Relicensing Study 3.3.16

Habitat Suitability Criteria for State-listed Mussel Species in the Connecticut River below Cabot Station

Study Report

Northfield Mountain Pumped Storage Project (No. 2485) and Turners Falls Hydroelectric Project (No. 1889)

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LIST OF ABBREVIATIONS

cfs	cubic feet per second
cm	centimeter
FERC	Federal Energy Regulatory Commission
FirstLight	FirstLight Hydro Generating Company
ft/s	feet per second
HSI	Habitat Suitability Index
IFIM	Instream Flow Incremental Methodology
ILP	Integrated Licensing Process
in.	inch
m	meter
m/s	meter per second
mm	millimeter
PAD	Pre-Application Document
PSP	Proposed Study Plan
RSS	Relative Shear Stress
RSP	Revised Study Plan
SD1	Scoping Document 1
SD2	Scoping Document 2
SPDL	Study Plan Determination Letter
SS	Shear Stress
VY	Vermont Yankee Nuclear Power Plant

1 INTRODUCTION

FirstLight Hydro Generating Company (FirstLight) is the current licensee of the Northfield Mountain Pumped Storage Project (FERC No. 2485) and the Turners Falls Hydroelectric Project (FERC No. 1889). FirstLight has initiated with the Federal Energy Regulatory Commission (FERC, the Commission) the process of relicensing the two Projects using the FERC's Integrated Licensing Process (ILP). The current licenses for Northfield Mountain and Turners Falls Projects were issued on May 14, 1968 and May 5, 1980, respectively, with both set to expire on April 30, 2018.

As part of the ILP, FERC conducted a public scoping process during which various resource issues were identified. On October 31, 2012, FirstLight filed its Pre-Application Document (PAD) and Notice of Intent with the FERC. The PAD included FirstLight's preliminary list of proposed studies. On December 21, 2012, FERC issued Scoping Document 1 (SD1) and preliminarily identified resource issues and concerns. On January 30 and 31, 2013, FERC held scoping meetings for the two Projects. FERC issued Scoping Document 2 (SD2) on April 15, 2013.

FirstLight filed its Proposed Study Plan (PSP) on April 15, 2013 and, per the Commission regulations, held a PSP meeting at the Northfield Visitors Center on May 14, 2013. Thereafter, FirstLight held ten resource-specific study plan meetings to allow for more detailed discussions on each PSP and on studies not being proposed. On June 28, 2013, FirstLight filed with the Commission an Updated PSP to reflect further changes to the PSP based on comments received at the meetings. On or before July 15, 2013, stakeholders filed written comments on the Updated PSP. FirstLight filed a Revised Study Plan (RSP) on August 14, 2013 with FERC addressing stakeholder comments.

On August 27, 2013 Entergy Corp. announced that the Vermont Yankee Nuclear Power Plant (VY), located on the downstream end of the Vernon Impoundment on the Connecticut River and upstream of the two Projects, would be closing no later than December 29, 2014. With the closure of VY, it was anticipated that certain environmental baseline conditions would change during the relicensing study period. On September 13, 2013, FERC issued its first Study Plan Determination Letter (SPDL) in which many of the studies were approved or approved with FERC modification. However, due to the impending closure of VY, FERC did not act on 19 proposed or requested studies pertaining to aquatic resources. The SPDL for these 19 studies was deferred until after FERC held a technical meeting with stakeholders on November 25, 2013 regarding any necessary adjustments to the proposed and requested study designs and/or schedules due to the impending VY closure.

FERC issued its second SPDL on the remaining 19 studies on February 21, 2014, approving the RSP with certain modifications. In the February 21, 2014 SPDL, FERC approved the RSP for Study No. 3.3.16 *Habitat Assessment, Surveys and Modeling of Suitable Habitat for State-Listed Mussel Species in the Connecticut River below Cabot* with one modification as listed below:

- FERC recommended that FirstLight consult with the Massachusetts Division of Fisheries and Wildlife Natural Heritage and Endangered Species Program (NHESP) during the selection process to determine an appropriate panel of experts to develop habitat suitability index (HSI) criteria for Study No. 3.3.1 Instream Flow Studies in Bypass Channel and below Cabot Station.

This report presents the results of the HSI development for three state-listed mussel species using the Delphi technique. The state-listed mussel species, hereafter called "target species," include Yellow Lampmussel (*Lampsilis cariosa*; Endangered), Tidewater Mucket (*Leptodea ochracea*; Special Concern), and Eastern Pondmussel (*Ligumia nasuta*; Special Concern).

1.1 Study Objectives

This study had two objectives:

1. Delineate, through field surveys, populations of state-listed mussels and suitable habitat from Cabot Station downstream to the Route 116 Bridge. Characterize the distribution, abundance, demographics, and habitat use of these populations. Identify and map potential habitat for state-listed species based on habitat preference of each species.
2. Develop binary HSI curves for all state-listed mussel species that occur in the 35-mile reach downstream from Cabot Station, using species-specific data from the Connecticut River and other rivers in the Northeast, along with relevant publications and expert review. These HSI curves will be used in the Instream Flow Incremental Methodology (IFIM) (Study No. 3.3.1) to evaluate the potential effects of Project operations on state-listed mussel species.

An interim report for Study No. 3.3.16 was issued on January 29, 2015, which presented the results of the mussel survey and habitat assessment conducted in the Connecticut River from Cabot Station downstream to the Route 116 Bridge in Sunderland, MA. That report accomplished the first study objective.

This report presents the results of the HSI curve development. The potential effects of Project operations on state-listed mussel species and their habitat will be discussed in a separate report (Study No. 3.3.1 Instream Flow Study).

2 METHODS

The three target species were not found in Reaches 1-4 (as defined by the Instream Flow Study No. 3.3.1) during surveys conducted in 2011 (Biodrawversity 2012) and 2014 (FirstLight's Interim Report for Study No. 3.3.16); however, all three have been documented in Reach 5 (Tighe & Bond 2014), which is defined in Study No. 3.3.1 as the Connecticut River from Route 116 Bridge in Sunderland downstream for approximately 22 miles to a natural hydraulic control located in the vicinity of Dinosaur Footprints Reservation, upstream of the Holyoke Dam.

FirstLight developed binary HSI criteria for these species in cooperation with NHESP, based on existing information and expert review via the Delphi technique (Crance 1987). Binary HSI criteria will be used in habitat modeling as described in the IFIM study methods (Study No. 3.3.1).

2.1 Approach to HSI Development

FirstLight gathered, reviewed, and synthesized available information on the distribution and habitat preference of target species in the Project area. Sources included journal articles, government and consultant reports, case studies, insight from regional experts, and field data collected by FirstLight in 2014.

FirstLight drafted a framework for binary HSI criteria for key parameters for each species, and drafted a questionnaire to solicit opinion of regional experts via a Delphi process (Crance 1987). This questionnaire was reviewed by NHESP (see correspondence dated 11/13/2015 in Appendix A). Parameters included water depth, flow velocity (benthic), substrate particle size, cover, shear stress, and relative shear stress, and are defined for the panelists as follows:

- **Depth** where individual mussels or mussel beds occur.
- **Flow velocity** refers to benthic (or "nose') velocity that mussels are subjected to.
- **Substrate** is specifically what mussels burrow in and generally where they spend their lives (recognizing limited mobility), and refers to dominant particle sizes in the top ~10cm of the river/lake bottom.
- **Cover** is any feature that can provide reduced lighting, reduced flow velocity, increased isolation; something that mussels can get under or behind. It may be important to host fish, which would in turn influence habitat suitability for mussels.
- **Shear stress** is the force exerted on the streambed by water per unit area of streambed, and is reflective of the stream's flow intensity and its ability to entrain and transport sediment particles. **Relative shear stress** is the ratio of observed to critical shear stress; critical shear stress is the shear stress that is required to initiate movement for a given particle size.

NHESP was contacted for collaboration in developing a list of potential experts to serve on the Delphi panel (see correspondence from February 2015 in Appendix A). Regional experts were identified and asked to participate. Those willing to participate were provided background information and the Round 1 questionnaire (Appendix B) that provided the framework for drafting binary HSI scores for key parameters.

FirstLight summarized Round 1 responses, compiled any new information cited by experts, and developed a Round 2 questionnaire (Appendix C) that included draft binary HSI criteria. Round 2 included a supplemental document explaining the complexities of shear stress parameters as they relate to sediment movement and mussel behavior and habitat, and asked experts to carefully consider these parameters. The Round 2 questionnaire and the shear stress document were provided to NHESP for review before they were sent to Delphi panelists, and modified per NHESP comments (see correspondence dated 1/26/2016 and 2/2/2016 in Appendix A).

FirstLight summarized Round 2 responses, compiled any new cited sources of information, fine-tuned the draft binary HSI criteria, and developed a Round 3 questionnaire (Appendix D). Round 3 also included a supplemental document that further explained challenges of using shear stress parameters as binary suitability criteria and provided Project-specific context. This supplemental document concluded with a recommendation that HSI curves would not be developed for shear stress parameters, but rather, the IFIM study would use binary HSIs for water depth, flow velocity, and substrate. Shear stress parameters would be considered as constraints or limiting factors in the final analyses. Delphi panelists were asked to provide final comments on the Round 3 questionnaire and on the supplemental document, specifically the recommendation against developing shear stress HSI curves.

All literature sources provided by panelists are available upon request.

2.2 Delphi Panelists

Experts who agreed to participate included Dr. Heather Galbraith (US Geological Survey – Northern Appalachian Research Laboratory), Dr. David Strayer (Cary Institute of Ecosystem Studies), Dr. Barry Wicklow (St. Anselm's College), and Dr. Cynthia Loftin (US Geological Survey/Maine Cooperative Fish and Wildlife Research Unit). FirstLight's mussel consultant, Ethan Nedeau of Biodrawversity, stepped down as moderator of the Delphi process to serve a similar role as the other experts, and Jason George of Gomez and Sullivan took over the role as moderator with some assistance from Ethan Nedeau. Peter Hazelton and Jesse Leddick (NHESP) reviewed the Delphi questionnaires and supplemental documents on shear stress. Dr. Heather Galbraith did not provide responses to the three rounds, thus the final binary HSI criteria were based on input from the other panelists and supplemental information.

3 RESULTS

The Delphi process was conducted over three rounds, resulting in agreement on binary HSI values for water depth, benthic velocity, substrate, and cover for juveniles and adults of each of the three target species. Panelists also concurred with the proposal to not develop specific HSI values for shear stress, but rather, shear stress and relative shear stress should be considered as potential constraints or limiting factors in the instream flow study analyses. Each of the proposed binary HSI values is presented in Table 3-1 using metric units and in Table 3-2 using standard units; each parameter and the pertinent Delphi results are presented below.

3.1 Water Depth

Tables 3-1 and 3-2 show the proposed binary HSI values for water depth for juveniles and adults of each species. More complete data, along with supporting studies and comments of Delphi panelists, are included in Appendix D. All Delphi panelists accepted these Round 3 binary HSI values for water depth.

In general, experts concur that mussels can persist and even thrive in very shallow water, as long as the shallow conditions do not expose them to other stressors such as thermal stress or increased risk of predation. Of the three mussel species, eastern pondmussels are most apt to be found in very shallow water. In fact, there is evidence that gravid females will migrate into extremely shallow water prior to release of glochidia, presumably to increase potential encounters with host fish. In the lower end of the Holyoke impoundment in the Connecticut River, eastern pondmussels were found almost exclusively in nearshore environments in depths less than one meter, usually within or upslope of dense beds of aquatic vegetation and coarse woody debris. In other rivers, such as Mill River (MA) and Farmington River (CT), eastern pondmussels were often found in only centimeters of water, within a meter of the water line. Likewise, tidewater muckets have been found within the intertidal zone, or just downslope, in the tidal portions of the Connecticut River, and they have also been found in high densities in less than a foot of water in lakes of southeastern Massachusetts. For the final binary HSI values, the conclusion of the Delphi Panel is that depths greater than 10 cm (0.33 feet) are considered suitable and depths less than 10 cm are considered unsuitable for all species. There is no evidence that there is an upper depth limit for any of these species.

3.2 Benthic Velocity

Tables 3-1 and 3-2 show the proposed binary HSI values for benthic water velocity for juveniles and adults of each species. More complete data, along with supporting studies and comments of Delphi panelists, are included in Appendix D. All Delphi panelists accepted these Round 3 binary HSI values for benthic water velocity.

Since all three species live in lakes and ponds, and in slow, depositional environments in rivers, no flow (velocity = 0) is considered optimal. There was general agreement of declining suitability with increasing velocity, although this may be related more to substrate stability rather than physiological adaptation to living in faster water. All three species have been found in small rivers in moderate to high flow velocities; yellow lampmussels in particular have been found in fast flows in Maine (examples: Penobscot River, Passadumkeag River, Mattawamkeag River, and Sebasticook River) and in Pennsylvania (Susquehanna River) although usually in deep runs or pools rather than in riffles. Eastern pondmussels have also been found in high numbers in small to moderate-sized rivers, such as Mill River (Massachusetts), Farmington River (Connecticut), and several rivers in southeastern Massachusetts. In faster-flowing rivers, they are usually found closer to streambanks and other refugia, yet in close proximity to fast flows. Tidewater muckets have also been found in a wide range of stream sizes and flow velocities, but generally seem to occur in flow refugia and depositional environments within those rivers that have a wide range of flow velocities. For the final binary HSI scores, the threshold from suitable to unsuitable velocities is based on the mobilization of the fine-grained particles that all three species tend to prefer.

3.3 Substrate Particle Size

Tables 3-1 and 3-2 show the proposed binary HSI values for substrate particle sizes for juveniles and adults of each species. Panelists were asked to consider dominant particle sizes in the top ~10cm of the river/lake bottom. More complete data, along with supporting studies and comments of Delphi panelists, are included in Appendix D. All Delphi panelists accepted these Round 3 binary HSI values for substrate particle size.

There was agreement that the optimal substrates for all three species includes fine-grained material such as silt, sand, and fine gravel. This is supported by field observations throughout each species' range in a wide variety of habitats (lakes, ponds, small and large rivers). Although organic material/detritus may be an important component of the substrate, areas where organic material is the dominant substrate (such as accumulations of leaves, senescent vegetation, detritus) are not ideal for any of the species. This may be due to a poor environment for burrowing or remaining upright, or poor chemical environment (e.g., low oxygen) in areas with dead/decaying organic material. For the binary HSI values, substrate consisting primarily of organic material is considered unsuitable for all three species. Clay was also found to be unsuitable. Substrate sizes ranging from mud/silt up to coarse gravel are considered suitable for all three species, even though suitability begins to drop for eastern pondmussel and tidewater mucket at particle sizes larger than 32 mm. The proposed binary HSI curve for yellow lampmussels is slightly different than for the other two species, as yellow lampmussels seem to occur more often in coarser gravel, especially in rivers in Maine, Pennsylvania, and New York. Large cobble, boulder, and bedrock are considered not suitable for any species, although these coarser materials may sometimes be an essential component of a mussel bed because they help to anchor the substrate and stabilize finer-grained materials, and may also provide cover/flow refuge for mussels.

3.4 Cover

Tables 3-1 and 3-2 show the proposed binary HSI values for cover for juveniles and adults of each species. More complete data, along with supporting studies and comments of Delphi panelists, are included in Appendix D. All Delphi panelists accepted these Round 3 binary HSI values for cover, although all agreed that these criteria provide little value in assessing effects of flow operations on mussels. Therefore, this parameter will not be used in the habitat modeling exercise in Study No. 3.3.1.

Mussels do not seem to be particularly responsive to cover, and the type of cover (as defined in the Round 1 questionnaire – Appendix B) does not seem to matter. All three species can exist within or near cover of all types, such as beds of submerged aquatic vegetation, coarse wood, steep banks with overhanging vegetation, and coarse rock. Based on the responses from panelists, and considering habitat data from across each species' range, all cover types were consolidated. The suitability values for eastern pondmussel and tidewater mucket were identical. Yellow lampmussels do not seem to occur in areas with dense cover. Certainly within their range in the lower Connecticut River, yellow lampmussels have been found primarily in more open areas, whereas the other two species may be closer to, or within, cover such as beds of submerged aquatic vegetation. Despite any minor modifications that could be made to these binary HSI values, the panelists concluded that cover was less important than other parameters in assessing effects of flow operations on mussels.

3.5 Shear Stress and Relative Shear Stress

The challenges of shear stress (SS) and relative shear stress (RSS) parameters are described in two separate documents included as supplements to the Round 2 and Round 3 Delphi questionnaires (see Appendix C and Appendix D). The main ideas of these two supplemental documents are described below.

Mussels live in rivers that can be naturally unstable environments and are morphologically and behaviorally adapted to living in these areas. Yellow lampmussel, eastern pondmussel, and tidewater mucket are generalists in terms of the types of waterbodies they inhabit (lakes and ponds, small to large rivers, freshwater tidal areas) and for the specific habitats that they inhabit within these waterbodies. Generally, all three species appear to prefer fine-grained sediment in lakes and rivers. When considering possible habitat suitability criteria for SS and RSS, it is worthwhile to consider that mussels can persist in areas that appear to have high SS and RSS based on relatively simple parameters of flow velocity, water depth, and resistance of particle sizes to movement.

The "onset of particle motion" may be a threshold for instability from a hydraulic modeling perspective, but mussels are well adapted to some amount of instability. It is a natural component of their habitat, especially for the three target species, which occur in fine-grained substrates in rivers. Hydraulic models that fail to account for mussel morphology and behavior, microhabitat selection, and other factors that may help to stabilize substrates (such as substrate cohesion, vegetation, embedded organic material, biofilms, and macroinvertebrates) will probably also fail to account for the persistence/stability of mussel beds. Hydraulic modeling of SS and RSS using simple parameters are likely to greatly overestimate the amount of shear at the streambed, the effects of shear on particle movement, and the effects of shear on mussels (via displacement) or mussel beds.

Available flow velocity, bathymetry, and substrate data in the Connecticut River where the state-listed mussel species of interest are located is rather coarse. Bank-to-bank variation in substrate particle size, vertical profiles of grain sizes in the streambed, and longitudinal variation in substrate particle size along the entire Project area is not well characterized. In addition, other components of substrate diversity that might influence resistance to particle movement (e.g., clay (increases cohesion), coarse wood, detritus, vegetation, biofilms, macroinvertebrates (including mussels themselves)) have not been well characterized. Thus, the RSS calculations based on very coarse-scale hydraulic and substrate data will provide very little insight into mussel habitat suitability. It would be difficult to use these data (or data from other rivers) to develop meaningful binary HSI for SS or RSS.

Based on the narrative in the supplemental document for the second round of the Delphi panel (Appendix C), and supporting literature such as Allen and Vaughn (2010), the most sensible area to focus on is high-flow SS and RSS. Allen and Vaughn (2010) concluded that, "*hydraulic variables estimated at high flows outperformed the same variables estimated at low flows. This result supports our hypothesis that hydraulic characteristics are more important to mussel habitat at high than at low flows, a conclusion that has been suggested by other authors* (Hardison & Layzer 2001, Howard & Cuffey 2003, Gangloff & Feminella 2007)."

At the United States Geological Survey (USGS) stream gage on the Connecticut River in Montague, MA (Gage No. 01170500), long-term flow data indicate a wide range of discharge, from <500 cfs to >140,000 cfs, with an annual mean of 15,840 cfs based on the period from October 1940 to December 2014. On an annual basis, the 80, 90, and 95 percentiles (or 20, 10, and 5 exceedance percentiles) are approximately 20,800, 32,400, and 44,700 cfs, respectively. These percentiles are commonly used to define "high flow" events. It is not unreasonable to assume that flows above these thresholds, especially the highest-end flows that approach or exceed 100,000 cfs, will mobilize large amounts of sediments and have the largest effect on mussel distributions.

The high end of FirstLight's operating range, or the discharge above which FirstLight has no control over water levels downstream from Cabot Station, is approximately 15,938 cfs[1], which equals the combined hydraulic capacity of Cabot Station and Station No. 1. This corresponds to approximately the 71 percentile, or the 29 exceedance percentile. This is less than half of the 90 percentile (or 10 exceedance percentile) of 32,400 cfs. Existing studies and feedback from Delphi panelists suggest that high-flow SS and RSS are the most relevant for mussel habitat, and based on Connecticut River flow data, these high-flows occur well outside of the operating range of the Turners Falls Project. If a binary HSI for SS and RSS was established,

[1] The power canal has a design capacity of approximately 18,000 cfs. There are several entities that can withdraw water from the canal.

the threshold would likely be based on conditions at a discharge at least 15,000 cfs higher than FirstLight's operating range. Although this does not discount the validity of the HSI development process, it does suggest that binary HSI for SS and RSS will provide no insight into the effects of FirstLight's flow operations on mussels or mussel habitat, at least on the coarse scale that we are currently working on. Also, since direct measurements of key parameters (water depth, flow velocity, etc.) are impossible to obtain at highest flows, they must be modeled, and there are limits to how well, and at what resolution, hydraulic models can reliably predict these parameters at the highest end of the flow range.

3.6 Summary and Next Steps

Based on information presented in this report and in the summary documents circulated as part of the second and third rounds of the Delphi process, and feedback from Delphi panelists, the objective of establishing an evidence-based and biologically meaningful HSI for SS or RSS is not achievable at this time with the previously stated data limitations. At this point, FirstLight intends to use the HSI for which the Delphi panelists have reached consensus (water depth, flow velocity, and substrate). These will be used in the IFIM study in the same way that the HSI for fish species are used. Based on the outputs of the IFIM, FirstLight will analyze the potential effects of flow operations on the three target mussel species and their habitat. At that point, FirstLight will consider the SS and RSS parameters as potential constraints or limiting factors.

This report concludes the Delphi process. The binary HSI values reflect the expert opinion of four panelists and are supported by literature and field observations. These binary values will now be used in the IFIM Study (Study 3.3.1) to assess the potential effects of flows and flow fluctuations on these mussel species in the study area.

