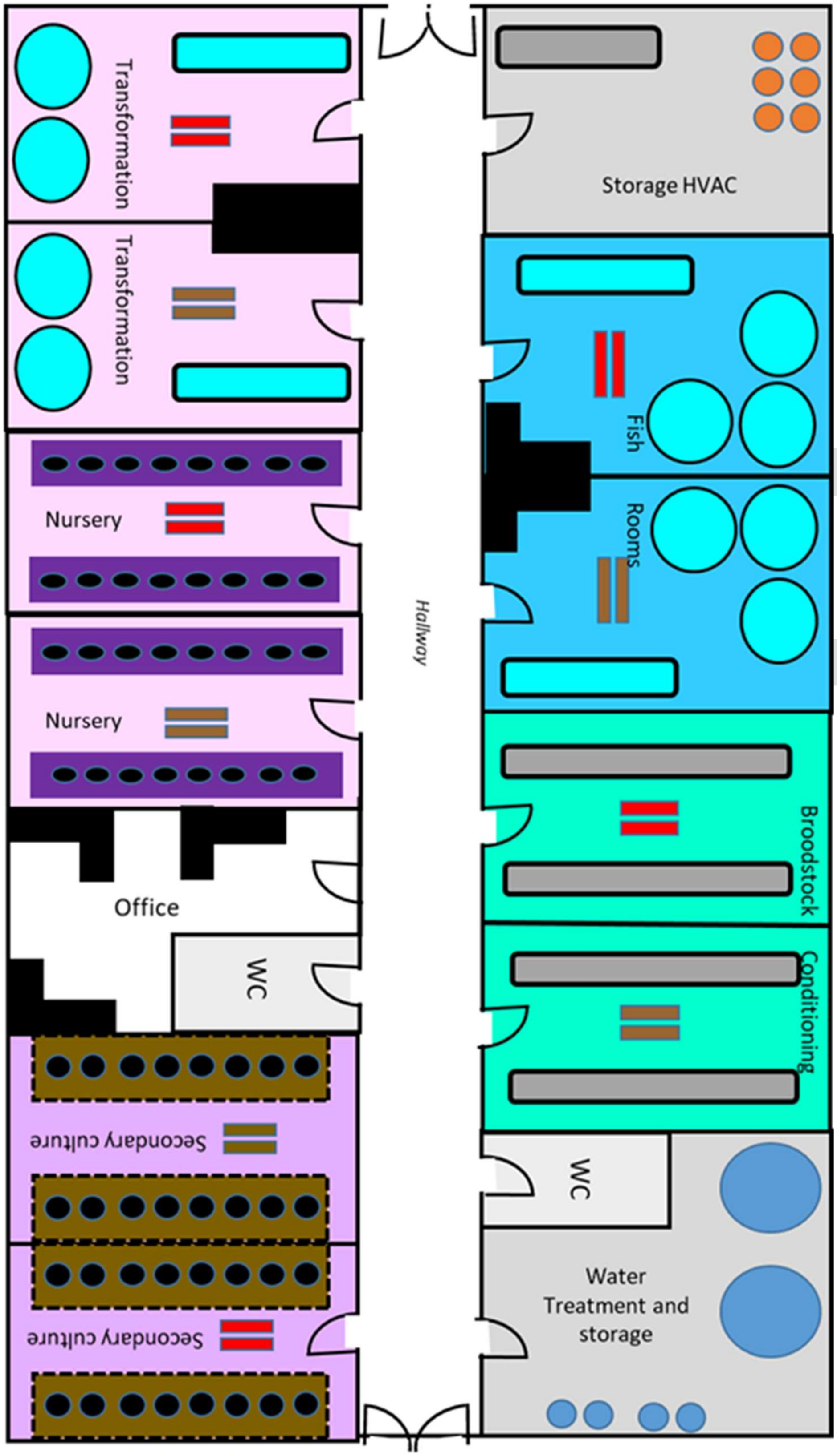
Variability in biological processes

- Mussel filtration rates vary due to environmental factors (e.g., temperature, stream flow rate, and concentration of suspended particulates) and physiological characteristics (e.g., age, sex, and reproductive status of an individual).
- Nutrient content of biodeposits depend on multiple factors
    - Species-specific biodeposition rates for candidate mussel species
    - Composition of suspended material (seston)
    - Nutrients that are assimilated into mussel tissue, especially during growth or reproduction

Ultimate fate of nutrients retained by mussels

- Nutrients that have been assimilated into mussel tissue and shell material may be released back into the system upon the death of an individual.
- The proportion of biodeposited and excreted nutrients incorporated into the food web and their exact impact on water quality downstream is unknown.