Table 3-1: Binary HSI Scores for Three Massachusetts State-Listed Mussel Species (metric units)

Parameter		Yellow Lampmussel		Eastern Pondmussel		Tidewater Mucket	
		Juvenile	Adult	Juvenile	Adult	Juvenile	Adult
Class	**Benthic Velocity Range (m/s)**						
1	<0.05	1	1	1	1	1	1
2	0.05 - 0.10	1	1	1	1	1	1
3	0.11 - 0.20	1	1	1	1	1	1
4	0.21 - 0.30	1	1	1	1	1	1
5	0.31 - 0.40	1	1	1	1	1	1
6	0.41 - 0.50	1	1	1	1	1	1
7	0.51 - 0.75	0	1	0	0	0	1
8	0.76 - 1.00	0	0	0	0	0	0
9	1.01 - 1.50	0	0	0	0	0	0
10	1.51 - 2.00	0	0	0	0	0	0
11	>2.0	0	0	0	0	0	0
Class	**Water Depth Range (m)**						
1	0	0	0	0	0	0	0
2	0.01 - 0.10	0	0	0	0	0	0
3	0.11 - 0.25	1	1	1	1	1	1
4	0.26 - 0.50	1	1	1	1	1	1
5	0.51 - 0.75	1	1	1	1	1	1
6	0.76 - 1.00	1	1	1	1	1	1
7	1.01 - 1.50	1	1	1	1	1	1
8	1.51 - 2.00	1	1	1	1	1	1
9	2.01 - 3.00	1	1	1	1	1	1
10	3.01 - 4.00	1	1	1	1	1	1
11	>4.00	1	1	1	1	1	1
Class	**Particle Size**						
1	Organic Material	0	0	0	0	0	0
2	Clay	0	0	0	0	0	0
3	<0.062 mm [mud/silt]	1	1	1	1	1	1
4	0.062 - 2.0 mm [sand]	1	1	1	1	1	1
5	2.0 - 32.0 mm [fine gravel]	1	1	1	1	1	1
6	32.0 - 64.0 mm [coarse gravel]	1	1	0	1	1	1
7	64.0 - 150.0 mm [small cobble]	1	1	0	0	0	0
8	150.0 - 250.0 mm [large cobble]	0	0	0	0	0	0
9	250.0 - 4,000 mm [boulder]	0	0	0	0	0	0
10	Bedrock	0	0	0	0	0	0
Class	**Percent Cover**						
1	0	1	1	1	1	1	1
2	1 - 10.0%	1	1	1	1	1	1
3	10.1 - 25.0%	1	1	1	1	1	1
4	26.1 - 50.0%	1	1	1	1	1	1
5	50.1 - 75.0%	1	1	1	1	1	1
6	75.1 - 100%	1	0	1	1	1	0

Table 3-2: Binary HSI Scores for Three Massachusetts State-Listed Mussel Species (standard units)

Parameter		Yellow Lampmussel		Eastern Pondmussel		Tidewater Mucket	
		Juvenile	Adult	Juvenile	Adult	Juvenile	Adult
Class	**Benthic Velocity Range (ft/s)**						
1	<0.16	1	1	1	1	1	1
2	0.16-0.34	1	1	1	1	1	1
3	0.35-0.67	1	1	1	1	1	1
4	0.68-0.99	1	1	1	1	1	1
5	1.00-1.32	1	1	1	1	1	1
6	1.33-1.65	1	1	1	1	1	1
7	1.66-2.47	0	1	0	0	0	1
8	2.48-3.29	0	0	0	0	0	0
9	3.30-4.93	0	0	0	0	0	0
10	4.94-6.56	0	0	0	0	0	0
11	>6.56	0	0	0	0	0	0
Class	**Water Depth Range (feet)**						
1	0	0	0	0	0	0	0
2	0.03-0.34	0	0	0	0	0	0
3	0.35-0.83	1	1	1	1	1	1
4	0.84-1.65	1	1	1	1	1	1
5	1.66-2.47	1	1	1	1	1	1
6	2.48-3.29	1	1	1	1	1	1
7	3.30-4.93	1	1	1	1	1	1
8	4.94-6.56	1	1	1	1	1	1
9	6.57-9.85	1	1	1	1	1	1
10	9.86-13.12	1	1	1	1	1	1
11	>13.12	1	1	1	1	1	1
Class	**Particle Size**						
1	Organic Material	0	0	0	0	0	0
2	Clay	0	0	0	0	0	0
3	<0.002 in [mud/silt]	1	1	1	1	1	1
4	0.002 – 0.08 in. [sand]	1	1	1	1	1	1
5	0.08- 1.26 in. [fine gravel]	1	1	1	1	1	1
6	1.26 – 2.52 in. [coarse gravel]	1	1	0	1	1	1
7	2.52 – 5.90 in. [small cobble]	1	1	0	0	0	0
8	5.90 – 9.84 in. [large cobble]	0	0	0	0	0	0
9	9.84 – 157.5 in. [boulder]	0	0	0	0	0	0
10	Bedrock	0	0	0	0	0	0
Class	**Percent Cover**						
1	0	1	1	1	1	1	1
2	1 - 10.0%	1	1	1	1	1	1
3	10.1 - 25.0%	1	1	1	1	1	1
4	26.1 - 50.0%	1	1	1	1	1	1
5	50.1 - 75.0%	1	1	1	1	1	1
6	75.1 - 100%	1	0	1	1	1	0

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APPENDIX A – CORRESPONDENCE

From: Ethan Nedeau <ethan@biodrawversity.com>
Sent: Wednesday, February 04, 2015 4:54 PM
To: Hazelton, Peter (FWE)
Cc: Jason George
Subject: HSI development for FirstLight
Attachments: Delphi Technique Paper.pdf

Hi Pete,
As you know, FirstLight is planning to develop habitat suitability criteria for yellow lampmussels, tidewater muckets, and eastern pondmussels using available data and expert opinion. The Delphi technique will be used; I have attached a paper describing the technique. Our proposed approach is to work with NHESP to identify regional experts, develop some of the background information and the questionnaire for the Delphi panel, work through the Delphi process, and finalize criteria. I expect to do much of this work but would greatly value any assistance you can provide, and any time that DFG will allow you to work on this project.

I was hoping we could utilize the remaining off-season to do the bulk of this work. Please let me know your availability to assist with this project, and when we might meet (or talk on the phone) to kick this off. My understanding is that I can work collaboratively with you and others on the Delphi panel, with oversight from Gomez & Sullivan (esp. Jason George), rather than communicating indirectly via the more cumbersome FERC process.

As a reminder of the process outlined in the FERC-approved study plan, this is basically what was presented at today's meeting in Greenfield.

FirstLight will develop Habitat Suitability Index (SI) criteria. These will be a hydrid of Category 1 (qualitative) and Category II (quantitative, using empirical data). SI criteria will be developed by analyzing existing data, soliciting input from regional experts, and the Delphi technique.

Species: Yellow Lampmussel (*Lampsilis cariosa*), Tidewater Mucket (*Leptodea ochracea*), Eastern Pondmussel (*Ligumia nasuta*)

Approach

- Gather, review, and synthesize available information on the distribution and habitat preference of target species in the project area. Sources: journal articles, government and consultant reports, case studies and insight from regional experts, and field data collected in 2014.

- Based on available information, draft SI criteria framework for key parameters for each species, and provide a written rationale for each criterion. Draft a questionnaire to solicit opinion of regional experts.

- Identify regional experts willing to be part of the Delphi panel. Provide each with background information and the questionnaire.

- Fine-tune, omit, or add SI criteria based on responses from the Delphi panel. Summarize the first round of responses, and send a new draft of SI criteria to the Delphi panel for final review and to resolve any outstanding issues raised during the first round.

- All sources of information, the process used to develop the final SI criteria, and the final SI criteria will be summarized in a written document and submitted to stakeholders for final review.

Many Thanks,
Ethan

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**New Address
Ethan Nedeau, Biodrawversity LLC
206 Pratt Corner Road, Leverett, MA 01054
Cell: (413) 253-6561 / Email: nedeau.ethan@gmail.com
Website: www.biodrawversity.com

From: Hazelton, Peter (FWE) <peter.hazelton@state.ma.us>
Sent: Friday, February 06, 2015 3:09 PM
To: Ethan Nedeau
Cc: Jason George; Leddick, Jesse (FWE)
Subject: RE: HSI development for FirstLight

Ethan,

Thank you for the invitation to collaborate on the Delphi panel. I think that this will be a useful approach moving forward and I look forward to being involved, but cannot say yet to what level that will be. I am leaving for a week of vacation today, and will have to discuss the opportunity with my superiors once I return after President's Day. In the meantime, please see an initial list of potential invitees for the Delphi panel, I look forward to discussing these further.

- David Smith – USGS https://profile.usgs.gov/drsmith
- David Strayer – Cary Institute of Ecosystem Studies http://www.caryinstitute.org/science-program/our-scientists/dr-david-l-strayer
- Steve Johnson & Sean Werle – New England Environmental, Inc. http://www.neeinc.com/about/people/steve-johnson/
- Heather Galbraith – USGS https://profile.usgs.gov/hgalbraith
- Cynthia Loftin – USGS Maine Cooperative Research Unit http://www.coopunits.org/Maine/People/Cyndy_Loftin/index.html
- Paul Lord – SUNY Oneonta http://www.oneonta.edu/academics/biology/faculty/lord.asp
- Matthew Ashton – Maryland Department of Natural Resources http://www.dnr.state.md.us/streams/profiles.asp
- John Alderman – Alderman Environmental Services, Inc. - https://sites.google.com/site/aldermanenvironmentalservices/home

From: Ethan Nedeau <ethan@biodrawversity.com>
Sent: Friday, November 13, 2015 10:10 AM
To: Hazelton, Peter (FWE); Jason George
Subject: Delphi, round 1
Attachments: Delphi Questionnaire.xlsx; Introduction and Instruction.docx

Hi Pete,
I have attached a draft questionnaire and cover letter/instruction for the first Delphi round. Jason George is going to be the moderator and I am going to complete the questionnaire in the same way as, and independent from, other panelists. I think this will help ensure that I don't exert too strong an influence over the responses from other panelists at the outset. One important aspect of the Delphi process that was not discussed much when we proposed it is anonymity, or at least independence, of the panelists to be sure the process is not overly biased. Once the first round responses are reviewed, we can decide the best approach to round 2.

For the Delphi panel, we are focusing on HSC that can be used in the hydraulic models (hydraulic variables that change with discharge). Panelists have the opportunity to suggest, and provide information on, parameters that we did not include.

Please look this over, send back any suggestions, and we will try to get this out to panelists soon after we get your response.

-Ethan

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**New Address
Ethan Nedeau, Biodrawversity LLC
206 Pratt Corner Road, Leverett, MA 01054
Cell: (413) 253-6561 / Email: nedeau.ethan@gmail.com
Website: www.biodrawversity.com

From:	Ethan Nedeau <ethan@biodrawversity.com>
Sent:	Friday, November 13, 2015 12:47 PM
To:	Hazelton, Peter (FWE)
Cc:	Jason George; Leddick, Jesse (FWE); Gary Lemay
Subject:	Re: Delphi, round 1

Thanks! Good idea to use the work "suitability" instead of "importance". I don't know why I switched that originally. Also, for shear stress and relative shear stress, we considered further dividing that into two categories: Low Flow (LF), so LF-SS and LF-RSS and High Flow (HF), so HF-SS and HF-RSS. Parameters will be analyzed across a range of flows, and some research has suggested that its the high-flow shear that is more important. Not sure if its critical to specify LF and HF in the questionnaire, or just leave it as is and see what kind of responses we get.

-Ethan

On Fri, Nov 13, 2015 at 12:23 PM, Hazelton, Peter (FWE) <Peter.Hazelton@massmail.state.ma.us> wrote:

Ethan & Jason,

These look really good. The only suggestion I have is a little more direction in the instructions (See track changes in the attached copy).

Also, regarding the shear variables: I understand the need to be more open ended in the approach to value ranges, but it is not clear what the ranking of importance is. For example, if low shear stress is "Important" does that mean it is protective of habitat (i.e. suitable) or less suitable? One might say that the High and Low shear stress are both important, but one has a negative relationship with juvenile density and the other has a positive relationship with juvenile density. Perhaps changing "Importance" to "Suitability" would provide more consistent results.

Pete

From: Jason George
Sent: Tuesday, January 26, 2016 12:16 PM
To: Hazelton, Peter (FWE)
Cc: Ethan Nedeau
Subject: Turners Falls Project - Mussel HSI curves - DRAFT Round 2
Attachments: RSS and Mussels_NHESP.docx; FL Delphi_Round 2.xlsx

Hi Pete, as discussed, attached is a draft of the Round 2 package for the mussel HSI curves development for the Turners Falls Project. It includes a memo regarding the shear stress parameters and an excel sheet with proposed criteria summarizing the panelists' Round 1 responses.

If you could let me know if you have any comments on the attached by Wednesday of next week, I'd appreciate it. The next step is to send this package out to the panelists to get concurrence on the HSIs.

If you have any questions, feel free to contact me, thanks.

Jason George
Environmental Scientist
Gomez and Sullivan Engineers, DPC
PO Box 2179
Henniker, NH 03242
Office: (603) 428-4960
Cell: (603) 340-7666
jgeorge@gomezandsullivan.com

From:	Hazelton, Peter (FWE) <Peter.Hazelton@MassMail.State.MA.US>
Sent:	Tuesday, February 02, 2016 1:58 PM
To:	Jason George
Cc:	Leddick, Jesse (FWE); Marold, Misty-Anne (FWE)
Subject:	RE: Turners Falls Project - Mussel HSI curves - DRAFT Round 2
Attachments:	Copy of FL Delphi_Round 2_20160201.xlsx; Round1_RSS and Mussels_NHESP_ 20160201.docx

Jason,

In general, the Delphi process appears to be moving forward and going well. We have a few suggestions regarding the draft materials to be forwarded to panelists for Round 2 review.

1. I noted at least two instances (see comments on the spreadsheet) where the proposed binary value (suitability value) does not match up with the composite or averaged values, and there is no explanation given. Please correct or, if these represent instances where FirstLight is proposing to deviate from the value derived from the Delphi data, include a discussion on why FirstLight is proposing to deviate, provide citations and justification for the deviation, and ask for further input/confirmation from panelists.

2. In the proposed methods, there were importance values to be assigned to each variable by the panelists. These were not summarized in the data provided here. I recommend that these be summarized in the data sent to panelists, including any proposal by FirstLight regarding the use of those importance values to inform HSI development and binary values.

3. We would suggest that any data or references used by panelists in making their decisions and/or recommendations be catalogued in an appendix provided to all panelists. This should facilitate greater access to references and information among the panelists, and in the end, a more informed result. Similarly, when the Delphi is concluded and FirstLight is pulling together study plan reports, we would also request that data/references – plus all panelist responses - be included as an appendix to the report to insure transparency and access to supporting materials.

4. It appears that FirstLight would like to use a composite HSI for all three species, and for both lifestages (juveniles and adults). This rasises significant concerns and appears inconsistent with other taxa.

For example, if habitat is suitable for an adult mussel within the upper reaches of the project area, but not suitable for a juvenile, then the habitat is likely not suitable for the population as a whole given that there will be no recruitment or retention of juveniles. This is exactly why fish are modeled at larval, juvenile, adult and even spawning stages to understand and represent the variation in habitat suitability within members of a population. Further, composite HSIs seem inconsistent with feedback from the Delphi panel, as panelist responses suggest variation in the tolerance to parameters across species and lifestages. Habitat modeling should be conducted separately for each species and lifestage. Alternatively, if a composite is proposed, it should be protective of the most vulnerable species/lifestage based on preliminary modeling of each life-stage.

Although the above comment applies primarily to subsequent modeling of the data, we would also suggest outlining this proposal in draft materials forwarded to panelists for Round 2 review and comment. We also propose additional consultation between the Division and FirstLight on this point. This might be a great opportunity to discuss and come to agreement on a mutually acceptable solution in advance of submitting study plan reports next month.

Pete

APPENDIX B – ROUND 1 INSTRUCTIONS TO DELPHI PANEL

Instructions

Consider the relationships between habitat suitability for the three target species and two life stages (juvenile and adult) and each of the seven variables: water depth, water velocity, substrate, cover, shear stress, and relative shear stress. Information you provide will help form the basis of preliminary HSC, which will then be presented for consideration in Round 2.

Complete the tables in the each of the worksheets. For each species and lifestage, provide a corresponding suitability score from the table on the left of the scoring table at each variable level. Provide a confidence score (High, Medium, Low) for each lifestage depending on your personal level of certainty in suitability estimation.

Please note that for the two parameters related to shear, the questionnaire is more open-ended as we attempt to gather general information on these parameters and also consider both the limitations of the hydraulic models that will be used and the specific environmental conditions within the geographic scope of the study.

There are fields for you to list references, data sources, or any information that you wish to use as a basis of your suitability rankings. Also include any comments, ideas, logic, etc. It is important that you use your “gut feeling” or opinion, even if no empirical data are available. You may choose to ignore all available data or information, and use only your “gut feeling: or opinion as the basis of your responses. If you mention a reference, please give the complete citation and send the monitor a copy, unless it is readily available online.

If you feel that a parameter or a life stage other than those list are important, and should be considered for an HSC, please clearly define it, explain how the parameter is quantified, and provide any supplemental information.

Parameter: **Flow Velocity**

Definition: Flow velocity refers to benthic (or "nose') velocity that mussels are subjected to. Other velocity measurements (e.g., mean column velocity, surface velocity) are sometimes measured/reported. Please specify what you mean by velocity when providing suitability scores. Feel free to provide any thoughts on available velocity data, relationship to mussels, or considerations that would not be captured in this questionnaire.

Expert:		Date:	

	HS Score	Description
<< Increasing Suitability <<	0.0	Entirely Unsuitable
	0.1	
	0.2	
	0.3	
	0.4	
	0.5	Moderate Suitability
	0.6	
	0.7	
	0.8	
	0.9	
	1.0	Perfectly Suitable
Confidence	H	High
	M	Medium
	L	Low

		L. cariosa		*L. ochracea*		*L. nasuta*	
Class	Velocity Range (m/s)	Juvenile	Adult	Juvenile	Adult	Juvenile	Adult
1	<0.05						
2	0.05 - 0.10						
3	0.11 - 0.20						
4	0.21 - 0.30						
5	0.31 - 0.40						
6	0.41 - 0.50						
7	0.51 - 0.75						
8	0.76 - 1.00						
9	1.01 - 1.50						
10	1.51 - 2.00						
11	>2.0						
Confidence about species/stage							

Notes, Qualifiers, etc..

List case studies, publications, or datasets upon which the scoring was based.

#	Species	River/Lake	Project Name	Information Available?

More Notes, Comments, etc.

Parameter: **Water Depth**

Definition: Depth where individual mussels or mussel beds occur. Please indicate reason(s) for low or high suitability. Feel free to provide any thoughts on available depth data, relationship to mussels, or considerations that would not be captured in this questionnaire.

Expert:		Date:	

	HS Score	Description
<< Increasing Suitability <<	0.0	Entirely Unsuitable
	0.1	
	0.2	
	0.3	
	0.4	
	0.5	Moderate Suitability
	0.6	
	0.7	
	0.8	
	0.9	
	1.0	Perfectly Suitable
Confidence	H	High
	M	Medium
	L	Low

		L. cariosa		*L. ochracea*		*L. nasuta*	
Class	Depth Range (m)	Juvenile	Adult	Juvenile	Adult	Juvenile	Adult
1	0						
2	0.01 - 0.10						
3	0.11 - 0.25						
4	0.26 - 0.50						
5	0.51 - 0.75						
6	0.76 - 1.00						
7	1.01 - 1.50						
8	1.51 - 2.00						
9	2.01 - 3.00						
10	3.01 - 4.00						
11	>4.00						
Confidence about species/stage							

Notes, Qualifiers, etc..

List case studies, publications, or datasets upon which the scoring was based.

#	Species	River/Lake	Project Name	Information Available?

More Notes, Comments, etc.

Parameter: **Substrate**

Definition: Substrate is specifically what mussels burrow in and generally where they spend their lives (recognizing limited mobility), and refers to dominant particle sizes in the top ~10cm of the river/lake bottom. If you choose to consider substrate in an alternate or additional way, please provide the rationale for that. Please indicate reason(s) for low or high suitability. Feel free to provide any thoughts on available substrate data, relationship to mussels, or considerations that would not be captured in this questionnaire.

Expert:		Date:	

	HS Score	Description
<< Increasing Suitability <<	0.0	Entirely Unsuitable
	0.1	
	0.2	
	0.3	
	0.4	
	0.5	Moderate Suitability
	0.6	
	0.7	
	0.8	
	0.9	
	1.0	Perfectly Suitable
Confidence	H	High
	M	Medium
	L	Low

			L. cariosa		*L. ochracea*		*L. nasuta*	
Class	**Substrate Name**	**Particle Size**	**Juvenile**	**Adult**	**Juvenile**	**Adult**	**Juvenile**	**Adult**
1	Organic Material							
2	Mud/Clay							
3	Silt	<0.062 mm						
4	Sand	0.062 - 2.0 mm						
5	Fine Gravel	2.0 - 32.0 mm						
6	Coarse Gravel	32.0 - 64.0 mm						
7	Small Cobble	64.0 - 150.0 mm						
8	Large Cobble	150.0 - 250.0 mm						
9	Boulder	250.0 - 4,000 mm						
10	Bedrock							
Confidence about species/stage								

Notes, Qualifiers, etc..

List case studies, publications, or datasets upon which the scoring was based.

#	Species	River/Lake	Project Name	Information Available?
1				
2				
3				
4				
5				

More Notes, Comments, etc.

Parameter: **Cover**

Definition: Cover is any feature that can provide reduced lighting, reduced flow velocity, increased isolation; something that mussels can get under or behind. It may be important to host fish, which would in turn influence habitat suitability for mussels. If you choose to consider cover in an alternate or additional way, please provide the rationale for that. Please indicate reason(s) for low or high suitability. Feel free to provide any thoughts on cover, relationship to mussels or host fish, or considerations that would not be captured in this questionnaire.

Expert:		Date:	

	HS Score	Description
<< Increasing Suitability <<	0.0	Entirely Unsuitable
	0.1	
	0.2	
	0.3	
	0.4	
	0.5	Moderate Suitability
	0.6	
	0.7	
	0.8	
	0.9	
	1.0	Perfectly Suitable
Confidence	H	High
	M	Medium
	L	Low

			L. cariosa		*L. ochracea*		*L. nasuta*	
Cover Type	Cover Class	Percent Cover	Juvenile	Adult	Juvenile	Adult	Juvenile	Adult
Aq. Vegetation	1	0						
	2	1 - 10.0%						
	3	10.1 - 25.0%						
	4	26.1 - 50.0%						
	5	50.1 - 75.0%						
	6	75.1 - 100%						
Coarse Wood	1	0						
	2	1 - 10.0%						
	3	10.1 - 25.0%						
	4	26.1 - 50.0%						
	5	50.1 - 75.0%						
	6	75.1 - 100%						
Detritus	1	0						
	2	1 - 10.0%						
	3	10.1 - 25.0%						
	4	26.1 - 50.0%						
	5	50.1 - 75.0%						
	6	75.1 - 100%						
Coarse Rock	1	0						
	2	1 - 10.0%						
	3	10.1 - 25.0%						
	4	26.1 - 50.0%						
	5	50.1 - 75.0%						
	6	75.1 - 100%						
Confidence about species/stage								

Notes, Qualifiers, etc..

List case studies, publications, or datasets upon which the scoring was based.

#	Species	River/Lake	Project Name	Information Available?
1				
2				
3				
4				
5				

More Notes, Comments, etc.

Parameter: **Shear Stress and Relative Shear Stress (RSS)**

Definition: Shear stress is the force exerted on the streambed by water per unit area of streambed, and is reflective of the stream's flow intensity and its ability to entrain and transport sediment particles. Relative shear stress is the ratio of observed to critical shear stress; critical shear stress is the shear stress that is required to initiate movement for a given particle size.Typically the particle size associated with RSS calculations is the bed's median particle size (i.e., D50) (Allen and Vaughn 2010).

Expert:	

Date:	

	Rank	Description
Suitability	0.0	Not Suitable
	0.5	Moderately Suitable
	1.0	Perfectly Suitable
Confidence	H	High
	M	Medium
	L	Low

			L. cariosa		*L. ochracea*		*L. nasuta*	
Cover Type	**Class**	**Range**	**Juvenile**	**Adult**	**Juvenile**	**Adult**	**Juvenile**	**Adult**
Shear Stress	Low	to be determined						
	Medium	to be determined						
	High	to be determined						
RSS	Low	to be determined						
	Medium	to be determined						
	High	to be determined						
Confidence about species/stage								

Notes, Qualifiers, etc..

List case studies, publications, or datasets particularly relevant to shear.

#	Species	River/Lake	Project Name	Information Available?
1				
2				
3				
4				
5				

More Notes, Comments, etc.

APPENDIX C – DELPHI PANEL ROUND 2 MATERIALS

Instructions

Based on Round 1 responses, we have developed draft binary HSI curves for water depth, benthic water velocity, substrate, and cover.

Binary means that the final suitability score is either 0 or 1. In general, if the composite score from Delphi panelists for a each value/range for each parameter was less than 0.5, the resulting binary score was 0.0, and otherwise the binary score was 1.0. We deviated from this in some instances, and these are noted on the attached summaries for your consideration.

We aimed to develop separate curves for juveniles and adults. In some cases, the binary curves for juveniles and adults came out identical. The curves for the three species were quite similar, which is not unexpected considering that they all seem to prefer similar types of habitats.

Please note that for the two parameters related to shear, we are seeking additional input from panelists before proposing specific numeric criteria. Please see the attached summary (Word document) on shear stress and relative shear stress to understand the types of challenges we are considering for these parameters.

For Round 2, we ask that you review the individual panelists scores, proposed binary scores, and the moderator's notes on the proposed HSI curves (at the bottom of the Summary sheet). There is space for you to add additional comments (yellow shaded fields).

If you feel the curves are incorrect and need to be adjusted, please provide specific recommendations and a rationale. Please list references, data sources, or any information for modifications to the proposed binary curves.

The citations that panelists provided are compiled in the Information sheet, and specific comments that panelists provided are in the Comments sheet. Please review these.

If you feel that we are still missing a key parameter that should be considered for an HSI, please clearly define it, explain how the parameter is quantified, and provide any supplemental information.

Summary of Proposed HSI Curves

J = juvenile, A = adult.

A combined J+A binary curve is only proposed if the separate juvenile and adult binary curves were identical.

Grey highlighting: proposed final HSI Curve for that species, life stage, or in some cases combined.

Shear Stress and Relative Shear Stress curves are still tentative based on Round 2 feedback.

				Lampsilis cariosa					*Ligumia nasuta*					*Ligumia nasuta*				
Parameter	**Class**	**Benthic Velocity Range (m/s)**		**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**
Flow Velocity	1	<0.05		1.00	1.00	1.00	1.00	-	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-
Flow Velocity	2	0.05 - 0.10		1.00	1.00	1.00	1.00	-	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-
Flow Velocity	3	0.11 - 0.20		1.00	1.00	1.00	1.00	-	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-
Flow Velocity	4	0.21 - 0.30		0.90	1.00	1.00	1.00	-	0.90	1.00	1.00	1.00	1.00	0.90	1.00	1.00	1.00	-
Flow Velocity	5	0.31 - 0.40		0.75	1.00	1.00	1.00	-	0.75	1.00	1.00	1.00	1.00	0.75	1.00	1.00	1.00	-
Flow Velocity	6	0.41 - 0.50		0.75	1.00	0.90	1.00	-	0.70	1.00	0.90	1.00	1.00	0.70	1.00	0.90	1.00	-
Flow Velocity	7	0.51 - 0.75		0.40	0.00	0.50	1.00	-	0.30	0.00	0.35	0.00	0.00	0.60	0.00	0.70	1.00	-
Flow Velocity	8	0.76 - 1.00		0.30	0.00	0.40	0.00	-	0.20	0.00	0.30	0.00	0.00	0.55	0.00	0.60	0.00	-
Flow Velocity	9	1.01 - 1.50		0.20	0.00	0.30	0.00	-	0.10	0.00	0.10	0.00	0.00	0.20	0.00	0.25	0.00	-
Flow Velocity	10	1.51 - 2.00		0.10	0.00	0.20	0.00	-	0.10	0.00	0.00	0.00	0.00	0.20	0.00	0.10	0.00	-
Flow Velocity	11	>2.0		0.00	0.00	0.10	0.00	-	0.10	0.00	0.00	0.00	0.00	0.10	0.00	0.10	0.00	-
Parameter	**Class**	**Water Depth Range (m)**		**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**
Water Depth	1	0		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water Depth	2	0.01 - 0.10		0.65	0.00	0.65	0.00	0.00	0.60	0.00	0.65	0.00	0.00	0.65	0.00	0.65	0.00	0.00
Water Depth	3	0.11 - 0.25		0.75	1.00	0.75	1.00	1.00	0.80	1.00	0.85	1.00	1.00	0.80	1.00	0.85	1.00	1.00
Water Depth	4	0.26 - 0.50		0.90	1.00	1.00	1.00	1.00	0.90	1.00	1.00	1.00	1.00	0.90	1.00	1.00	1.00	1.00
Water Depth	5	0.51 - 0.75		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Water Depth	6	0.76 - 1.00		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Water Depth	7	1.01 - 1.50		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Water Depth	8	1.51 - 2.00		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Water Depth	9	2.01 - 3.00		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Water Depth	10	3.01 - 4.00		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Water Depth	11	>4.00		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Parameter	**Class**	**Particle Size**	**Substrate Name**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**
Substrate	1		Organic Material	0.00	0.00	0.10	0.00	0.00	0.10	0.00	0.25	0.00	-	0.10	0.00	0.10	0.00	0.00
Substrate	2		Mud/Clay	0.25	1.00	0.40	1.00	1.00	0.70	1.00	0.70	1.00	-	0.75	1.00	0.80	1.00	1.00
Substrate	3	<0.062 mm	Silt	0.60	1.00	0.65	1.00	1.00	0.90	1.00	0.90	1.00	-	0.90	1.00	0.90	1.00	1.00
Substrate	4	0.062 - 2.0 mm	Sand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	1.00	1.00	1.00	1.00	1.00
Substrate	5	2.0 - 32.0 mm	Fine Gravel	0.90	1.00	1.00	1.00	1.00	0.90	1.00	1.00	1.00	-	0.90	1.00	1.00	1.00	1.00
Substrate	6	32.0 - 64.0 mm	Coarse Gravel	0.65	1.00	0.80	1.00	1.00	0.40	0.00	0.50	1.00	-	0.70	1.00	0.90	1.00	1.00
Substrate	7	64.0 - 150.0 mm	Small Cobble	0.55	1.00	0.60	1.00	1.00	0.25	0.00	0.30	0.00	-	0.25	0.00	0.45	0.00	0.00
Substrate	8	150.0 - 250.0 mm	Large Cobble	0.25	0.00	0.25	0.00	0.00	0.25	0.00	0.25	0.00	-	0.25	0.00	0.35	0.00	0.00
Substrate	9	250.0 - 4,000 mm	Boulder	0.10	0.00	0.10	0.00	0.00	0.20	0.00	0.10	0.00	-	0.20	0.00	0.10	0.00	0.00
Substrate	10		Bedrock	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.10	0.00	-	0.00	0.00	0.00	0.00	0.00
Parameter	**Class**	**Percent Cover**		**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**
Cover	1	0		1.00	1.00	1.00	1.00	-	0.90	1.00	0.80	1.00	1.00	1.00	1.00	1.00	1.00	-
Cover	2	1 - 10.0%		1.00	1.00	1.00	1.00	-	0.95	1.00	0.90	1.00	1.00	1.00	1.00	1.00	1.00	-
Cover	3	10.1 - 25.0%		0.75	1.00	0.75	1.00	-	0.50	1.00	0.50	1.00	1.00	0.80	1.00	1.00	1.00	-
Cover	4	26.1 - 50.0%		0.50	1.00	0.50	1.00	-	0.50	1.00	0.50	1.00	1.00	0.50	1.00	0.60	1.00	-
Cover	5	50.1 - 75.0%		0.35	1.00	0.30	1.00	-	0.50	1.00	0.50	1.00	1.00	0.50	1.00	0.35	1.00	-
Cover	6	75.1 - 100%		0.10	1.00	0.00	0.00	-	0.40	1.00	0.40	1.00	1.00	0.50	1.00	0.10	0.00	-
Parameter		**Class**		**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**
Shear Stress	SS	Low		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Medium		0.70	1.00	0.90	1.00	1.00	0.75	1.00	0.75	1.00	1.00	0.70	1.00	0.75	1.00	1.00
		High		0.10	0.00	0.25	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.15	0.00	0.25	0.00	0.00
Relative SS	RSS	Low		1.00	1.00	1.00	1.00	-	1.00	1.00	1.00	1.00	-	1.00	1.00	1.00	1.00	-
		Medium		0.50	0.00	0.90	1.00	-	0.50	0.00	0.75	1.00	-	0.50	0.00	0.75	1.00	-
		High		0.00	0.00	0.10	0.00	-	0.00	0.00	0.25	0.00	-	0.00	0.00	0.25	0.00	-

Notes on Proposed HSI Curves

Benthic flow velocity: Since all three species live in lakes and ponds, and in slow, depositional environments in rivers, no flow (velocity = 0) is considered optimal. There was general agreement of declining suitability with increasing velocity, although this may be related more to substrate stability rather than physiological adaptation to living in faster water. All three species have been found in small rivers in moderate to high flow velocities; yellow lampmussels in particular have been found in fast flows in Maine (examples: Penobscot River, Passadumkeag River, Mattawamkeag River) and in Pennsylvania (Susquehanna River) although usually in deep runs or pools rather than in riffles. Eastern pondmussels have also been found in high numbers in small to moderate-sized rivers, such as Mill River (MA), Farmington River (CT), several rivers in southeastern MA. In these faster-flowing rivers, they are usually found closer to streambanks and other refugia, yet in close proximity to fast flows. Tidewater muckets have also been found in a wide range of stream sizes and flow velocities, but generally seem to occur in flow refugia and depositional environments within those rivers that have a wide range of flow velocities. For the purposes of the proposed HSI curve, although we recognize that there will be wide variation and opinions on habitat suitability at the upper end of flow values (i.e., approaching and exceeding 1 m/s), we base the final proposed curve on the effects of flows on mobilizing the fine-grained particles that all three species tend to prefer, rather than on any physiological stress imposed by strong flows.

Feedback from Panelist (attach any files or supporting evidence, as needed):

Substrate: There was general agreement that the optimal substrates for all three species was fine-grained material such as silt, sand, and fine gravel. This is generally supported by field observations throughout each species' range in a wide variety of habitats (lakes, ponds, small and large rivers). Although organic material/detritus is an important component of the substrate, we generally believe that areas where organic material is the dominant substrate (such as accumulations of leaves, senescent vegetation, detritus) are not ideal for any of the species. This may be due to a poor environment for burrowing or remaining upright, or poor chemical environment (i.e., low oxygen) in areas with dead/decaying organic material. For the proposed binary curve, organic material is considered unsuitable for all three species. Everything from mud/clay up to coarse gravel is considered suitable for all three species in the binary curve, even though suitability scores do begin to drop for eastern pondmussel and tidewater mucket at particle sizes larger than 32 mm. The proposed binary curve for yellow lampmussels is slightly different than for the other two species, as yellow lampmussels do seem to occur more often in coarser gravel, especially in rivers in Maine, Pennsylvania, and New York. Large cobble, boulder, and bedrock are not suitable for any species, although these coarser materials may sometimes be an essential component of a mussel bed because they help to anchor the substrate and stabilize finer-grained materials, and

Feedback from Panelist (attach any files or supporting evidence, as needed):

Water Depth: The only full consensus was that a water depth of zero is unsuitable! In general, it is assumed that mussels can persist and even thrive in very shallow water, as long as the shallow conditions do not lead to other stressors such as thermal stress or increased risk of predation. Of the three mussel species, eastern pondmussels are more apt to be found in very shallow water...in fact, there is even evidence that gravid females will migrate into extremely shallow water prior to release of glochidia, presumably to increase potential encounters with host fish. In the lower end of the Holyoke impoundment in the Connecticut River, eastern pondmussels were found almost exclusively in nearshore environments in depths less than 3 ft, usually within or upslope of dense beds of aquatic vegetation and coarse woody debris. In other rivers, such as Mill River (MA) and Farmington River (CT), eastern pondmussels were often found in only inches of water, within 1-2 ft of the water line. Likewise, tidewater muckets have been found within the intertidal zone, or just downslope, in the tidal portions of the Connecticut River, and they have also been found in high densities in less than a foot of water in lakes of southeastern Massachusetts. Nevertheless, for the binary curve, we do propose that anything less than 10 cm is unsuitable for all three species, mainly due to risks of existing in such a shallow environment. For the binary curve, we propose that everything greater than 10cm is optimal for all species. There is no evidence that there is an upper depth limit for any of these species. Depending on Round 2 feedback, we may propose a separate binary curve for yellow lampmussels with 0 for the third depth class, as yellow lampmussels seem to occur less often in extremely shallow water.

Feedback from Panelist (attach any files or supporting evidence, as needed):

Cover: Mussels do not seem to be particularly responsive to cover, and the type of cover (as we defined it in the Round 1 questionnaire) seems to not matter. All three species can exist within or near cover of all types, such as beds of submerged aquatic vegetation, coarse wood, steep banks with overhanging vegetation, and coarse rock. Based on the responses and considering habitat data from across each species' range, we consolidated all cover types. The binary curves for eastern pondmussel and tidewater mucket ended up being the same. Yellow lampmussels seem to not occur in areas with dense cover. Certainly within their range in the lower Connecticut River, yellow lampmussels have been found primarily in more open areas, whereas the other two species may be closer to or within cover such as SAV beds. Despite any minor modifications that could be made to these curves, we think its safe to conclude that cover will be less important than other parameters in assessing effects of flow operations on mussels.

Feedback from Panelist (attach any files or supporting evidence, as needed):

Shear Stress and Relative Shear Stress: Please see attached text document for more details.

Feedback from Panelist (attach any files or supporting evidence, as needed):It would be helpful if you added comments on the attached word document, which describes the challenges with these two parameters.

Yellow Lampmussel			Raw Scores										Juvenile				Adult					
			P1	P2	P3	P4	P5	P1	P2	P3	P4	P5										
Parameter	Class	Velocity Range (m/s)	J	J	J	J	J	A	A	A	A	A	Mean	Median	Curve**	Binary**	Mean	Median	Curve**	Binary**	J+A Binary**	Rationale for Noted Departure
Flow Velocity	1	<0.05	1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
Flow Velocity	2	0.05 - 0.10	1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
Flow Velocity	3	0.11 - 0.20	1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
Flow Velocity	4	0.21 - 0.30	1.0	0.8	0.7	1.0		1.0	1.0	1.0	1.0		0.88	0.90	0.90	1.00	1.00	1.00	1.00	1.00	-	
Flow Velocity	5	0.31 - 0.40	1.0	0.5	0.5	1.0		1.0	1.0	0.7	1.0		0.75	0.75	0.75	1.00	0.93	1.00	1.00	1.00	-	
Flow Velocity	6	0.41 - 0.50	1.0	0.5	0.3	1.0		1.0	1.0	0.5	1.0		0.70	0.75	0.75	1.00	0.88	1.00	0.90	1.00	-	
Flow Velocity	7	0.51 - 0.75	0.3	0.3	0.1	1.0		0.3	0.5	0.3	1.0		0.43	0.30	0.40	0.00	0.53	0.40	0.50	1.00	-	
Flow Velocity	8	0.76 - 1.00	0.3	0.1	0.0	1.0		0.3	0.3	0.1	1.0		0.35	0.20	0.30	0.00	0.43	0.30	0.40	0.00	-	
Flow Velocity	9	1.01 - 1.50	0.1	0.0	0.0	1.0		0.1	0.1	0.0	1.0		0.28	0.05	0.20	0.00	0.30	0.10	0.30	0.00	-	
Flow Velocity	10	1.51 - 2.00	0.1	0.0	0.0	1.0		0.1	0.0	0.0	1.0		0.28	0.05	0.10	0.00	0.28	0.05	0.20	0.00	-	
Flow Velocity	11	>2.0	0.1	0.0	0.0	0.6		0.1	0.0	0.0	0.6		0.18	0.05	0.00	0.00	0.18	0.05	0.10	0.00	-	
Parameter	**Class**	**Depth Range (m)**																				
Water Depth	1	0	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Water Depth	2	0.01 - 0.10	1.0	1.0	0.0	0.4		1.0	1.0	0.0	0.4		0.60	0.70	0.65	0.00	0.60	0.70	0.65	0.00	0.00	Although both juveniles and adults can survive in water less than 10cm, we consider this unsuitable due to risks of dessication, predation, etc.
Water Depth	3	0.11 - 0.25	1.0	1.0	0.0	0.8		1.0	1.0	0.0	0.8		0.70	0.90	0.75	1.00	0.70	0.90	0.75	1.00	1.00	
Water Depth	4	0.26 - 0.50	1.0	1.0	0.3	1.0		1.0	1.0	0.3	1.0		0.83	1.00	0.90	1.00	0.83	1.00	1.00	1.00	1.00	
Water Depth	5	0.51 - 0.75	1.0	1.0	0.7	1.0		1.0	1.0	0.7	1.0		0.93	1.00	1.00	1.00	0.93	1.00	1.00	1.00	1.00	
Water Depth	6	0.76 - 1.00	1.0	1.0	0.9	1.0		1.0	1.0	0.9	1.0		0.98	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	
Water Depth	7	1.01 - 1.50	1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	8	1.51 - 2.00	1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	9	2.01 - 3.00	1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	10	3.01 - 4.00	1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	11	>4.00	1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Parameter	**Class**	**Particle Size / Substrate Name**																				
Substrate	1	Organic Material	-	0.0	0.1	0.0		-	0.0	0.4	0.0		0.03	0.00	0.00	0.00	0.13	0.00	0.10	0.00	0.00	
Substrate	2	Mud/Clay	1.0	0.0	0.2	0.0		1.0	0.0	0.5	0.0		0.30	0.10	0.25	1.00	0.38	0.25	0.40	1.00	1.00	Observations from the range of waterbodies that yellow lampmussels inhabit suggest that both mud and clay are suitable substrates. Its not clear how different "mud" is from "silt". We welcome any ideas on this.
Substrate	3	<0.062 mm Silt	1.0	0.5	0.7	0.3		1.0	0.5	0.8	0.3		0.63	0.60	0.60	1.00	0.65	0.65	0.65	1.00	1.00	
Substrate	4	0.062 - 2.0 mm Sand	1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Substrate	5	2.0 - 32.0 mm Fine Gravel	1.0	0.5	1.0	1.0		1.0	1.0	1.0	1.0		0.88	1.00	0.90	1.00	1.00	1.00	1.00	1.00	1.00	
Substrate	6	32.0 - 64.0 mm Coarse Gravel	1.0	0.0	0.4	1.0		1.0	0.5	0.7	1.0		0.60	0.70	0.65	1.00	0.80	0.85	0.80	1.00	1.00	
Substrate	7	64.0 - 150.0 mm Small Cobble	1.0	0.0	0.1	1.0		1.0	0.3	0.2	1.0		0.53	0.55	0.55	1.00	0.63	0.65	0.60	1.00	1.00	
Substrate	8	150.0 - 250.0 mm Large Cobble	0.3	0.0	0.0	1.0		0.3	0.0	0.0	1.0		0.33	0.15	0.25	0.00	0.33	0.15	0.25	0.00	0.00	
Substrate	9	250.0 - 4,000 mm Boulder	0.1	0.0	0.0	1.0		0.1	0.0	0.0	1.0		0.28	0.05	0.10	0.00	0.28	0.05	0.10	0.00	0.00	
Substrate	10	Bedrock	0.1	0.0	0.0	0.0		0.1	0.0	0.0	0.0		0.03	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	
Parameter	**Class**	**Percent Cover**																				
Cover	1	0	-	1.0	1.0	1.0		-	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
Cover	2	1 - 10.0%	-	1.0	1.0	1.0		-	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	There is no evidence to suggest that dense cover is unsuitable for yellow lampmussels, especially for juveniles that tend to remain buried and can benefit from the flow refuge/stability that cover can provide.
Cover	3	10.1 - 25.0%	-	0.0	1.0	1.0		-	0.0	1.0	1.0		0.67	1.00	0.75	1.00	0.67	1.00	0.75	1.00	-	
Cover	4	26.1 - 50.0%	-	0.0	1.0	0.5		-	0.0	0.9	0.5		0.50	0.50	0.50	1.00	0.47	0.50	0.50	1.00	-	
Cover	5	50.1 - 75.0%	-	0.0	0.9	0.3		-	0.0	0.7	0.3		0.40	0.30	0.35	1.00	0.33	0.30	0.30	1.00	-	
Cover	6	75.1 - 100%	-	0.0	0.8	0.0		-	0.0	0.5	0.0		0.27	0.00	0.10	1.00	0.17	0.00	0.00	0.00	-	
Parameter																						
Shear Stress	SS	Low	1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
		Medium	1.0	0.0	0.5	1.0		1.0	1.0	0.5	1.0		0.63	0.75	0.70	1.00	0.88	1.00	0.90	1.00	1.00	
		High	0.3	0.0	0.0	0.5		0.3	0.0	0.0	1.0		0.20	0.15	0.10	0.00	0.33	0.15	0.25	0.00	0.00	
Relative SS	RSS	Low	1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
		Medium	1.0	0.0	0.5	0.5		1.0	1.0	0.5	1.0		0.50	0.50	0.50	0.00	0.88	1.00	0.90	1.00	-	
		High	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.5		0.00	0.00	0.00	0.00	0.13	0.00	0.10	0.00	-	

*P = Panelists (1-5); still waiting on scores for Panelist 5. J = Juvenile. A = Adult

**The proposed scores for juveniles, adults, and combined life stages is based on range of scores provided, rationale provided by experts for their scores, and other case studies and publications.