Sample Hatchery Design



CALCULATIONS

To calculate population size to achieve restoration goal

* Assume the average river width downstream of Conowingo Dam = 0.5 mile

– The area of 1 river mile:

river length x river width = area of river
1609m x 805m=1,295,245 m^2

– Population size:

area of river x mussel density = estimated population size
1,295,245 m^2 x 2.6 mussels/m^2 = 3.4 million mussels/river mile
1,295,245 m^2 x 2.8 mussels/m^2 = 3.6 million mussels/river mile

To calculate standing stock of nutrients within mussel tissue and shell material

– Pounds of N per area = (mussel density x 0.7 g N/mussel) / 453.6 g/lb
– Pounds of P per area = (mussel density x 0.009 g P/mussel) / 453.6 g/lb

To calculate nutrient translocation via biodeposition

– TSS per mussel/time = TSS in water x water filtered per mussel/time

11 mg/L x 2.6 L/hr = 28.6 mg TSS/mussel/hr

– Annual removal of TSS per mussel

28.6 mg/hr x **18 hr/day** x 365 days/year x (1 lb/453,592 mg) =
0.41 lbs TSS/mussel annually
28.6 mg/hr x **24 hr/day** x 365 days/year x (1 lb/453,592 mg) =
0.55 lbs TSS/mussel annually

– Nitrogen filtered/time = mg N/kg TSS x (1 kg/1 e+6 mg) x TSS mg/mussel

2,967 mg N/ kg TSS x (1 kg/1,000,000 mg) x 28.6 mg TSS/mussel =
0.08 mg N/mussel/hour

– Annual removal of N per mussel:

0.08 mg/hr x **18 hr/day** x 365 days/year x (1 lb/453,592 mg) =
0.0012 lbs N/mussel annually
0.08 mg/hr x **24 hr/day** x 365 days/year x (1 lb/453,592 mg) =
0.0015 lbs N/mussel annually

– Phosphorus filtered/time = mg P/kg TSS x (1 kg/1 e+6 mg) x TSS mg/mussel

1,170 mg P/ kg TSS x (1 kg/1,000,000 mg) x 28.6 mg TSS/mussel =
0.03 mg P/mussel/hour

– Annual removal of P per mussel:

0.03 mg/hr x **18 hr/day** x 365 days/year x (1 lb/453,592 mg) =
0.0004 lbs P/mussel annually
0.03 mg/hr x **24 hr/day** x 365 days/year x (1 lb/453,592 mg) =
0.0006 lbs P/mussel annually

To extrapolate denitrification from the DuPage River to the Susquehanna River

- Mussel-mediated denitrification = denitrification rate x mussel density x river area
- Mussel-mediated denitrification = 0.0897 $g/m^2/day$ (Hoellein et al. 2017)

0.0897 $g/m^2/day$ x 2.7 $mussels/m^2$ x 1,295,245 m^2 x (1 kg/1,000 g) = 313.7 Kg/day per river mile

313.7 Kg/day x 2.2 pounds/Kg x 365 days/year = 251,901 pounds of N per year per river mile

Symbols

Grams = g
Hour = hr
Kilograms = kg
Liters = L
Meter = m
Milligrams = mg
Nitrogen = N
Phosphorus = P
Pounds = lbs
TSS =total suspended solids

Conversions

1 mile = 1,609 meters
1 pound = 453.6 grams
1 pound = 453,592 milligrams
1 kilogram = 1,000,000 milligrams

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