Marked to indicate a deviation from the Delphi panelists scores and the proposed binary score for that species/life stage.
Usually, the binary score (which must be 0 or 1, by definition) is 0 if panelists scores are less than 0.5, and 1 if panelists scores are 0.5 or higher.

Eastern Pondmussel				Raw Scores										Juvenile				Adult					
				P1	P2	P3	P4	P5	P1	P2	P3	P4	P5										
Parameter	**Class**	**Velocity Range (m/s)**		**J**	**J**	**J**	**J**	**J**	**A**	**A**	**A**	**A**	**A**	**Mean**	**Median**	**Curve****	**Binary****	**Mean**	**Median**	**Curve****	**Binary****	**J+A Binary****	**Rationale for Noted Departure**
Flow Velocity	1	<0.05		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Flow Velocity	2	0.05 - 0.10		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Flow Velocity	3	0.11 - 0.20		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Flow Velocity	4	0.21 - 0.30		1.0	0.8	0.7	1.0		1.0	1.0	0.9	1.0		0.88	0.90	0.90	1.00	0.98	1.00	1.00	1.00	1.00	
Flow Velocity	5	0.31 - 0.40		1.0	0.5	0.5	1.0		1.0	1.0	0.7	1.0		0.75	0.75	0.75	1.00	0.93	1.00	1.00	1.00	1.00	
Flow Velocity	6	0.41 - 0.50		1.0	0.5	0.2	1.0		1.0	1.0	0.4	1.0		0.68	0.75	0.70	1.00	0.85	1.00	0.90	1.00	1.00	
Flow Velocity	7	0.51 - 0.75		0.3	0.3	0.0	0.4		0.3	0.5	0.2	0.4		0.25	0.30	0.30	0.00	0.35	0.35	0.35	0.00	0.00	
Flow Velocity	8	0.76 - 1.00		0.3	0.1	0.0	0.4		0.3	0.3	0.0	0.4		0.20	0.20	0.20	0.00	0.25	0.30	0.30	0.00	0.00	
Flow Velocity	9	1.01 - 1.50		0.1	0.0	0.0	0.2		0.1	0.1	0.0	0.2		0.08	0.05	0.10	0.00	0.10	0.10	0.10	0.00	0.00	
Flow Velocity	10	1.51 - 2.00		0.1	0.0	0.0	0.2		0.1	0.0	0.0	0.2		0.08	0.05	0.10	0.00	0.08	0.05	0.00	0.00	0.00	
Flow Velocity	11	>2.0		0.1	0.0	0.0	0.2		0.1	0.0	0.0	0.2		0.08	0.05	0.10	0.00	0.08	0.05	0.00	0.00	0.00	
Parameter	**Class**	**Depth Range (m)**																					
Water Depth	1	0		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Water Depth	2	0.01 - 0.10		1.0	1.0	0.1	0.4		1.0	1.0	0.1	0.4		0.63	0.70	0.60	0.00	0.63	0.70	0.65	0.00	0.00	Although both juveniles and adults can survive in water less than 10cm, we consider this unsuitable due to risks of dessication, predation, etc.
Water Depth	3	0.11 - 0.25		1.0	1.0	0.3	0.8		1.0	1.0	0.5	0.8		0.78	0.90	0.80	1.00	0.83	0.90	0.85	1.00	1.00	
Water Depth	4	0.26 - 0.50		1.0	1.0	0.5	1.0		1.0	1.0	0.8	1.0		0.88	1.00	0.90	1.00	0.95	1.00	1.00	1.00	1.00	
Water Depth	5	0.51 - 0.75		1.0	1.0	0.8	1.0		1.0	1.0	1.0	1.0		0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	6	0.76 - 1.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	7	1.01 - 1.50		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	8	1.51 - 2.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	9	2.01 - 3.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	10	3.01 - 4.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	11	>4.00		1.0	1.0	1.0	1.0		1.0	1.0	0.8	1.0		1.00	1.00	1.00	1.00	0.95	1.00	1.00	1.00	1.00	
Parameter	**Class**	**Particle Size**	**Substrate Name**																				
Substrate	1		Organic Material	-	0.0	0.6	0.0		-	0.0	0.8	0.0		0.20	0.00	0.10	0.00	0.27	0.00	0.25	0.00	-	
Substrate	2		Mud/Clay	1.0	0.5	1.0	0.0		1.0	0.5	1.0	0.0		0.63	0.75	0.70	1.00	0.63	0.75	0.70	1.00	-	
Substrate	3	<0.062 mm	Silt	1.0	1.0	1.0	0.4		1.0	1.0	1.0	0.4		0.85	1.00	0.90	1.00	0.85	1.00	0.90	1.00	-	
Substrate	4	0.062 - 2.0 mm	Sand	1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
Substrate	5	2.0 - 32.0 mm	Fine Gravel	1.0	0.5	1.0	1.0		1.0	0.5	1.0	1.0		0.88	1.00	0.90	1.00	0.88	1.00	1.00	1.00	-	
Substrate	6	32.0 - 64.0 mm	Coarse Gravel	0.3	0.0	0.4	1.0		0.3	0.0	0.6	1.0		0.43	0.35	0.40	0.00	0.48	0.45	0.50	1.00	-	
Substrate	7	64.0 - 150.0 mm	Small Cobble	0.3	0.0	0.1	1.0		0.3	0.0	0.1	1.0		0.35	0.20	0.25	0.00	0.35	0.20	0.30	0.00	-	
Substrate	8	150.0 - 250.0 mm	Large Cobble	0.3	0.0	0.0	1.0		0.3	0.0	0.0	1.0		0.33	0.15	0.25	0.00	0.33	0.15	0.25	0.00	-	
Substrate	9	250.0 - 4,000 mm	Boulder	0.1	0.0	0.0	1.0		0.1	0.0	0.0	1.0		0.28	0.05	0.20	0.00	0.28	0.05	0.10	0.00	-	
Substrate	10		Bedrock	0.1	0.0	0.0	1.0		0.1	0.0	0.0	1.0		0.28	0.05	0.20	0.00	0.28	0.05	0.10	0.00	-	
Parameter	**Class**	**Percent Cover**																					
Cover	1	0		-	1.0	0.8	-		-	1.0	0.6	-		0.90	0.90	0.90	1.00	0.80	0.80	0.80	1.00	1.00	There is no evidence to suggest that dense cover is unsuitable for eastern pondmussels, especially for juveniles that tend to remain buried and can benefit from the flow refuge/stability that cover can provide. In the Connecticut River, eastern pondmussels were nearly always found within or near dense nearshore cover.
Cover	2	1 - 10.0%		-	1.0	0.9	-		-	1.0	0.8	-		0.95	0.95	0.95	1.00	0.90	0.90	0.90	1.00	1.00	
Cover	3	10.1 - 25.0%		-	0.0	1.0	-		-	0.0	1.0	-		0.50	0.50	0.50	1.00	0.50	0.50	0.50	1.00	1.00	
Cover	4	26.1 - 50.0%		-	0.0	1.0	-		-	0.0	1.0	-		0.50	0.50	0.50	1.00	0.50	0.50	0.50	1.00	1.00	
Cover	5	50.1 - 75.0%		-	0.0	1.0	-		-	0.0	1.0	-		0.50	0.50	0.50	1.00	0.50	0.50	0.50	1.00	1.00	
Cover	6	75.1 - 100%		-	0.0	0.8	-		-	0.0	0.8	-		0.40	0.40	0.40	1.00	0.40	0.40	0.40	1.00	1.00	
Parameter																							
Shear Stress	SS	Low		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
		Medium		1.0	0.0	0.5	1.0		1.0	1.0	0.5	1.0		0.63	0.75	0.75	1.00	0.88	1.00	0.75	1.00	1.00	
		High		0.3	0.0	0.0	0.5		0.3	0.0	0.0	1.0		0.20	0.15	0.00	0.00	0.33	0.15	0.25	0.00	0.00	
Relative SS	RSS	Low		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
		Medium		1.0	0.0	0.5	0.5		1.0	1.0	0.5	1.0		0.50	0.50	0.50	0.00	0.88	1.00	0.75	1.00	-	
		High		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.5		0.00	0.00	0.00	0.00	0.13	0.00	0.25	0.00	-	

*P = Panelists (1-5); still waiting on scores for Panelist 5. J = Juvenile. A = Adult

**The proposed scores for juveniles, adults, and combined life stages is based on range of scores provided, rationale provided by experts for their scores, and other case studies and publications.

Marked to indicate a deviation from the Delphi panelists scores and the proposed binary score for that species/life stage.
Usually, the binary score (which must be 0 or 1, by definition) is 0 if panelists scores are less than 0.5, and 1 if panelists scores are 0.5 or higher.

Tidewater Mucket				Raw Scores*																			
				P1	P2	P3	P4	P5	P1	P2	P3	P4	P5	Juvenile				Adult					
Parameter	Class	Velocity Range (m/s)		J	J	J	J	J	A	A	A	A	A	Mean	Median	Curve**	Binary**	Mean	Median	Curve**	Binary**	J+A Binary**	Rationale for Noted Departure
Flow Velocity	1	<0.05		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
Flow Velocity	2	0.05 - 0.10		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
Flow Velocity	3	0.11 - 0.20		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
Flow Velocity	4	0.21 - 0.30		1.0	0.8	0.7	1.0		1.0	1.0	0.9	1.0		0.88	0.90	0.90	1.00	0.98	1.00	1.00	1.00	-	
Flow Velocity	5	0.31 - 0.40		1.0	0.5	0.5	1.0		1.0	1.0	0.7	1.0		0.75	0.75	0.75	1.00	0.93	1.00	1.00	1.00	-	
Flow Velocity	6	0.41 - 0.50		1.0	0.5	0.2	1.0		1.0	1.0	0.4	1.0		0.68	0.75	0.70	1.00	0.85	1.00	0.90	1.00	-	
Flow Velocity	7	0.51 - 0.75		1.0	0.3	0.0	1.0		1.0	0.5	0.2	1.0		0.58	0.65	0.60	0.00	0.68	0.75	0.70	1.00	-	There seemed to be some inconsistency with scoring that suggested L. ochracea preferred higher flows than L. cariosa. Binary scores wereadjusted to match that of L. cariosa, as this is more consistent with field observations throughout the species range.
Flow Velocity	8	0.76 - 1.00		1.0	0.1	0.0	1.0		1.0	0.3	0.0	1.0		0.53	0.55	0.55	0.00	0.58	0.65	0.60	0.00	-	
Flow Velocity	9	1.01 - 1.50		0.1	0.0	0.0	1.0		0.1	0.1	0.0	1.0		0.28	0.05	0.20	0.00	0.30	0.10	0.25	0.00	-	
Flow Velocity	10	1.51 - 2.00		0.1	0.0	0.0	1.0		0.1	0.0	0.0	1.0		0.28	0.05	0.20	0.00	0.28	0.05	0.10	0.00	-	
Flow Velocity	11	>2.0		0.1	0.0	0.0	0.6		0.1	0.0	0.0	0.6		0.18	0.05	0.10	0.00	0.18	0.05	0.10	0.00	-	
Parameter	Class	Depth Range (m)																					
Water Depth	1	0		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Water Depth	2	0.01 - 0.10		1.0	1.0	0.1	0.4		1.0	1.0	0.1	0.4		0.63	0.70	0.65	0.00	0.63	0.70	0.65	0.00	0.00	Although both juveniles and adults can survive in water less than 10cm, we consider this unsuitable due to risks of dessication, predation, etc.
Water Depth	3	0.11 - 0.25		1.0	1.0	0.3	0.8		1.0	1.0	0.4	0.8		0.78	0.90	0.80	1.00	0.80	0.90	0.85	1.00	1.00	
Water Depth	4	0.26 - 0.50		1.0	1.0	0.5	1.0		1.0	1.0	0.7	1.0		0.88	1.00	0.90	1.00	0.93	1.00	1.00	1.00	1.00	
Water Depth	5	0.51 - 0.75		1.0	1.0	0.8	1.0		1.0	1.0	0.9	1.0		0.95	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	
Water Depth	6	0.76 - 1.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	7	1.01 - 1.50		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	8	1.51 - 2.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	9	2.01 - 3.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	10	3.01 - 4.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	11	>4.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Parameter	Class	Particle Size	Substrate Name																				
Substrate	1		Organic Material	-	0.0	0.3	0.0		-	0.0	0.5	0.0		0.10	0.00	0.10	0.00	0.17	0.00	0.10	0.00	0.00	
Substrate	2		Mud/Clay	1.0	1.0	0.6	0.0		1.0	1.0	0.8	0.0		0.65	0.80	0.75	1.00	0.70	0.90	0.80	1.00	1.00	
Substrate	3	<0.062 mm	Silt	1.0	1.0	1.0	0.4		1.0	1.0	1.0	0.4		0.85	1.00	0.90	1.00	0.85	1.00	0.90	1.00	1.00	
Substrate	4	0.062 - 2.0 mm	Sand	1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Substrate	5	2.0 - 32.0 mm	Fine Gravel	1.0	0.5	1.0	1.0		1.0	1.0	1.0	1.0		0.88	1.00	0.90	1.00	1.00	1.00	1.00	1.00	1.00	
Substrate	6	32.0 - 64.0 mm	Coarse Gravel	1.0	0.3	0.4	1.0		1.0	1.0	0.5	1.0		0.68	0.70	0.70	1.00	0.88	1.00	0.90	1.00	1.00	
Substrate	7	64.0 - 150.0 mm	Small Cobble	0.3	0.0	0.0	1.0		0.3	0.5	0.1	1.0		0.33	0.15	0.25	0.00	0.48	0.40	0.45	0.00	0.00	
Substrate	8	150.0 - 250.0 mm	Large Cobble	0.3	0.0	0.0	1.0		0.3	0.3	0.0	1.0		0.33	0.15	0.25	0.00	0.40	0.30	0.35	0.00	0.00	
Substrate	9	250.0 - 4,000 mm	Boulder	0.1	0.0	0.0	1.0		0.1	0.0	0.0	1.0		0.28	0.05	0.20	0.00	0.28	0.05	0.10	0.00	0.00	
Substrate	10		Bedrock	0.1	0.0	0.0	0.0		0.1	0.0	0.0	0.0		0.03	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	
Parameter	Class	Percent Cover																					
Cover	1	0		-	1.0	0.8	1.0		-	1.0	0.8	1.0		0.93	1.00	1.00	1.00	0.93	1.00	1.00	1.00	-	
Cover	2	1 - 10.0%		-	1.0	1.0	1.0		-	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
Cover	3	10.1 - 25.0%		-	0.0	1.0	1.0		-	0.0	1.0	1.0		0.67	1.00	0.80	1.00	0.67	1.00	1.00	1.00	-	There is no evidence to suggest that dense cover is unsuitable for tidewater muckets, especially for juveniles that tend to remain buried and can benefit from the flow refuge/stability that cover can provide.
Cover	4	26.1 - 50.0%		-	0.0	1.0	0.5		-	0.0	1.0	0.5		0.50	0.50	0.50	1.00	0.50	0.50	0.60	1.00	-	
Cover	5	50.1 - 75.0%		-	0.0	1.0	0.3		-	0.0	0.8	0.3		0.43	0.30	0.50	1.00	0.37	0.30	0.35	1.00	-	
Cover	6	75.1 - 100%		-	0.0	0.8	0.0		-	0.0	0.7	0.0		0.27	0.00	0.50	1.00	0.23	0.00	0.10	0.00	-	
Parameter																							
Shear Stress	SS	Low		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
		Medium		1.0	0.0	0.5	1.0		1.0	1.0	0.5	1.0		0.63	0.75	0.70	1.00	0.88	1.00	0.75	1.00	1.00	
		High		0.3	0.0	0.0	0.5		0.3	0.0	0.0	1.0		0.20	0.15	0.15	0.00	0.33	0.15	0.25	0.00	0.00	
Relative SS	RSS	Low		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
		Medium		1.0	0.0	0.5	0.5		1.0	1.0	0.5	1.0		0.50	0.50	0.50	0.00	0.88	1.00	0.75	1.00	-	
		High		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.5		0.00	0.00	0.00	0.00	0.13	0.00	0.25	0.00	-	

*P = Panelists (1-5); still waiting on scores for Panelist 5. J = Juvenile. A = Adult

**The proposed scores for juveniles, adults, and combined life stages is based on range of scores provided, rationale provided by experts for their scores, and other case studies and publications.

Marked to indicate a deviation from the Delphi panelists scores and the proposed binary score for that species/life stage.
Usually, the binary score (which must be 0 or 1, by definition) is 0 if panelists scores are less than 0.5, and 1 if panelists scores are 0.5 or higher.

Case studies, publications, or datasets upon which the scoring was based.

Species	River/Lake	Project Name	Information Available?
Alasmidonta heterodon	NY Delaware River	Maloney et al. 2012. Freshwater Biology 57:1315-1327.	Yes
Eastern Pondmussel	Connecticut River and tributaries in CT	State-wide mussel surveys for CT DEEP and misc. environmental review prc	Yes - Biodrawversity datasets
Eastern Pondmussel	Connecticut River in MA	Studies for Holyoke Gas & Electric in the Holyoke Dam impoundment	Yes - FERC record & Biodrawversity datasets, HGE client
Eastern Pondmussel	Lab experiments	French and Ackermann 2014. Freshwater Science. 2014. 33(1):46–55	Yes
Eastern Pondmussel	Lakes and ponds in southeastern MA	Coastal pond research for NHESP and misc. environmental review projects	Yes - Biodrawversity datasets, NHESP primary client
Eastern Pondmussel	Mill River in Whately, MA	Mussel relocation and monitoring for Whately Municipal Well Project	Yes - Biodrawversity dataset, client Town of Whately, oversight from NHESP
Eastern Pondmussel	Waterbodies in southeast New Hampshire	Research for NHFG and misc. environmental review projects	Yes - Biodrawversity datasets, NHFG primary client
Eastern Pondmussel	Webatuck Creek, Allegheny River basin, Lake Taghkanic, Niagara River		based on casual observations of field conditions rather than measurements; some data in Strayer 1999 JNABS 18: 468-476.
Tidewater Mucket	Connecticut River and tributaries in CT	State-wide mussel surveys for CT DEEP and misc. environmental review prc	Yes - Biodrawversity datasets
Tidewater Mucket	Connecticut River in MA	Studies for Holyoke Gas & Electric in the Holyoke Dam impoundment	Yes - FERC record & Biodrawversity datasets, HGE client
Tidewater Mucket	Hudson River estuary		based on casual observations of field conditions rather than measurements
Tidewater Mucket	Lakes and ponds in southeastern MA	Coastal pond research for NHESP and misc. environmental review projects	Yes - Biodrawversity datasets, NHESP primary client
Tidewater Mucket	PA streams	Ortmann, 1919. Naiads of PA	Yes
Tidewater Mucket	Penobscot River in ME	Penobscot River Restoration Project	Yes - Biodrawversity dataset, PRRT client, oversight by MDIFW
Tidewater Mucket	Susquehanna River in MD	Conowingo Dam relicensing project	Yes - FERC record. Gomez & Sullivan lead consultant, Biodrawversity/Normandeau dataset.
Yellow Lampmussel	Connecticut River and tributaries in CT	State-wide mussel surveys for CT DEEP and misc. environmental review prc	Yes - Biodrawversity datasets
Yellow Lampmussel	Connecticut River in MA	Studies for Holyoke Gas & Electric in the Holyoke Dam impoundment	Yes - FERC record & Biodrawversity datasets, HGE client
Yellow Lampmussel	Kennebec and Penobscot watersheds in ME	Statewide surveys in the last 25 years	Yes - MDIFW database, Biodrawversity datasets
Yellow Lampmussel	PA streams	Ortmann, 1919. Naiads of PA	Yes
Yellow Lampmussel	Penobscot River in ME	Penobscot River Restoration Project	Yes - Biodrawversity dataset, PRRT client, oversight by MDIFW
Yellow Lampmussel	Susquehanna River basin streams	basin-wide survey	based on casual observations of field conditions rather than measurements
Yellow Lampmussel	Susquehanna River in PA	Mussel Survey and Hydraulic Analysis for Bell Bend Nuclear Project	Yes - FERC record & Biodrawversity dataset (Kleinschmidt lead consultant)
Multiple species	Louisiana	Wesley and Brown 2013. Freshwater Science, 2013, 32(1):193–203	Yes
Multiple species	NY	Strayer 1999. North American Benthological Society 18:468-476	Yes
Multiple species	NY river	Strayer 1999. North American Benthological Society 18:468-476.	Yes
Multiple species	OK	Vaughn and Taylor 2000. Ecography 23:11-20.	Yes
Multiple species	OK River	Allen and Vaughn 2010. J. North Am. Benthological Society 29:383-394.	Yes
Multiple species	Upper Mississippi	Steuer 2008. Hydrobiologia (2008) 610:67–82	Yes
Multiple species	Upper Mississippi	Zigler et al. 2008. Hydrobiologia 598:343-360.	Yes
All three species	CT River	Nadeau 2008. Freshwater mussels of the CT River watershed	Yes
All three species	NY rivers	Strayer and Jirka 1997. Pearly mussels of NY state	Yes

Additional Comments from Panelists

Water Depth

There appears to be no upper limit on the depth that these species will inhabit, except that they often do not occur well below the thermocline in stratified lakes. Of the three, yellow lampmussel seems to occur in the greatest range of depths, in water well in excess of 5 meters, whereas tidewater mucket and eastern pondmussel tend to occur in shallow to intermediate depths in more complex habitats (such as near weed beds, or on sloping streambanks). Eastern pondmussels may actually migrate into shallow water during the spawning season to make themselves more visible to host fish, then migrate back down into deeper water after spawning season is complete. In the tidal Connecticut River, eastern pondmussel and tidewater mucket may track daily tides or remain close to the interidal-subtidal boundary, such that they may be found in only centimeters of water at low tide. Overall, habitat suitability criteria should probably focus on the shallow end of the depth spectrum.

I don't believe that any of these species cares about water depth, other than the possibility of being dried out or overheated at very shallow depths. We routinely collected ochracea from the Hudson estuary at depths of >4m before zebra mussels arrived (some data in Strayer et al. Freshwater Biology 31: 239-248, 1994)

Depth does not seem to be predictive of mussel distribution.

Substrate

I believe that these species, like most unionids, are nearly indifferent to sediment grain size per se, and may tolerate a wide range of grain sizes depending on the hydraulic and chemical habitat. Some data for nasuta and ochracea were published in the 2 papers that I'm enclosing (JNABS 18: 468-476, Freshwater Biology 31: 239-248

I don't know what you mean by "organic material". FYI, we often collect nasuta from soft clay/silt in Webatuck Creek

Interstitial oxygen gradient in fine sediments is likely to limit juvenile distribution for all three species. I have found L. cariosa and L. ochracea in fine sand in ponds in Maine. Substate size may be less predictive than shear stress during floods. I found L. nasuta in mud in the Framingham River, MA.

All mussel species are burrowers, therefore they will always prefer substrates in which they can burrow. The presence of other substrates, such as coarse rock (large gravel, cobble, boulder, even bedrock) may be important for its role in anchoring/stabilizing the streambed and keeping fine sediments from being mobilized, and also by increasing substrate permeability and thus exchange of water, gases, nutrients between the water column and the upper layer of substrate. Therefore, mussels may have a direct relationship with substrates they prefer to burrow in, and an indirect relatiobnship with substrates that help to promate/retain their preferred substrates and improve the quality of the benthic environment. Substrate diversity may be as important as any single substrate type, and its worthwhile to consider habitat suitability scores that account for diversity. For example, yellow lampmussels prefer to burrow in sand and are rarely found in cobble, but a riverbed that contains only sand is not as suitable as a riverbed that contains both sand and cobble (or other coarse rock). Of the three species, Eastern Pondmussel seem most tolerant of organics, mud, clay, and silt, followed by Tidewater Mucket and Yellow Lampmussel. All three species seem to prefer sand and fine gravel, then suitability diminishes with increasing grain size.

Cover

Sorry, I don't have any observations about this. I have seen mussels in and around vegetation (including nasuta, in a lake), detritus, large rocks, etc., but don't know whether these favor or disfavor mussels. I suppose that cover could either stabilize or destabilize sediments, which ought to affect mussels.

I don't think that cover explains mussel distribution very well; although it may provide flow refuges for both adult and juvenile mussels. Vaughn and Taylor 2000 relate mussel distribution to host fish distribution which may involve cover, but mussels primarily require optimal environments (stable habitats.)

Of the three species, L. nasuta seems to have the strongest affinity for instream cover, whether it be vegetation, coarse wood, detritus, rock, or even the streambank (overhanging vegetation, steep banks, root wads, etc). Therefore, suitability scores are lower for NO cover, then optimal for increasing amounts of cover until the highest values where suitability drops. I think this is because at some point, the amount of cover starts to exert too strong an influence on other factors such as mobility, circulation of flow (and thus delivery of nutrients, dissolved oxygen, etc), substrate quality, etc. L. nasuta seems to need some cover, but too much of certain kinds of cover (like detritus, or coarse rock) may be unsuitable. L. cariosa, on the other hand, seems to prefer areas without significant cover, and suitability decreases as the amount of cover (of any type) increases. L. ochracea is more intermediate -- like N. nasuta, it does seem to prefer some amount of instream cover but can tolerate fairly high amounts of cover, especially aquatic vegetation and coarse wood.

Shear Stress

I believe that sediment stability during high flows is critically important to unionids. If the sediment moves (which will depend on shear stress, sediment grain size, and sediment bedding), the site is likely to be unsuitable to unionids. The critical value will be not shear stress per se, but whether RSS>1 during high water. I suspect that base-flow shear stress is not very important. This factor is discussed in the "habitat" chapter of my mussel ecology book, which provides additional references.

Juveniles cannot become established when bed shear stress exceeds a critical threshold

Few studies have specifically calcuated shear stress or relative shear stress for mussels/mussel beds, especially for these three species. In a very general sense, we can infer suitabilities based on observations/measurements of flow velocity and substrate from most of the case studies listed. But its difficult to consider exact ranges, since precise SS or RSS values are hard to understand/contextualize. Generally, all three species inhabit areas with fine substrates and light flow velocities, so they must be sensitive to SS and RSS at the higher end of the spectrum. Low SS and RSS should be optimal for all three species, and high SS and RSS should be poor.

Water Velocity (Benthic)

I assume you mean velocities under base flow conditions. Many mussel populations will be subjected to much higher velocities during floods. I haven't provided separate ratings for adults and juveniles because I don't know of any evidence that adults and juveniles prefer different conditions. I do not believe that current speed by itself is likely to be an important limit on the distribution or abundance of these species (except for extremely high flows), and so is not likely by itself to be effective in a HSC. People may think of ochracea as a quiet-water species, but it was abundant in the upper Hudson River estuary, where tidal flows often exceed 1 m/s

No specific data on velocity and these species but see: Maloney et al. 2012. Freshwater Biology 57:1315-1327. Allen and Vaughn 2010. J. North Am. Benthological Society 29:383-394. Gangloff and Feminella 2006. Freshwater Biology 52:64-74. Wesley and Brown 2013. Freshwater Science, 2013, 32(1):193–203.

All three species inhabit and generally reach their highest densities in lakes and slow-flowing rivers. Suitability diminishes with velocity.

I am assuming that this is velocity that the larvae and adults are experiencing after settling. I am not personnally familiar with L. nasuta, so this is a guess, given the general kinds of sites I suspect it is found in. I have not measured flow velocities in my work, so I am guessing these suitabilities based on my recollection of the sites where we surveyed for YLM and TWM.

Memo

To: **Turners Falls Hydroelectric Project Mussel Delphi Panel**
From: **Jason George, Gomez and Sullivan Engineers**
Date: **February 11, 2016**
RE: **Shear Stress (SS), Relative Shear Stress (RSS), and Mussel Habitat Suitability**

Mussels are morphologically and behaviorally adapted to living in naturally unstable riverine environments. We are focusing on three species that are generalists in terms of the types of waterbodies they inhabit (lakes and ponds, small to large rivers, freshwater tidal areas) and for the specific habitats that they inhabit within these waterbodies. Generally, all three species appear to prefer fine-grained sediment in lakes and rivers. When considering possible habitat suitability criteria for SS and RSS, its worthwhile to consider some ideas about how mussels can persist in areas that appear to have high SS and RSS based on relatively simple parameters of flow velocity, water depth, and resistance of particle sizes to movement.

In the Connecticut River, yellow lampmussels have been found bank to bank over several miles of river, from the Holyoke Dam up to the Hadley Dike. They are usually found in broad flat sandbars in a range of water depths (1-25 ft), even in areas with fairly high flow velocities and near-constant bedload (such as the area between the Route 9 Bridge and Rainbow Beach), although highest densities are in the broad sandbars upstream and downstream of Mitches Island and also near Brunelle's Marina. Of the three species, yellow lampmussels exist in areas of the Connecticut River where SS and RSS are likely to be important. In contrast, eastern pondmussels are found almost exclusively in shallow water (<3 ft) very close to the riverbank, usually within or near dense beds of *Vallisneria* and *Elodea* that fringe the shoreline, and often within/among woody debris. In these areas, flow velocity is very slow (or zero) at all times: SS and RSS is never likely a concern for eastern pondmussels in this system. Tidewater muckets are extremely rare in the project area; only 3 live mussels have ever been found despite numerous surveys over nearly three decades. Elsewhere in the Connecticut River in Connecticut, this species is numerous from bank to bank, occurring with eastern pondmussels near riverbanks and near yellow lampmussels in sandbars.

Mussel Morphology and Behavior

In the Connecticut River, an average yellow lampmussel has a shell length of 3 inches, and in its natural position in the substrate, its large muscular foot extends at least another 2 inches. Unless it is actively moving somewhere, it orients itself nearly vertical in the substrate with its posterior end nearly flush with the surface of the substrate, and the tip of its foot anchored somewhere 4-5 inches below the surface of the sediment. The center of its mass is about 2-2.5 inches below the surface of the substrate. They use the foot for both horizontal and vertical movement…in a split second, the can close their mantles and completely bury themselves with a quick contraction of their foot. Mussels also nearly always point themselves directly upstream.

Importance? Mussels are deeply anchored and streamlined. Most of a mussel's mass, as well as its strong and responsive foot, are deep within the sediment anchoring it in place. It is actually very difficult to extract a mussel from the streambed until you can grasp its center of mass, which often requires some digging around the posterior end. You can "fan away" sediment from around a mussel with strong/turbulent flows and it remains in position until you get down well below its center of mass, and even then, it may remain in position if it does not retract its foot. This suggests that minor bedload, such as that may affect the top 1-2 inches of sediment, would not displace a mussel. Mussels are also responsive…they can bury themselves, or move horizontally. If displaced, they may only be transported short distances as they use their foot to re-anchor themselves. Mussels exist even in streambeds that are mostly sand and are subject to high flow velocities, often congregating near features that may anchor sediments, such as buried logs, coarse rock, or beds of aquatic vegetation.

Streambed Complexity

There is considerable variation in substrate in rivers, both in terms of ways we often think about it (from bank to bank, or along a rivers length) but also vertically. Vertical sediment profiles in a streambed often reveal coarser and more compact layers at depth, with finer-grained and looser sediment near the surface. This is important because although mussels may appear to be living in the finer-grained, loose sediment visible at the surface, the center of their body mass and their feet may be anchored more deeply in the coarser and more compact underlying sediments. Flow velocities that may set fine-grained sediments at the surface into motion may have little effect on the coarser and more compact underlying sediments. If we are to consider SS or RSS values that are capable of displacing mussels, we need to consider substrate type(s) and substrate cohesiveness in the portion of the streambed where mussels are anchored, rather than the substrate where their posterior edge exists. It is difficult to capture this in traditional hydraulic modeling and substrate mapping.

Many factors contribute to substrate stability and resistance to particle movement.

- **Wood/detritus:** fully buried, partly buried, or unburied logs/branches and other detritus help to stabilize the streambed and keep sediment in place, even during flows that should be high enough to transport those sediments.
- **Vegetation:** the roots, stems, and leaves of aquatic vegetation provide stability. Roots help with sediment cohesion, and stems and leaves greatly slow and dissipate flows, disrupt bedload, and promote more deposition.
- **Biofilms and Aufwuchs:** a variety of bacteria, algae, plants, and animals form complex films and surface growth over streambeds and other submerged surfaces. Psammophilic (sand-loving) algae/bacteria can help to establish a biofilm over fine-grained sediments, and it gets thicker and more robust as it is colonized by more and more algae/bacteria, meiofauna, tube-building and case-making macroinvertebrates. In areas of the lower Holyoke Dam impoundment where yellow lampmussels occur, we have observed a very substantial biofilm (in some cases, 5-10 mm thick) overlying very large areas of the streambed. The underlying sand is not subjected to flows, and the biofilm is much more resistant to flow velocity than the underlying fine-grained mineral substrate. You can almost think of it as “topsoil” in the forest.
- **Macroinvertebrates:** as mentioned before, tube-building and case making invertebrates, clams, mussels all help to stabilize the sediment. Insects bind sand particles together with silk. Mussels actively filter tiny particles and then deposit much larger particles, often encased with mucous (this process is called biodeposition). All of these things help to bind the mineral particles, increase sediment cohesion, and thus increase the resistance of these particles to transport. Mussels themselves effectively serve a similar role as large gravel or small cobbles, perhaps even more effectively because of their streamlining and large foot…thus, mussels can self-stabilize their own beds.

What does it take to displace mussels and scour away a mussel bed?

It is important to note that at any single point in the streambed (such as the location of a mussel or mussel bed), there is both export and import of sediment. Flows may reach a level where fine sediments around a mussel are scoured, but presumably fine sediment is also re-filling from upstream. For most flow events, the net effect is that mussels may be subjected to heavy bedload and scour, but can withstand it without being displaced. For the most part, mussels can “clamp up” or “hunker down” until the flows subside.

Flows necessary to displace mussels and disrupt mussel beds would need to completely scour the top few inches of substrate in a short amount of time. (i.e., export >>>> import at any point in the mussel bed). It would need to be strong enough to overcome any sediment cohesion/compaction, to scour both the fine-grained surface sediments AND the coarser-grained subsurface sediments, and to lift/transport bed-stabilizing elements such as embedded wood, roots, rock, and mussels themselves. This has been referred to as “mass wasting” and would probably require great deal of force. It is likely that a flood of greater than 20 yr recurrence intervals may have this potential, but normal seasonal or 5-yr high-flow events probably do not. Tropical Storm Irene is an example of a flow event that indeed caused “mass wasting” in rivers throughout parts of New England, especially Vermont.

The trouble with SS and RSS

The "onset of particle motion" may be a threshold for instability from a hydraulic modeling perspective, but mussels are very well adapted to some amount of instability. It is a natural component of their habitat, especially for our three target species that occur in fine-grained substrates in rivers. Hydraulic models that fail to account for some of the things described above will probably also fail to account for the persistence/stability of mussel beds. Hydraulic modeling of shear stress and RSS using simple parameters are likely to greatly overpredict:

- The amount of shear at the streambed
- The effects of shear on particle movement
- The effects of shear on mussels (via displacement) or mussel beds

Substrate type, and experimental studies of the resistance of particle sizes to flow velocity, comprises the denominator of the RSS equation. Because fine-grained sediments, such as fine sand, are the easiest particles to move, areas with these sediments will appear to have the highest levels of RSS (with otherwise similar water depths and flow velocities). This may seem counterintuitive if we agree that RSS is an important parameter for mussels and that mussels inhabit areas with low RSS. Lowest RSS values will generally be for areas with bedrock or very coarse-grained materials because these materials strongly resist movement; however, mussels do not prefer these substrates.

Available flow velocity, bathymetry, and substrate data in the Connecticut River where the state-listed mussel species of interest are located is rather coarse. Bank-to-bank variation in substrate particle size, vertical profiles of grain sizes in the streambed, and longitudinal variation in substrate particle size along the entire project area is not well characterized. In addition, other components of substrate diversity that might influence resistance to particle movement (e.g., clay (increases cohesion), coarse wood, detritus, vegetation, biofilms, macroinvertebrates (including mussels themselves) have not been well characterized. Thus, the RSS calculations based on very coarse-scale hydraulic and substrate data will provide very little insight into mussel habitat suitability. It would be difficult to use these data (or data from other rivers) to develop meaningful numeric habitat suitability criteria. For example, Morales et al. (2006)[1] proposed an HSI for RSS as:

- RSS < 1.0 = Suitable
- RSS 1.0 – 1.25 = Marginal
- RSS >1.25 = Unsuitable

But for the Connecticut River, RSS calculations for transects within or near yellow lampmussel beds were typically >>5, even for a 1.5-yr flood (see chart below). These areas have high densities of adult yellow lampmussels and neither quantitative nor qualitative sampling has suggested a decline in the years they have been studied (2005 to 2015) despite several very high flow events during that period.

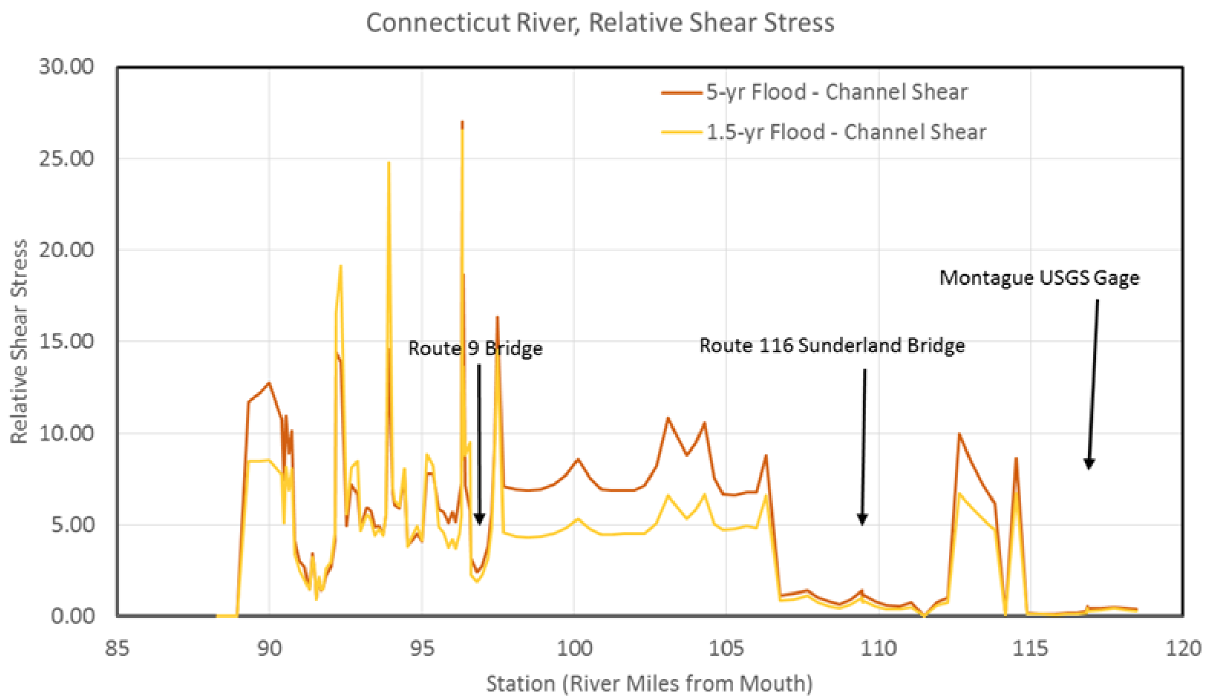
Suggestions?

What do we do with SS and RSS? The main problem with RSS is that it does not account for the many other elements that contribute to bed stability, or how mussels may be congregated (or actually create) these areas of bed stability. It only tells you when particles of a certain size begin to move, which is not that meaningful because mussels are adapted to bedload. A case could be made that SS and RSS may not be ideal parameters for our analysis, even though researchers have suggested they are generally important to mussels. It is likely that 2D or even 3D hydraulic modeling, with detailed substrate and bathymetry data, would be necessary to a more insightful analysis of SS and RSS, but these datasets are not available to us.

[1] Effects of substrate and hydrodynamic conditions on the formation of mussel beds in a large river
Y. Morales, L. J. Weber, A. E. Mynett, and T. J. Newton
Journal of the North American Benthological Society 2006 25 (3), 664-676

The Delphi process is being used to develop binary HSI curves for three mussel species that may occur in the project area. Based on what is described in this document, we are uncertain how to proceed with SS and RSS, as we do not know what ranges of values to suggest for the panelists to consider and score. Our proposed next step is to send out the HSI curves developed in Round 1 to the panelists with the information above and ask for a recommendation on the importance of the shear stress parameters to these species.

One goal of the relicensing study plan is to "…evaluate the potential effects of Project operations on state-listed mussel species." The relicensing study envisioned applying modeling to determine hydraulic parameters such as SS and RSS. Based on the cursory analysis above, RSS calculations for transects within or near yellow lampmussel beds were typically >>5, even for a 1.5-yr flood (approximately 75,000 cfs). It is important to remember that the range of flow fluctuations that can be controlled by the Turners Falls Project is up to approximately 16,000 cfs. Any changes to SS or RSS based on Project operations are of a much smaller magnitude compared to those shear stresses experienced under higher flow conditions.



APPENDIX D – DELPHI PANEL ROUND 3 MATERIALS

Instructions

Based on Round 1 and Round 2 responses, we have developed binary HSI curves for water depth, benthic water velocity, substrate, and cover.

Binary means that the final suitability score is either 0 or 1. In general, if the composite score from Delphi panelists for a each value/range for each parameter was less than 0.5, the resulting binary score was 0.0, and otherwise the binary score was 1.0. We deviated from this in some instances, and these are noted on the attached summaries.

We aimed to develop separate curves for juveniles and adults. In some cases, the binary curves for juveniles and adults came out identical. The curves for the three species were quite similar, which is not unexpected considering that they all seem to prefer similar types of habitats.

Please see attached summary document on SS and RSS for how we plan to incorporate those two challenging parameters.

For Round 3, we ask that you review the final binary scores and the moderator's notes on the proposed HSI curves (at the bottom of the Summary sheet). There is space for you to add additional comments (yellow shaded fields).

If you feel the curves are incorrect and need to be adjusted, please provide specific recommendations and a rationale. Please list references, data sources, or any information for modifications to the proposed binary curves.

The citations that panelists provided are compiled in the Information sheet, and specific comments that panelists provided are in the Comments sheet. Please review these.

If you feel that we are still missing a key parameter that should be considered for an HSI, please clearly define it, explain how the parameter is quantified, and provide any supplemental information.

Summary of Proposed HSI Curves

J = juvenile, A = adult.

A combined J+A binary curve is only proposed if the separate juvenile and adult binary curves were identical.

Grey highlighting: final HSI Curve for that species, life stage, or in some cases combined.

			Lampsilis cariosa					*Ligumia nasuta*					*Leptodea ochracea*				
Parameter	**Class**	**Benthic Velocity Range (m/s)**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**
Flow Velocity	1	<0.05	1.00	1.00	1.00	1.00	-	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-
Flow Velocity	2	0.05 - 0.10	1.00	1.00	1.00	1.00	-	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-
Flow Velocity	3	0.11 - 0.20	1.00	1.00	1.00	1.00	-	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-
Flow Velocity	4	0.21 - 0.30	0.90	1.00	1.00	1.00	-	0.90	1.00	1.00	1.00	1.00	0.90	1.00	1.00	1.00	-
Flow Velocity	5	0.31 - 0.40	0.75	1.00	1.00	1.00	-	0.75	1.00	1.00	1.00	1.00	0.75	1.00	1.00	1.00	-
Flow Velocity	6	0.41 - 0.50	0.75	1.00	0.90	1.00	-	0.70	1.00	0.90	1.00	1.00	0.70	1.00	0.90	1.00	-
Flow Velocity	7	0.51 - 0.75	0.40	0.00	0.50	1.00	-	0.30	0.00	0.35	0.00	0.00	0.60	0.00	0.70	1.00	-
Flow Velocity	8	0.76 - 1.00	0.30	0.00	0.40	0.00	-	0.20	0.00	0.30	0.00	0.00	0.55	0.00	0.60	0.00	-
Flow Velocity	9	1.01 - 1.50	0.20	0.00	0.30	0.00	-	0.10	0.00	0.10	0.00	0.00	0.20	0.00	0.25	0.00	-
Flow Velocity	10	1.51 - 2.00	0.10	0.00	0.20	0.00	-	0.10	0.00	0.00	0.00	0.00	0.20	0.00	0.10	0.00	-
Flow Velocity	11	>2.0	0.00	0.00	0.10	0.00	-	0.10	0.00	0.00	0.00	0.00	0.10	0.00	0.10	0.00	-

Parameter	**Class**	**Water Depth Range (m)**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**
Water Depth	1	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water Depth	2	0.01 - 0.10	0.65	0.00	0.65	0.00	0.00	0.60	0.00	0.65	0.00	0.00	0.65	0.00	0.65	0.00	0.00
Water Depth	3	0.11 - 0.25	0.75	1.00	0.75	1.00	1.00	0.80	1.00	0.85	1.00	1.00	0.80	1.00	0.85	1.00	1.00
Water Depth	4	0.26 - 0.50	0.90	1.00	1.00	1.00	1.00	0.90	1.00	1.00	1.00	1.00	0.90	1.00	1.00	1.00	1.00
Water Depth	5	0.51 - 0.75	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Water Depth	6	0.76 - 1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Water Depth	7	1.01 - 1.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Water Depth	8	1.51 - 2.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Water Depth	9	2.01 - 3.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Water Depth	10	3.01 - 4.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Water Depth	11	>4.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Parameter	**Class**	**Particle Size**	**Substrate Name**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**
Substrate	1		Organic Material	0.00	0.00	0.10	0.00	0.00	0.10	0.00	0.25	0.00	-	0.10	0.00	0.10	0.00	0.00
Substrate	2		Clay	0.25	0.00	0.30	0.00	0.00	0.70	0.00	0.70	0.00	-	0.75	0.00	0.80	0.00	0.00
Substrate	3	<0.062 mm	Mud/Silt	0.60	1.00	0.65	1.00	1.00	0.90	1.00	0.90	1.00	-	0.90	1.00	0.90	1.00	1.00
Substrate	4	0.062 - 2.0 mm	Sand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	1.00	1.00	1.00	1.00	1.00
Substrate	5	2.0 - 32.0 mm	Fine Gravel	0.90	1.00	1.00	1.00	1.00	0.90	1.00	1.00	1.00	-	0.90	1.00	1.00	1.00	1.00
Substrate	6	32.0 - 64.0 mm	Coarse Gravel	0.65	1.00	0.80	1.00	1.00	0.40	0.00	0.50	1.00	-	0.70	1.00	0.90	1.00	1.00
Substrate	7	64.0 - 150.0 mm	Small Cobble	0.55	1.00	0.60	1.00	1.00	0.25	0.00	0.30	0.00	-	0.25	0.00	0.45	0.00	0.00
Substrate	8	150.0 - 250.0 mm	Large Cobble	0.25	0.00	0.25	0.00	0.00	0.25	0.00	0.25	0.00	-	0.25	0.00	0.35	0.00	0.00
Substrate	9	250.0 - 4,000 mm	Boulder	0.10	0.00	0.10	0.00	0.00	0.20	0.00	0.10	0.00	-	0.20	0.00	0.10	0.00	0.00
Substrate	10		Bedrock	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.10	0.00	-	0.00	0.00	0.00	0.00	0.00

Parameter	**Class**	**Percent Cover**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**	**J - Curve**	**J-Binary**	**A-Curve**	**A-Binary**	**J+A-Binary**
Cover	1	0	1.00	1.00	1.00	1.00	-	0.90	1.00	0.80	1.00	1.00	1.00	1.00	1.00	1.00	-
Cover	2	1 - 10.0%	1.00	1.00	1.00	1.00	-	0.95	1.00	0.90	1.00	1.00	1.00	1.00	1.00	1.00	-
Cover	3	10.1 - 25.0%	0.75	1.00	0.75	1.00	-	0.50	1.00	0.50	1.00	1.00	0.80	1.00	1.00	1.00	-
Cover	4	26.1 - 50.0%	0.50	1.00	0.50	1.00	-	0.50	1.00	0.50	1.00	1.00	0.50	1.00	0.60	1.00	-
Cover	5	50.1 - 75.0%	0.35	1.00	0.30	1.00	-	0.50	1.00	0.50	1.00	1.00	0.50	1.00	0.35	1.00	-
Cover	6	75.1 - 100%	0.10	1.00	0.00	0.00	-	0.40	1.00	0.40	1.00	1.00	0.50	1.00	0.10	0.00	-

Notes on Proposed HSI Curves

Benthic flow velocity: Since all three species live in lakes and ponds, and in slow, depositional environments in rivers, no flow (velocity = 0) is considered optimal. There was general agreement of declining suitability with increasing velocity, although this may be related more to substrate stability rather than physiological adaptation to living in faster water. All three species have been found in small rivers in moderate to high flow velocities; yellow lampmussels in particular have been found in fast flows in Maine (examples: Penobscot River, Passadumkeag River, Mattawamkeag River) and in Pennsylvania (Susquehanna River) although usually in deep runs or pools rather than in riffles. Eastern pondmussels have also been found in high numbers in small to moderate-sized rivers, such as Mill River (MA), Farmington River (CT), several rivers in southeastern MA. In these faster-flowing rivers, they are usually found closer to streambanks and other refugia, yet in close proximity to fast flows. Tidewater muckets have also been found in a wide range of stream sizes and flow velocities, but generally seem to occur in flow refugia and depositional environments within those rivers that have a wide range of flow velocities. For the purposes of the proposed HSI curve, although we recognize that there will be wide variation and opinions on habitat suitability at the upper end of flow values (i.e., approaching and exceeding 1 m/s), we base the final proposed curve on the effects of flows on mobilizing the fine-grained particles that all three species tend to prefer, rather than on any physiological stress imposed by strong flows.

Feedback from Panelist (attach any files or supporting evidence, as needed):

Substrate: There was general agreement that the optimal substrates for all three species was fine-grained material such as silt, sand, and fine gravel. This is generally supported by field observations throughout each species' range in a wide variety of habitats (lakes, ponds, small and large rivers). Although organic material/detritus is an important component of the substrate, we generally believe that areas where organic material is the dominant substrate (such as accumulations of leaves, senescent vegetation, detritus) are not ideal for any of the species. This may be due to a poor environment for burrowing or remaining upright, or poor chemical environment (i.e., low oxygen) in areas with dead/decaying organic material. For the proposed binary curve, organic material is considered unsuitable for all three species. Due to Round 2 feedback, "Clay/Mud" was changed to include only Clay and scored as unsuitable for all three species. Everything from mud/silt up to coarse gravel is considered suitable for all three species in the binary curve, even though suitability scores do begin to drop for eastern pondmussel and tidewater mucket at particle sizes larger than 32 mm. The proposed binary curve for yellow lampmussels is slightly different than for the other two species, as yellow lampmussels do seem to occur more often in coarser gravel, especially in rivers in Maine, Pennsylvania, and New York. Large cobble, boulder, and bedrock are not suitable for any species, although these coarser materials may sometimes be an essential component of a mussel bed because they help to anchor the substrate and stabilize finer-grained materials, and may also provide cover/flow refuge for mussels.

Feedback from Panelist (attach any files or supporting evidence, as needed):

Water Depth: The only full consensus was that a water depth of zero is unsuitable! In general, it is assumed that mussels can persist and even thrive in very shallow water, as long as the shallow conditions do not lead to other stressors such as thermal stress or increased risk of predation. Of the three mussel species, eastern pondmussels are more apt to be found in very shallow water...in fact, there is even evidence that gravid females will migrate into extremely shallow water prior to release of glochidia, presumably to increase potential encounters with host fish. In the lower end of the Holyoke impoundment in the Connecticut River, eastern pondmussels were found almost exclusively in nearshore environments in depths less than 3 ft, usually within or upslope of dense beds of aquatic vegetation and coarse woody debris. In other rivers, such as Mill River (MA) and Farmington River (CT), eastern pondmussels were often found in only inches of water, within 1-2 ft of the water line. Likewise, tidewater muckets have been found within the intertidal zone, or just downslope, in the tidal portions of the Connecticut River, and they have also been found in high densities in less than a foot of water in lakes of southeastern Massachusetts. Nevertheless, for the binary curve, we do propose that anything less than 10 cm is unsuitable for all three species, mainly due to risks of existing in such a shallow environment. For the binary curve, we propose that everything greater than 10cm is optimal for all species. There is no evidence that there is an upper depth limit for any of these species. Depending on Round 2 feedback, we may propose a separate binary curve for yellow lampmussels with 0 for the third depth class, as yellow lampmussels seem to occur less often in extremely shallow water.

Feedback from Panelist (attach any files or supporting evidence, as needed):

Cover: Mussels do not seem to be particularly responsive to cover, and the type of cover (as we defined it in the Round 1 questionnaire) seems to not matter. All three species can exist within or near cover of all types, such as beds of submerged aquatic vegetation, coarse wood, steep banks with overhanging vegetation, and coarse rock. Based on the responses and considering habitat data from across each species' range, we consolidated all cover types. The binary curves for eastern pondmussel and tidewater mucket ended up being the same. Yellow lampmussels seem to not occur in areas with dense cover. Certainly within their range in the lower Connecticut River, yellow lampmussels have been found primarily in more open areas, whereas the other two species may be closer to or within cover such as SAV beds. Despite any minor modifications that could be made to these curves, we think its safe to conclude that cover will be less important than other parameters in assessing effects of flow operations on mussels.

Feedback from Panelist (attach any files or supporting evidence, as needed):

Shear Stress and Relative Shear Stress: Please see attached text document for more details.

Feedback from Panelist (attach any files or supporting evidence, as needed): It would be helpful if you added comments on the attached word document, which describes the challenges with these two parameters.

Yellow Lampmussel				Raw Scores										Juvenile					Adult					
				P1	P2	P3	P4	P5	P1	P2	P3	P4	P5											
Parameter	**Class**	**Velocity Range (m/s)**		**J**	**J**	**J**	**J**	**J**	**A**	**A**	**A**	**A**	**A**	**Mean**	**Median**	**Curve****	**Binary****		**Mean**	**Median**	**Curve****	**Binary****	**J+A Binary****	**Rationale for Noted Departure**
Flow Velocity	1	<0.05		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00	-	
Flow Velocity	2	0.05 - 0.10		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00	-	
Flow Velocity	3	0.11 - 0.20		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00	-	
Flow Velocity	4	0.21 - 0.30		1.0	0.8	0.7	1.0		1.0	1.0	1.0	1.0		0.88	0.90	0.90	1.00		1.00	1.00	1.00	1.00	-	
Flow Velocity	5	0.31 - 0.40		1.0	0.5	0.5	1.0		1.0	1.0	0.7	1.0		0.75	0.75	0.75	1.00		0.93	1.00	1.00	1.00	-	
Flow Velocity	6	0.41 - 0.50		1.0	0.5	0.3	1.0		1.0	1.0	0.5	1.0		0.70	0.75	0.75	1.00		0.88	1.00	0.90	1.00	-	
Flow Velocity	7	0.51 - 0.75		0.3	0.3	0.1	1.0		0.3	0.5	0.3	1.0		0.43	0.30	0.40	0.00		0.53	0.40	0.50	1.00	-	
Flow Velocity	8	0.76 - 1.00		0.3	0.1	0.0	1.0		0.3	0.3	0.1	1.0		0.35	0.20	0.30	0.00		0.43	0.30	0.40	0.00	-	
Flow Velocity	9	1.01 - 1.50		0.1	0.0	0.0	1.0		0.1	0.1	0.0	1.0		0.28	0.05	0.20	0.00		0.30	0.10	0.30	0.00	-	
Flow Velocity	10	1.51 - 2.00		0.1	0.0	0.0	1.0		0.1	0.0	0.0	1.0		0.28	0.05	0.10	0.00		0.28	0.05	0.20	0.00	-	
Flow Velocity	11	>2.0		0.1	0.0	0.0	0.6		0.1	0.0	0.0	0.6		0.18	0.05	0.00	0.00		0.18	0.05	0.10	0.00	-	
Parameter	**Class**	**Depth Range (m)**																						
Water Depth	1	0		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0		0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	
Water Depth	2	0.01 - 0.10		1.0	1.0	0.0	0.4		1.0	1.0	0.0	0.4		0.60	0.70	0.65	0.00		0.60	0.70	0.65	0.00	0.00	Although both juveniles and adults can survive in water less than 10cm, we consider this unsuitable due to risks of dessication, predation, etc.
Water Depth	3	0.11 - 0.25		1.0	1.0	0.0	0.8		1.0	1.0	0.0	0.8		0.70	0.90	0.75	1.00		0.70	0.90	0.75	1.00	1.00	
Water Depth	4	0.26 - 0.50		1.0	1.0	0.3	1.0		1.0	1.0	0.3	1.0		0.83	1.00	0.90	1.00		0.83	1.00	1.00	1.00	1.00	
Water Depth	5	0.51 - 0.75		1.0	1.0	0.7	1.0		1.0	1.0	0.7	1.0		0.93	1.00	1.00	1.00		0.93	1.00	1.00	1.00	1.00	
Water Depth	6	0.76 - 1.00		1.0	1.0	0.9	1.0		1.0	1.0	0.9	1.0		0.98	1.00	1.00	1.00		0.98	1.00	1.00	1.00	1.00	
Water Depth	7	1.01 - 1.50		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00	1.00	
Water Depth	8	1.51 - 2.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00	1.00	
Water Depth	9	2.01 - 3.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00	1.00	
Water Depth	10	3.01 - 4.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00	1.00	
Water Depth	11	>4.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00	1.00	
Parameter	**Class**	**Particle Size**	**Substrate Name**																					
Substrate	1		Organic Material	-	0.0	0.1	0.0		-	0.0	0.4	0.0		0.03	0.00	0.00	0.00		0.13	0.00	0.10	0.00	0.00	
Substrate	2		Clay	1.0	0.0	0.2	0.0		1.0	0.0	0.5	0.0		0.30	0.10	0.25	0.00		0.38	0.25	0.30	0.00	0.00	
Substrate	3	<0.062 mm	Mud/Silt	1.0	0.5	0.7	0.3		1.0	0.5	0.8	0.3		0.63	0.60	0.60	1.00		0.65	0.65	0.65	1.00	1.00	Observations from the range of waterbodies that yellow lampmussels inhabit suggest that both mud and clay are suitable substrates. Its not clear how different "mud" is from "silt". We welcome any ideas on this.
Substrate	4	0.062 - 2.0 mm	Sand	1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00	1.00	
Substrate	5	2.0 - 32.0 mm	Fine Gravel	1.0	0.5	1.0	1.0		1.0	1.0	1.0	1.0		0.88	1.00	0.90	1.00		1.00	1.00	1.00	1.00	1.00	
Substrate	6	32.0 - 64.0 mm	Coarse Gravel	1.0	0.0	0.4	1.0		1.0	0.5	0.7	1.0		0.60	0.70	0.65	1.00		0.80	0.85	0.80	1.00	1.00	
Substrate	7	64.0 - 150.0 mm	Small Cobble	1.0	0.0	0.1	1.0		1.0	0.3	0.2	1.0		0.53	0.55	0.55	1.00		0.63	0.65	0.60	1.00	1.00	Substrate class changed from "Mud/Clay" to Clay
Substrate	8	150.0 - 250.0 mm	Large Cobble	0.3	0.0	0.0	1.0		0.3	0.0	0.0	1.0		0.33	0.15	0.25	0.00		0.33	0.15	0.25	0.00	0.00	Substrate Class changed from "Silt" to "Mud/Silt"
Substrate	9	250.0 - 4,000 mm	Boulder	0.1	0.0	0.0	1.0		0.1	0.0	0.0	1.0		0.28	0.05	0.10	0.00		0.28	0.05	0.10	0.00	0.00	
Substrate	10		Bedrock	0.1	0.0	0.0	0.0		0.1	0.0	0.0	0.0		0.03	0.00	0.00	0.00		0.03	0.00	0.00	0.00	0.00	
Parameter	**Class**	**Percent Cover**																						
Cover	1	0		-	1.0	1.0	1.0		-	1.0	1.0	1.0		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00	-	
Cover	2	1 - 10.0%		-	1.0	1.0	1.0		-	1.0	1.0	1.0		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00	-	There is no evidence to suggest that dense cover is unsuitable for yellow lampmussels, especially for juveniles that tend to remain buried and can benefit from the flow refuge/stability that cover can provide.
Cover	3	10.1 - 25.0%		-	0.0	1.0	1.0		-	0.0	1.0	1.0		0.67	1.00	0.75	1.00		0.67	1.00	0.75	1.00	-	
Cover	4	26.1 - 50.0%		-	0.0	1.0	0.5		-	0.0	0.9	0.5		0.50	0.50	0.50	1.00		0.47	0.50	0.50	1.00	-	
Cover	5	50.1 - 75.0%		-	0.0	0.9	0.3		-	0.0	0.7	0.3		0.40	0.30	0.35	1.00		0.33	0.30	0.30	1.00	-	
Cover	6	75.1 - 100%		-	0.0	0.8	0.0		-	0.0	0.5	0.0		0.27	0.00	0.10	1.00		0.17	0.00	0.00	0.00	-	
Parameter																								
Shear Stress	SS	Low		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00	1.00	We are not proposing binary HSC at this time.
		Medium		1.0	0.0	0.5	1.0		1.0	1.0	0.5	1.0		0.63	0.75	0.70	1.00		0.88	1.00	0.90	1.00	1.00	
		High		0.3	0.0	0.0	0.5		0.3	0.0	0.0	1.0		0.20	0.15	0.10	0.00		0.33	0.15	0.25	0.00	0.00	
Relative SS	RSS	Low		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00	-	
		Medium		1.0	0.0	0.5	0.5		1.0	1.0	0.5	1.0		0.50	0.50	0.50	0.00		0.88	1.00	0.90	1.00	-	
		High		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.5		0.00	0.00	0.00	0.00		0.13	0.00	0.10	0.00	-	

*P = Panelists (1-5); still waiting on scores for Panelist 5. J = Juvenile. A = Adult

**The proposed scores for juveniles, adults, and combined life stages is based on range of scores provided, rationale provided by experts for their scores, and other case studies and publications.

Marked to indicate a deviation from the Delphi panelists scores and the proposed binary score for that species/life stage.
Usually, the binary score (which must be 0 or 1, by definition) is 0 if panelists scores are less than 0.5, and 1 if panelists scores are 0.5 or higher.

In first two rounds, this substrate class was called "Mud/Clay" and is now switched to just clay. Thus, we do not have panelist scores on suitability of clay. We are leaving the original scores here, but changing the proposed binary scores to 0.

Eastern Pondmussel				Raw Scores										Juvenile				Adult					
				P1	P2	P3	P4	P5	P1	P2	P3	P4	P5										
Parameter	Class	Velocity Range (m/s)		J	J	J	J	J	A	A	A	A	A	Mean	Median	Curve**	Binary**	Mean	Median	Curve**	Binary**	J+A Binary**	Rationale for Noted Departure
Flow Velocity	1	<0.05		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Flow Velocity	2	0.05 - 0.10		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Flow Velocity	3	0.11 - 0.20		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Flow Velocity	4	0.21 - 0.30		1.0	0.8	0.7	1.0		1.0	1.0	0.9	1.0		0.88	0.90	0.90	1.00	0.98	1.00	1.00	1.00	1.00	
Flow Velocity	5	0.31 - 0.40		1.0	0.5	0.5	1.0		1.0	1.0	0.7	1.0		0.75	0.75	0.75	1.00	0.93	1.00	1.00	1.00	1.00	
Flow Velocity	6	0.41 - 0.50		1.0	0.5	0.2	1.0		1.0	1.0	0.4	1.0		0.68	0.75	0.70	1.00	0.85	1.00	0.90	1.00	1.00	
Flow Velocity	7	0.51 - 0.75		0.3	0.3	0.0	0.4		0.3	0.5	0.2	0.4		0.25	0.30	0.30	0.00	0.35	0.35	0.35	0.00	0.00	
Flow Velocity	8	0.76 - 1.00		0.3	0.1	0.0	0.4		0.3	0.3	0.0	0.4		0.20	0.20	0.20	0.00	0.25	0.30	0.30	0.00	0.00	
Flow Velocity	9	1.01 - 1.50		0.1	0.0	0.0	0.2		0.1	0.1	0.0	0.2		0.08	0.05	0.10	0.00	0.10	0.10	0.10	0.00	0.00	
Flow Velocity	10	1.51 - 2.00		0.1	0.0	0.0	0.2		0.1	0.0	0.0	0.2		0.08	0.05	0.10	0.00	0.08	0.05	0.00	0.00	0.00	
Flow Velocity	11	>2.0		0.1	0.0	0.0	0.2		0.1	0.0	0.0	0.2		0.08	0.05	0.10	0.00	0.08	0.05	0.00	0.00	0.00	
Parameter	Class	Depth Range (m)																					
Water Depth	1	0		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Water Depth	2	0.01 - 0.10		1.0	1.0	0.1	0.4		1.0	1.0	0.1	0.4		0.63	0.70	0.60	0.00	0.63	0.70	0.65	0.00	0.00	Although both juveniles and adults can survive in water less than 10cm, we consider this unsuitable due to risks of dessication, predation, etc.
Water Depth	3	0.11 - 0.25		1.0	1.0	0.3	0.8		1.0	1.0	0.5	0.8		0.78	0.90	0.80	1.00	0.83	0.90	0.85	1.00	1.00	
Water Depth	4	0.26 - 0.50		1.0	1.0	0.5	1.0		1.0	1.0	0.8	1.0		0.88	1.00	0.90	1.00	0.95	1.00	1.00	1.00	1.00	
Water Depth	5	0.51 - 0.75		1.0	1.0	0.8	1.0		1.0	1.0	1.0	1.0		0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	6	0.76 - 1.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	7	1.01 - 1.50		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	8	1.51 - 2.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	9	2.01 - 3.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	10	3.01 - 4.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	11	>4.00		1.0	1.0	1.0	1.0		1.0	1.0	0.8	1.0		1.00	1.00	1.00	1.00	0.95	1.00	1.00	1.00	1.00	
Parameter	Class	Particle Size	Substrate Name																				
Substrate	1		Organic Material	-	0.0	0.6	0.0		-	0.0	0.8	0.0		0.20	0.00	0.10	0.00	0.27	0.00	0.25	0.00	-	
Substrate	2		Clay	1.0	0.5	1.0	0.0		1.0	0.5	1.0	0.0		0.63	0.75	0.70	0.00	0.63	0.75	0.70	0.00	-	Substrate class changed from "Mud/Clay" to Clay
Substrate	3	<0.062 mm	Mud/Silt	1.0	1.0	1.0	0.4		1.0	1.0	1.0	0.4		0.85	1.00	0.90	1.00	0.85	1.00	0.90	1.00	-	Substrate Class changed from "Silt" to "Mud/Silt"
Substrate	4	0.062 - 2.0 mm	Sand	1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
Substrate	5	2.0 - 32.0 mm	Fine Gravel	1.0	0.5	1.0	1.0		1.0	0.5	1.0	1.0		0.88	1.00	0.90	1.00	0.88	1.00	1.00	1.00	-	
Substrate	6	32.0 - 64.0 mm	Coarse Gravel	0.3	0.0	0.4	1.0		0.3	0.0	0.6	1.0		0.43	0.35	0.40	0.00	0.48	0.45	0.50	1.00	-	
Substrate	7	64.0 - 150.0 mm	Small Cobble	0.3	0.0	0.1	1.0		0.3	0.0	0.1	1.0		0.35	0.20	0.25	0.00	0.35	0.20	0.30	0.00	-	
Substrate	8	150.0 - 250.0 mm	Large Cobble	0.3	0.0	0.0	1.0		0.3	0.0	0.0	1.0		0.33	0.15	0.25	0.00	0.33	0.15	0.25	0.00	-	
Substrate	9	250.0 - 4,000 mm	Boulder	0.1	0.0	0.0	1.0		0.1	0.0	0.0	1.0		0.28	0.05	0.20	0.00	0.28	0.05	0.10	0.00	-	
Substrate	10		Bedrock	0.1	0.0	0.0	1.0		0.1	0.0	0.0	1.0		0.28	0.05	0.20	0.00	0.28	0.05	0.10	0.00	-	
Parameter	Class	Percent Cover																					
Cover	1	0		-	1.0	0.8	-		-	1.0	0.6	-		0.90	0.90	0.90	1.00	0.80	0.80	0.80	1.00	1.00	There is no evidence to suggest that dense cover is unsuitable for eastern pondmussels, especially for juveniles that tend to remain buried and can benefit from the flow refuge/stability that cover can provide. In the Connecticut River, eastern pondmussels were nearly always found within or near dense nearshore cover.
Cover	2	1 - 10.0%		-	1.0	0.9	-		-	1.0	0.8	-		0.95	0.95	0.95	1.00	0.90	0.90	0.90	1.00	1.00	
Cover	3	10.1 - 25.0%		-	0.0	1.0	-		-	0.0	1.0	-		0.50	0.50	0.50	1.00	0.50	0.50	0.50	1.00	1.00	
Cover	4	26.1 - 50.0%		-	0.0	1.0	-		-	0.0	1.0	-		0.50	0.50	0.50	1.00	0.50	0.50	0.50	1.00	1.00	
Cover	5	50.1 - 75.0%		-	0.0	1.0	-		-	0.0	1.0	-		0.50	0.50	0.50	1.00	0.50	0.50	0.50	1.00	1.00	
Cover	6	75.1 - 100%		-	0.0	0.8	-		-	0.0	0.8	-		0.40	0.40	0.40	1.00	0.40	0.40	0.40	1.00	1.00	
Parameter																							
Shear Stress	SS	Low		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	We are not proposing binary HSC at this time.
		Medium		1.0	0.0	0.5	1.0		1.0	1.0	0.5	1.0		0.63	0.75	0.75	1.00	0.88	1.00	0.75	1.00	1.00	
		High		0.3	0.0	0.0	0.5		0.3	0.0	0.0	1.0		0.20	0.15	0.00	0.00	0.33	0.15	0.25	0.00	0.00	
Relative SS	RSS	Low		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
		Medium		1.0	0.0	0.5	0.5		1.0	1.0	0.5	1.0		0.50	0.50	0.50	0.00	0.88	1.00	0.75	1.00	-	
		High		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.5		0.00	0.00	0.00	0.00	0.13	0.00	0.25	0.00	-	

*P = Panelists (1-5); still waiting on scores for Panelist 5. J = Juvenile. A = Adult

**The proposed scores for juveniles, adults, and combined life stages is based on range of scores provided, rationale provided by experts for their scores, and other case studies and publications.

Marked to indicate a deviation from the Delphi panelists scores and the proposed binary score for that species/life stage.
Usually, the binary score (which must be 0 or 1, by definition) is 0 if panelists scores are less than 0.5, and 1 if panelists scores are 0.5 or higher.

In first two rounds, this substrate class was called "Mud/Clay" and is now switched to just clay. Thus, we do not have panelist scores on suitability of clay. We are leaving the original scores here, but changing the proposed binary scores to 0.

Tidewater Mucket				Raw Scores*										Juvenile				Adult					
				P1	P2	P3	P4	P5	P1	P2	P3	P4	P5										
Parameter	Class	Velocity Range (m/s)		J	J	J	J	J	A	A	A	A	A	Mean	Median	Curve**	Binary**	Mean	Median	Curve**	Binary**	J+A Binary**	Rationale for Noted Departure
Flow Velocity	1	<0.05		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
Flow Velocity	2	0.05 - 0.10		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
Flow Velocity	3	0.11 - 0.20		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
Flow Velocity	4	0.21 - 0.30		1.0	0.8	0.7	1.0		1.0	1.0	0.9	1.0		0.88	0.90	0.90	1.00	0.98	1.00	1.00	1.00	-	
Flow Velocity	5	0.31 - 0.40		1.0	0.5	0.5	1.0		1.0	1.0	0.7	1.0		0.75	0.75	0.75	1.00	0.93	1.00	1.00	1.00	-	
Flow Velocity	6	0.41 - 0.50		1.0	0.5	0.2	1.0		1.0	1.0	0.4	1.0		0.68	0.75	0.70	1.00	0.85	1.00	0.90	1.00	-	
Flow Velocity	7	0.51 - 0.75		1.0	0.3	0.0	1.0		1.0	0.5	0.2	1.0		0.58	0.65	0.60	0.00	0.68	0.75	0.70	1.00	-	There seemed to be some inconsistency with scoring that suggested L. ochracea preferred higher flows than L. cariosa. Binary scores wereadjusted to match that of L. cariosa, as this is more consistent with field observations throughout the species range.
Flow Velocity	8	0.76 - 1.00		1.0	0.1	0.0	1.0		1.0	0.3	0.0	1.0		0.53	0.55	0.55	0.00	0.58	0.65	0.60	0.00	-	
Flow Velocity	9	1.01 - 1.50		0.1	0.0	0.0	1.0		0.1	0.1	0.0	1.0		0.28	0.05	0.20	0.00	0.30	0.10	0.25	0.00	-	
Flow Velocity	10	1.51 - 2.00		0.1	0.0	0.0	1.0		0.1	0.0	0.0	1.0		0.28	0.05	0.20	0.00	0.28	0.05	0.10	0.00	-	
Flow Velocity	11	>2.0		0.1	0.0	0.0	0.6		0.1	0.0	0.0	0.6		0.18	0.05	0.10	0.00	0.18	0.05	0.10	0.00	-	
Parameter	**Class**	**Depth Range (m)**																					
Water Depth	1	0		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Water Depth	2	0.01 - 0.10		1.0	1.0	0.1	0.4		1.0	1.0	0.1	0.4		0.63	0.70	0.65	0.00	0.63	0.70	0.65	0.00	0.00	Although both juveniles and adults can survive in water less than 10cm, we consider this unsuitable due to risks of dessication, predation, etc.
Water Depth	3	0.11 - 0.25		1.0	1.0	0.3	0.8		1.0	1.0	0.4	0.8		0.78	0.90	0.80	1.00	0.80	0.90	0.85	1.00	1.00	
Water Depth	4	0.26 - 0.50		1.0	1.0	0.5	1.0		1.0	1.0	0.7	1.0		0.88	1.00	0.90	1.00	0.93	1.00	1.00	1.00	1.00	
Water Depth	5	0.51 - 0.75		1.0	1.0	0.8	1.0		1.0	1.0	0.9	1.0		0.95	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	
Water Depth	6	0.76 - 1.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	7	1.01 - 1.50		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	8	1.51 - 2.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	9	2.01 - 3.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	10	3.01 - 4.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Water Depth	11	>4.00		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Parameter	**Class**	**Particle Size**	**Substrate Name**																				
Substrate	1		Organic Material	-	0.0	0.3	0.0		-	0.0	0.5	0.0		0.10	0.00	0.10	0.00	0.17	0.00	0.10	0.00	0.00	
Substrate	2		Clay	1.0	1.0	0.6	0.0		1.0	1.0	0.8	0.0		0.65	0.80	0.75	0.00	0.70	0.90	0.80	0.00	0.00	Substrate class changed from "Mud/Clay" to Clay
Substrate	3	<0.062 mm	Mud/Silt	1.0	1.0	1.0	0.4		1.0	1.0	1.0	0.4		0.85	1.00	0.90	1.00	0.85	1.00	0.90	1.00	1.00	Substrate Class changed from "Silt" to "Mud/Silt"
Substrate	4	0.062 - 2.0 mm	Sand	1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Substrate	5	2.0 - 32.0 mm	Fine Gravel	1.0	0.5	1.0	1.0		1.0	1.0	1.0	1.0		0.88	1.00	0.90	1.00	1.00	1.00	1.00	1.00	1.00	
Substrate	6	32.0 - 64.0 mm	Coarse Gravel	1.0	0.3	0.4	1.0		1.0	1.0	0.5	1.0		0.68	0.70	0.70	1.00	0.88	1.00	0.90	1.00	1.00	
Substrate	7	64.0 - 150.0 mm	Small Cobble	0.3	0.0	0.0	1.0		0.3	0.5	0.1	1.0		0.33	0.15	0.25	0.00	0.48	0.40	0.45	0.00	0.00	
Substrate	8	150.0 - 250.0 mm	Large Cobble	0.3	0.0	0.0	1.0		0.3	0.3	0.0	1.0		0.33	0.15	0.25	0.00	0.40	0.30	0.35	0.00	0.00	
Substrate	9	250.0 - 4,000 mm	Boulder	0.1	0.0	0.0	1.0		0.1	0.0	0.0	1.0		0.28	0.05	0.20	0.00	0.28	0.05	0.10	0.00	0.00	
Substrate	10		Bedrock	0.1	0.0	0.0	0.0		0.1	0.0	0.0	0.0		0.03	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	
Parameter	**Class**	**Percent Cover**																					
Cover	1	0		-	1.0	0.8	1.0		-	1.0	0.8	1.0		0.93	1.00	1.00	1.00	0.93	1.00	1.00	1.00	-	
Cover	2	1 - 10.0%		-	1.0	1.0	1.0		-	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
Cover	3	10.1 - 25.0%		-	0.0	1.0	1.0		-	0.0	1.0	1.0		0.67	1.00	0.80	1.00	0.67	1.00	1.00	1.00	-	There is no evidence to suggest that dense cover is unsuitable for tidewater muckets, especially for juveniles that tend to remain buried and can benefit from the flow refuge/stability that cover can provide.
Cover	4	26.1 - 50.0%		-	0.0	1.0	0.5		-	0.0	1.0	0.5		0.50	0.50	0.50	1.00	0.50	0.50	0.60	1.00	-	
Cover	5	50.1 - 75.0%		-	0.0	1.0	0.3		-	0.0	0.8	0.3		0.43	0.30	0.50	1.00	0.37	0.30	0.35	1.00	-	
Cover	6	75.1 - 100%		-	0.0	0.8	0.0		-	0.0	0.7	0.0		0.27	0.00	0.50	1.00	0.23	0.00	0.10	0.00	-	
Parameter																							
Shear Stress	SS	Low		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	We are not proposing binary HSC at this time.
		Medium		1.0	0.0	0.5	1.0		1.0	1.0	0.5	1.0		0.63	0.75	0.70	1.00	0.88	1.00	0.75	1.00	1.00	
		High		0.3	0.0	0.0	0.5		0.3	0.0	0.0	1.0		0.20	0.15	0.15	0.00	0.33	0.15	0.25	0.00	0.00	
Relative SS	RSS	Low		1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
		Medium		1.0	0.0	0.5	0.5		1.0	1.0	0.5	1.0		0.50	0.50	0.50	0.00	0.88	1.00	0.75	1.00	-	
		High		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.5		0.00	0.00	0.00	0.00	0.13	0.00	0.25	0.00	-	

*P = Panelists (1-5); still waiting on scores for Panelist 5. J = Juvenile. A = Adult

**The proposed scores for juveniles, adults, and combined life stages is based on range of scores provided, rationale provided by experts for their scores, and other case studies and publications.

Marked to indicate a deviation from the Delphi panelists scores and the proposed binary score for that species/life stage.
Usually, the binary score (which must be 0 or 1, by definition) is 0 if panelists scores are less than 0.5, and 1 if panelists scores are 0.5 or higher.

In first two rounds, this substrate class was called "Mud/Clay" and is now switched to just clay. Thus, we do not have panelist scores on suitability of clay. We are leaving the original scores here, but changing the proposed binary scores to 0.

Case studies, publications, or datasets upon which the scoring was based.

Species	River/Lake	Project Name	Information Available?
Alasmidonta heterodon	NY Delaware River	Maloney et al. 2012. Freshwater Biology 57:1315-1327.	Yes
Eastern Pondmussel	Connecticut River and tributaries in CT	State-wide mussel surveys for CT DEEP and misc. environmental review pro	Yes - Biodrawversity datasets
Eastern Pondmussel	Connecticut River in MA	Studies for Holyoke Gas & Electric in the Holyoke Dam impoundment	Yes - FERC record & Biodrawversity datasets, HGE client
Eastern Pondmussel	Lab experiments	French and Ackermann 2014. Freshwater Science. 2014. 33(1):46–55	Yes
Eastern Pondmussel	Lakes and ponds in southeastern MA	Coastal pond research for NHESP and misc. environmental review projects	Yes - Biodrawversity datasets, NHESP primary client
Eastern Pondmussel	Mill River in Whately, MA	Mussel relocation and monitoring for Whately Municipal Well Project	Yes - Biodrawversity dataset, client Town of Whately, oversight from NHESP
Eastern Pondmussel	Waterbodies in southeast New Hampshire	Research for NHFG and misc. environmental review projects	Yes - Biodrawversity datasets, NHFG primary client
Eastern Pondmussel	Webatuck Creek, Allegheny River basin, Lake Taghkanic, Niagara River		based on casual observations of field conditions rather than measurements; some data in Strayer 1999 JNABS 18: 468-476.
Tidewater Mucket	Connecticut River and tributaries in CT	State-wide mussel surveys for CT DEEP and misc. environmental review pro	Yes - Biodrawversity datasets
Tidewater Mucket	Connecticut River in MA	Studies for Holyoke Gas & Electric in the Holyoke Dam impoundment	Yes - FERC record & Biodrawversity datasets, HGE client
Tidewater Mucket	Hudson River estuary		based on casual observations of field conditions rather than measurements
Tidewater Mucket	Lakes and ponds in southeastern MA	Coastal pond research for NHESP and misc. environmental review projects	Yes - Biodrawversity datasets, NHESP primary client
Tidewater Mucket	PA streams	Ortmann, 1919. Naiads of PA	Yes
Tidewater Mucket	Penobscot River in ME	Penobscot River Restoration Project	Yes - Biodrawversity dataset, PRRT client, oversight by MDIFW
Tidewater Mucket	Susquehanna River in MD	Conowingo Dam relicensing project	Yes - FERC record. Gomez & Sullivan lead consultant, Biodrawversity/Normandeau dataset.
Yellow Lampmussel	Connecticut River and tributaries in CT	State-wide mussel surveys for CT DEEP and misc. environmental review pro	Yes - Biodrawversity datasets
Yellow Lampmussel	Connecticut River in MA	Studies for Holyoke Gas & Electric in the Holyoke Dam impoundment	Yes - FERC record & Biodrawversity datasets, HGE client
Yellow Lampmussel	Kennebec and Penobscot watersheds in ME	Statewide surveys in the last 25 years	Yes - MDIFW database, Biodrawversity datasets
Yellow Lampmussel	PA streams	Ortmann, 1919. Naiads of PA	Yes
Yellow Lampmussel	Penobscot River in ME	Penobscot River Restoration Project	Yes - Biodrawversity dataset, PRRT client, oversight by MDIFW
Yellow Lampmussel	Susquehanna River basin streams	basin-wide survey	based on casual observations of field conditions rather than measurements
Yellow Lampmussel	Susquehanna River in PA	Mussel Survey and Hydraulic Analysis for Bell Bend Nuclear Project	Yes - FERC record & Biodrawversity dataset (Kleinschmidt lead consultant)
Multiple species	Louisiana	Wesley and Brown 2013. Freshwater Science, 2013, 32(1):193–203	Yes
Multiple species	NY	Strayer 1999. North American Benthological Society 18:468-476	Yes
Multiple species	NY river	Strayer 1999. North American Benthological Society 18:468-476.	Yes
Multiple species	OK	Vaughn and Taylor 2000. Ecography 23:11-20.	Yes
Multiple species	OK River	Allen and Vaughn 2010. J. North Am. Benthological Society 29:383-394.	Yes
Multiple species	Upper Mississippi	Steuer 2008. Hydrobiologia (2008) 610:67–82	Yes
Multiple species	Upper Mississippi	Zigler et al. 2008. Hydrobiologia 598:343-360.	Yes
All three species	CT River	Nadeau 2008. Freshwater mussels of the CT River watershed	Yes
All three species	NY rivers	Strayer and Jirka 1997. Pearly mussels of NY state	Yes

Additional Comments from Panelists from the Round 1 and 2 Questionnaires

General: you haven't explained why you went to a binary scale (which could entail loss of information), nor how we are supposed to interpret the "1" and "0" scores. I therefore cannot comment on the new scale, which might or might not be an improvement.

Water Depth

There appears to be no upper limit on the depth that these species will inhabit, except that they often do not occur well below the thermocline in stratified lakes. Of the three, yellow lampmussel seems to occur in the greatest range of depths, in water well in excess of 5 meters, whereas tidewater mucket and eastern pondmussel tend to occur in shallow to intermediate depths in more complex habitats (such as near weed beds, or on sloping streambanks). Eastern pondmussels may actually migrate into shallow water during the spawning season to make themselves more visible to host fish, then migrate back down into deeper water after spawning season is complete. In the tidal Connecticut River, eastern pondmussel and tidewater mucket may track daily tides or remain close to the interidal-subtidal boundary, such that they may be found in only centimeters of water at low tide. Overall, habitat suitability criteria should probably focus on the shallow end of the depth spectrum.

I don't believe that any of these species cares about water depth, other than the possibility of being dried out or overheated at very shallow depths. We routinely collected ochracea from the Hudson estuary at depths of >4m before zebra mussels arrived (some data in Strayer et al. Freshwater Biology 31: 239-248, 1994)

Depth does not seem to be predictive of mussel distribution.

Substrate

I believe that these species, like most unionids, are nearly indifferent to sediment grain size per se, and may tolerate a wide range of grain sizes depending on the hydraulic and chemical habitat. Some data for nasuta and ochracea were published in the 2 papers that I'm enclosing (JNABS 18: 468-476, Freshwater Biology 31: 239-248

I don't know what you mean by "organic material". FYI, we often collect nasuta from soft clay/silt in Webatuck Creek

Interstitial oxygen gradient in fine sediments is likely to limit juvenile distribution for all three species. I have found L. cariosa and L. ochracea in fine sand in ponds in Maine. Substate size may be less predictive than shear stress during floods. I found L. nasuta in mud in the Framingham River, MA.

I doubt that there is any evidence that the species "prefer" fine sediments, although they may often be found there.

All mussel species are burrowers, therefore they will always prefer substrates in which they can burrow. The presence of other substrates, such as coarse rock (large gravel, cobble, boulder, even bedrock) may be important for its role in anchoring/stabilizing the streambed and keeping fine sediments from being mobilized, and also by increasing substrate permeability and thus exchange of water, gases, nutrients between the water column and the upper layer of substrate. Therefore, mussels may have a direct relationship with substrates they prefer to burrow in, and an indirect relatiobnship with substrates that help to promate/retain their preferred substrates and improve the quality of the benthic environment. Substrate diversity may be as important as any single substrate type, and its worthwhile to consider habitat suitability scores that account for diversity. For example, yellow lampmussels prefer to burrow in sand and are rarely found in cobble, but a riverbed that contains only sand is not as suitable as a riverbed that contains both sand and cobble (or other coarse rock). Of the three species, Eastern Pondmussel seem most tolerant of organics, mud, clay, and silt, followed by Tidewater Mucket and Yellow Lampmussel. All three species seem to prefer sand and fine gravel, then suitability diminishes with increasing grain size.

If you are categorizing mud and clay together into one type, I do not think it should be considered suitable. Clay particles are more cohesive than mud and silt particles and are likely to be compacted to the point of precluding burrowing. Mud is a mixture of water, soil, silt, and clay and likely more loosely associated than clay. Substrate with a larger component of mud than clay probably would be suitable for these species, but a substrate comprised more of clay than mud likely would be too dense. So, I think you should categorize clay and mud/clay mixture as unsuitable if you are going to combine them into one type. If you separate them, I would categorize clay as unsuitable because of the compacted nature and mud as suitable. Silt particles are loose (although they can become compacted), may be larger than clay but they are smaller than sand particles, and I think the mineral origin is quartz. Silt particles can easily become compacted but usually are suspended in water.

Cover

Sorry, I don't have any observations about this. I have seen mussels in and around vegetation (including nasuta, in a lake), detritus, large rocks, etc., but don't know whether these favor or disfavor mussels. I suppose that cover could either stabilize or destabilize sediments, which ought to affect mussels.

I don't think that cover explains mussel distribution very well; although it may provide flow refuges for both adult and juvenile mussels. Vaughn and Taylor 2000 relate mussel distribution to host fish distribution which may involve cover, but mussels primarily require optimal environments (stable habitats.)

I don't think these will be particularly useful in any subsequent analysis, but the HSI curves seem reasonable.

seems ok, but very uncertain; I am not aware of even one actual study on use or avoidance of cover by these species.

Of the three species, L. nasuta seems to have the strongest affinity for instream cover, whether it be vegetation, coarse wood, detritus, rock, or even the streambank (overhanging vegetation, steep banks, root wads, etc). Therefore, suitability scores are lower for NO cover, then optimal for increasing amounts of cover until the highest values where suitability drops. I think this is because at some point, the amount of cover starts to exert too strong an influence on other factors such as mobility, circulation of flow (and thus delivery of nutrients, dissolved oxygen, etc), substrate quality, etc. L. nasuta seems to need some cover, but too much of certain kinds of cover (like detritus, or coarse rock) may be unsuitable. L. cariosa, on the other hand, seems to prefer areas without significant cover, and suitability decreases as the amount of cover (of any type) increases. L. ochracea is more intermediate -- like N. nasuta, it does seem to prefer some amount of instream cover but can tolerate fairly high amounts of cover, especially aquatic vegetation and coarse wood.

Shear Stress

I believe that sediment stability during high flows is critically important to unionids. If the sediment moves (which will depend on shear stress, sediment grain size, and sediment bedding), the site is likely to be unsuitable to unionids. The critical value will be not shear stress per se, but whether RSS>1 during high water. I suspect that base-flow shear stress is not very important. This factor is discussed in the "habitat" chapter of my mussel ecology book, which provides additional references.

Juveniles cannot become established when bed shear stress exceeds a critical threshold

Few studies have specifically calcuated shear stress or relative shear stress for mussels/mussel beds, especially for these three species. In a very general sense, we can infer suitabilities based on observations/measurements of flow velocity and substrate from most of the case studies listed. But its difficult to consider exact ranges, since precise SS or RSS values are hard to understand/contextualize. Generally, all three species inhabit areas with fine substrates and light flow velocities, so they must be sensitive to SS and RSS at the higher end of the spectrum. Low SS and RSS should be optimal for all three species, and high SS and RSS should be poor.

I recommend either summarizing SS or RSS data from existing studies, or trying to compute SS and RSS from existing data, and focus on comparing the range of conditions that species exist in to the range of SS and RSS values in the Project area, and more importantly, the degree to which Project operations can affect SS and RSS values (understanding that the Project operates in a narrow range of flows). It is very likely that this would show that Project operations simply cannot push SS or RSS beyond the range that any of these species can occur in, and therefore that the Project does not affect mussels in this way. This is not to say that the Project may not affect mussels in other ways....

I don't think it is possible to define ranges at this point especially since RSS in or near mussel beds is >>5 for a 1.5 year flood. In comparison, for example, Allen and Vaughn found species richness was high when RSS was >1 but declined sharply when RSS was >2. (However, they state that they used only D50 to estimate substrate movement and that the presence of embedded mussels may also help stabilize the substrate.)

Although in general I agree with this summary of displacement during high flow events, I think there likely are annual normal high flow events that may displace mussels, especially juveniles. We saw this in a stream in Maine (Sandy Stream) in which we had pit-tagged yellow lampmussels and tidewater muckets. We relocated lampmussels >100 m downstream from the tag site where they had been tagged and released the previous summer. Between the late summer tag and release period and the subsequent relocation period the next summer, the stream experienced the normal seasonal flow dynamics. So, it did not take excessive or unusual flows to dislodge the mussels (all adult-sized.

In response to the statement "other components of substrate diversity that might influence resistance to particle movement have not been well characterized"...And even if they have, these features are so dynamic that it would be difficult to accurately predict suitability based on them, because they are so transient.

It might be that SS and RSS are not useful in an initial model application but in a subsequent assessment. That is, evaluate the suitability based on the other parameters, and then if they indicate potentially suitable conditions, then consider RSS and SS.

The Word document is interesting and thoughtful, but contains many broad, unsupported statements that are best viewed as hypotheses rather than established facts. In particular, it ignores the fact that marine flume studies have shown that organisms like mussels can destabilize (as well as stabilize) sediments depending on conditions, and is hampered by the lack of observations made during high flows (everyone has this problem, because it's hard or dangerous to make these observations!). Also, there isn't enough information presented about how the figure was produced to evaluate it (are shears calculated from local vertical current profiles?). Nevertheless, I think I probably reach a similar bottom line as the author - that we don't know enough about mussels, high-flow shears, or sediment mobility in the reach to make confident choices about critical thresholds for SS or RSS. However, we do know that SS/RSS are more likely to matter to mussels than depth, grain size, and base-flow current speed, which are known to perform poorly as predictors. One possible solution might be to assign sites in the highest quintile of RSS in the reach as '0', the second quintile as '0.25', the third quintile as '0.5', the fourth quintile as '0.75', and the lowest quintile as '1'. The objection that sites with the lowest RSS contain unsuitably coarse substrata (boulders, bedrock) is easily dealt with if you retain the grain size HSI, which would screen out these sites as unsuitable. In any case, thank you for taking seriously our suggestions to consider SS/RSS as a predictor.

It would be beneficial to have a summary of exactly what datasets are available and the type of hydraulic modeling and IFIM that are proposed. It may not be worth the time to develop sophisticated SS and RSS HSIs for each species IF they are not compatible with the information that is available for the hydraulic analysis and IFIM. Since we are proposing to use relatively simplistic binary criteria, we only need to find a threshold between suitable and unsuitable.

In reality, such a threshold probably does not even exist, as it would be influenced by a variety of river-specific or location-specific factors, or even time-specific factors (for example, shear stress may be more important at certain times of the year). So any binary curve, in the end, will be subjective and probably won't adequately predict where mussels occur, or allow one to determine effects of project operations.

Is it possible to use existing field-collected data to compute a range of SS and RSS that species exist in, say in the Penobscot River and Susquehanna River and others (some of these datasets were listed in the last round of comments), and compare that range to (1) the range of SS and RSS values in the Project area, and (2) the range of SS and RSS in the Project area WITHIN the operating range of Cabot Station? If, during peak generation at Cabot Station, SS and RSS values are still well within the range that species occur in, then clearly the Project is not affecting the species via SS or RSS. Do Project operations even influence benthic water velocity and depth at all? To what extent? And where? And how does that compare to SS and RSS that may occur outside of the Project's operating range? (focus on high-flow SS and RSS, like during 5, 10 or greater recurrence interval floods).

Water Velocity (Benthic)

I assume you mean velocities under base flow conditions. Many mussel populations will be subjected to much higher velocities during floods. I haven't provided separate ratings for adults and juveniles because I don't know of any evidence that adults and juveniles prefer different conditions. I do not believe that current speed by itself is likely to be an important limit on the distribution or abundance of these species (except for extremely high flows), and so is not likely by itself to be effective in a HSC. People may think of ochracea as a quiet-water species, but it was abundant in the upper Hudson River estuary, where tidal flows often exceed 1 m/s

No specific data on velocity and these species but see: Maloney et al. 2012. Freshwater Biology 57:1315-1327. Allen and Vaughn 2010. J. North Am. Benthological Society 29:383-394. Gangloff and Feminella 2006. Freshwater Biology 52:64-74. Wesley and Brown 2013. Freshwater Science, 2013, 32(1):193–203.

Scores for velocity seem broadly ok, though I wouldn't have much confidence in them, and the statement that there is "declining suitability with increasing velocity" would seem to have little empirical support, at least for cariosa and ochracea, which sometimes are abundant in strong currents.

All three species inhabit and generally reach their highest densities in lakes and slow-flowing rivers. Suitability diminishes with velocity.

I am assuming that this is velocity that the larvae and adults are experiencing after settling. I am not personnally familiar with L. nasuta, so this is a guess, given the general kinds of sites I suspect it is found in. I have not measured flow velocities in my work, so I am guessing these suitabilities based on my recollection of the sites where we surveyed for YLM and TWM.

Below are formulas used to calculate shear stress (SS), critical shear stress (CSS), and relative shear stress (RSS) based on defined constants and variables of water depth, flow velocity, and median bed particle size.

Some of these details are for context; for the SS and RSS Calculator (different worksheet), SS, CSS, and RSS are based on calculations using the Mannings roughness coefficient (n = 0.04) and a constant Shields parameter of 0.047.

Shear Stress (EGL Slope)

$$\tau = \gamma * R_h * S$$

Parameter	Value	Units	Description
D_{50}	50	mm	Median bed particle size. Typically based off of a sieve analysis or pebble count.
γ	62.4	lb/ft^3	Specific weight of water. Typically assumed to be 62.4 lb/ft^3. Technically ranges from 62.42 @ 32 degF to 59.83 @ 212 degF. It is 62.0 @ 100 degF, so 62.4 is a reasonable assumption.
R_h	10	ft	Hydraulic radius. Calculated as a cross-section's wetted area divided by wetted perimeter. For wide cross-sections this is near the same as water depth, which it is commonly substituted for.
S_{EGL}	0.001	ft/ft (unitless)	Energy grade line slope. A cross-section's energy grade line is a theoretical line above the water surface calculated as an elevation where EGL = W.S.Elev. + $V^2/2g$. V = water velocity (ft/s), g = gravity acceleration (32.2 ft/s^2). Since EGL isn't easily measured (you need WSE and velocity measurements) or model results, this is often subtituted with the WSE slope or the river bed slope, since over long distances they should be approximately the same.
Calculated			
τ_{bed}	0.624	lb/ft^2	Shear stress at the streambed. Represents a force over an area. Used to predict sediment mobilization
$\tau_{C, Shields}$	0.794	lb/ft^2	Critical shear stress. Uses the Shields equation assuming a constant sheilds parameter of 0.047. Already converted from N/m2 to lb/ft2.
$\tau_{C, Colorado}$	0.220	lb/ft^2	Critical shear stress. Uses the Rosgen chart equation for the Colorado data.
$\tau_{C, Leopold}$	0.653	lb/ft^2	Critical shear stress. Uses the Rosgen chart equation for the Leopold, Wolman, and Miller data.
$RSS_{Shields}$	0.785	unitless	Relative shear stress, the ratio of bed shear stress divided by critical shear stress for the given particle size. Uses Shields critical shear stress.
$RSS_{Colorado}$	2.830	unitless	Relative shear stress, the ratio of bed shear stress divided by critical shear stress for the given particle size. Uses Colorado critical shear stress.
$RSS_{Leopold}$	0.956	unitless	Relative shear stress, the ratio of bed shear stress divided by critical shear stress for the given particle size. Uses Leopold critical shear stress.

Manning Equation $V = \frac{1.49}{n} * R_h^{2/3} * S^{1/2}$

Note: The 1.49 becomes 1.0 if you're using SI units.

Shear stress combined with Manning Equation

$$\tau = \frac{\gamma * V^2 * n^2}{1.49^2 * d^{1/3}}$$

Parameter	Value	Units	Description
D_{50}	50	mm	Median bed particle size. Typically based off of a sieve analysis or pebble count.
γ	62.4	lb/ft^3	Specific weight of water. Typically assumed to be 62.4 lb/ft^3. Technically ranges from 62.42 @ 32 degF to 59.83 @ 212 degF. It is 62.0 @ 100 degF, so 62.4 is a reasonable assumption.
n	0.04	empirical	Manning's n roughness coefficient. Higher numbers represent rougher channels. This webpage shows how n can vary quite a bit depending on the channel/flow surface (http://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm). For the CT River, generally probably between 0.025 and 0.045. This is set individually at each model cross-section, and can be sub-divided within a cross-section if the channel makeup varies. Typically have a different 'n' value for in-channel and overbank areas.
R_h	10	ft	Hydraulic radius. Calculated as a cross-section's wetted area divided by wetted perimeter. For wide cross-sections this is near the same as water depth, which it is commonly substituted for. That's why it shows up as 'd' in many equations.
S_{EGL}	0.001	ft/ft (unitless)	Energy grade line slope. A cross-section's energy grade line is a theoretical line above the water surface calculated as an elevation where EGL = W.S.Elev. + $V^2/2g$. V = water velocity (ft/s), g = gravity acceleration (32.2 ft/s^2). Since EGL isn't easily measured (you need WSE and velocity measurements) or model results, this is often subtituted with the WSE slope or the river bed slope, since over long distances they should be approximately the same.
Calculated			
V	5.47	ft/s	Average cross-sectional velocity (or depth-averaged water column velocity if in 2D)
τ_{bed}	0.624	lb/ft^2	Shear stress at the streambed. Represents a force over an area. Used to predict sediment mobilization
$\tau_{C, Shields}$	0.794	lb/ft^2	Critical shear stress. Uses the Shields equation assuming a constant sheilds parameter of 0.047. Already converted from N/m2 to lb/ft2.
$\tau_{C, Colorado}$	0.220	lb/ft^2	Critical shear stress. Uses the Rosgen chart equation for the Colorado data.
$\tau_{C, Leopold}$	0.653	lb/ft^2	Critical shear stress. Uses the Rosgen chart equation for the Leopold, Wolman, and Miller data.
$RSS_{Shields}$	0.785	unitless	Relative shear stress, the ratio of bed shear stress divided by critical shear stress for the given particle size. Uses Shields critical shear stress.
$RSS_{Colorado}$	2.830	unitless	Relative shear stress, the ratio of bed shear stress divided by critical shear stress for the given particle size. Uses Colorado critical shear stress.
$RSS_{Leopold}$	0.956	unitless	Relative shear stress, the ratio of bed shear stress divided by critical shear stress for the given particle size. Uses Leopold critical shear stress.
Notice how if you plug the same input parameters into the two above equations that you end up with the same shear stress.			

Shear stress combined with Manning Equation (standalone, not tied to above equations)

$$\tau = \frac{\gamma * V^2 * n^2}{1.49^2 * d^{1/3}}$$

Parameter	Value	Units	Description
γ	62.4	lb/ft^3	Specific weight of water. Typically assumed to be 62.4 lb/ft^3. Technically ranges from 62.42 @ 32 degF to 59.83 @ 212 degF. It is 62.0 @ 100 degF, so 62.4 is a reasonable assumption.

n	0.04	empirical	Manning's n roughness coefficient. Higher numbers represent rougher channels. This webpage shows how n can vary quite a bit depending on the channel/flow surface (http://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm). For the CT River, generally probably between 0.025 and 0.045. This is set individually at each model cross-section, and can be sub-divided within a cross-section if the channel makeup varies. Typically have a different 'n' value for in-channel and overbank areas.
R_h or d	10	ft	Hydraulic radius. Calculated as a cross-section's wetted area divided by wetted perimeter. For wide cross-sections this is near the same as water depth, which it is commonly substituted for. That's why it shows up as 'd' in many equations.
V	5.47	ft/s	Average water column velocity
Calculated			
τ_{bed}	0.625	lb/ft^2	Shear stress at the streambed. Represents a force over an area. Used to predict sediment mobilization

Relative shear stress (standalone)

Parameter	Value	Units	Description
D_{50}	100	mm	Median bed particle size. Typically based off of a sieve analysis or pebble count.
τ_{bed}	0.625	lb/ft2	Shear stress at the streambed. Represents a force over an area. Used to predict sediment mobilization
Calculated			
$\tau_{C, Shields}$	1.589	lb/ft^2	Critical shear stress. Uses the Shields equation assuming a constant sheilds parameter of 0.047. Already converted from N/m2 to lb/ft2.
$\tau_{C, Colorado}$	0.566	lb/ft^2	Critical shear stress. Uses the Rosgen chart equation for the Colorado data.
$\tau_{C, Leopold}$	1.270	lb/ft^2	Critical shear stress. Uses the Rosgen chart equation for the Leopold, Wolman, and Miller data.
$RSS_{Shields}$	0.393	unitless	Relative shear stress, the ratio of bed shear stress divided by critical shear stress for the given particle size. Uses Shields critical shear stress.
$RSS_{Colorado}$	1.104	unitless	Relative shear stress, the ratio of bed shear stress divided by critical shear stress for the given particle size. Uses Colorado critical shear stress.
$RSS_{Leopold}$	0.492	unitless	Relative shear stress, the ratio of bed shear stress divided by critical shear stress for the given particle size. Uses Leopold critical shear stress.

This calculator computes SS, CSS, and RSS based on formulas provided in the Formulas worksheet. We are primarily using it to visualize how SS and RSS change due to incremental changes in water depth (d), water velocity (V), or median particle size (D50).

Constant	0.025 to 0.045	Depth (ft)	Velocity (ft/s)	Shear Stress (lb/ft2)	Particle Size	Critical Shear Stress	Relative Shear Stress
γ	n	d	V	τbed	D50	Shields	Shields
62.4	0.04	6.00	0.100	0.000	2	0.032	0.008
62.4	0.04	6.00	0.125	0.000	2	0.032	0.012
62.4	0.04	6.00	0.150	0.001	2	0.032	0.018
62.4	0.04	6.00	0.175	0.001	2	0.032	0.024
62.4	0.04	6.00	0.200	0.001	2	0.032	0.031
62.4	0.04	6.00	0.225	0.001	2	0.032	0.039
62.4	0.04	6.00	0.250	0.002	2	0.032	0.049
62.4	0.04	6.00	0.275	0.002	2	0.032	0.059
62.4	0.04	6.00	0.300	0.002	2	0.032	0.070
62.4	0.04	6.00	0.325	0.003	2	0.032	0.082
62.4	0.04	6.00	0.350	0.003	2	0.032	0.095
62.4	0.04	6.00	0.375	0.003	2	0.032	0.110
62.4	0.04	6.00	0.400	0.004	2	0.032	0.125
62.4	0.04	6.00	0.425	0.004	2	0.032	0.141
62.4	0.04	6.00	0.450	0.005	2	0.032	0.158
62.4	0.04	6.00	0.475	0.006	2	0.032	0.176
62.4	0.04	6.00	0.500	0.006	2	0.032	0.195
62.4	0.04	6.00	0.525	0.007	2	0.032	0.215
62.4	0.04	6.00	0.550	0.007	2	0.032	0.236
62.4	0.04	6.00	0.575	0.008	2	0.032	0.257
62.4	0.04	6.00	0.600	0.009	2	0.032	0.280
62.4	0.04	6.00	0.625	0.010	2	0.032	0.304
62.4	0.04	6.00	0.650	0.010	2	0.032	0.329
62.4	0.04	6.00	0.675	0.011	2	0.032	0.355
62.4	0.04	6.00	0.700	0.012	2	0.032	0.382
62.4	0.04	6.00	0.725	0.013	2	0.032	0.409
62.4	0.04	6.00	0.750	0.014	2	0.032	0.438
62.4	0.04	6.00	0.775	0.015	2	0.032	0.468
62.4	0.04	6.00	0.800	0.016	2	0.032	0.498
62.4	0.04	6.00	0.825	0.017	2	0.032	0.530
62.4	0.04	6.00	0.850	0.018	2	0.032	0.563
62.4	0.04	6.00	0.875	0.019	2	0.032	0.596
62.4	0.04	6.00	0.900	0.020	2	0.032	0.631
62.4	0.04	6.00	0.925	0.021	2	0.032	0.666
62.4	0.04	6.00	0.950	0.022	2	0.032	0.703
62.4	0.04	6.00	0.975	0.024	2	0.032	0.740
62.4	0.04	6.00	1.000	0.025	2	0.032	0.779
62.4	0.04	6.00	1.025	0.026	2	0.032	0.818
62.4	0.04	6.00	1.050	0.027	2	0.032	0.859
62.4	0.04	6.00	1.075	0.029	2	0.032	0.900
62.4	0.04	6.00	1.100	0.030	2	0.032	0.942
62.4	0.04	6.00	1.125	0.031	2	0.032	0.986
62.4	0.04	6.00	1.150	0.033	2	0.032	1.030
62.4	0.04	6.00	1.175	0.034	2	0.032	1.075
62.4	0.04	6.00	1.200	0.036	2	0.032	1.121
62.4	0.04	6.00	1.225	0.037	2	0.032	1.169
62.4	0.04	6.00	1.250	0.039	2	0.032	1.217
62.4	0.04	6.00	1.275	0.040	2	0.032	1.266
62.4	0.04	6.00	1.300	0.042	2	0.032	1.316
62.4	0.04	6.00	1.325	0.043	2	0.032	1.367
62.4	0.04	6.00	1.350	0.045	2	0.032	1.419
62.4	0.04	6.00	1.375	0.047	2	0.032	1.472
62.4	0.04	6.00	1.400	0.049	2	0.032	1.526
62.4	0.04	6.00	1.425	0.050	2	0.032	1.581
62.4	0.04	6.00	1.450	0.052	2	0.032	1.637
62.4	0.04	6.00	1.475	0.054	2	0.032	1.694
62.4	0.04	6.00	1.500	0.056	2	0.032	1.752
62.4	0.04	6.00	1.525	0.058	2	0.032	1.811
62.4	0.04	6.00	1.550	0.059	2	0.032	1.871
62.4	0.04	6.00	1.575	0.061	2	0.032	1.932
62.4	0.04	6.00	1.600	0.063	2	0.032	1.994
62.4	0.04	6.00	1.625	0.065	2	0.032	2.056
62.4	0.04	6.00	1.650	0.067	2	0.032	2.120
62.4	0.04	6.00	1.675	0.069	2	0.032	2.185
62.4	0.04	6.00	1.700	0.072	2	0.032	2.251
62.4	0.04	6.00	1.725	0.074	2	0.032	2.317
62.4	0.04	6.00	1.750	0.076	2	0.032	2.385
62.4	0.04	6.00	1.775	0.078	2	0.032	2.454
62.4	0.04	6.00	1.800	0.080	2	0.032	2.523
62.4	0.04	6.00	1.825	0.082	2	0.032	2.594
62.4	0.04	6.00	1.850	0.085	2	0.032	2.665
62.4	0.04	6.00	1.875	0.087	2	0.032	2.738
62.4	0.04	6.00	1.900	0.089	2	0.032	2.811
62.4	0.04	6.00	1.925	0.092	2	0.032	2.886
62.4	0.04	6.00	1.950	0.094	2	0.032	2.961
62.4	0.04	6.00	1.975	0.097	2	0.032	3.038
62.4	0.04	6.00	2.000	0.099	2	0.032	3.115
62.4	0.04	6.00	2.025	0.101	2	0.032	3.194
62.4	0.04	6.00	2.050	0.104	2	0.032	3.273
62.4	0.04	6.00	2.075	0.107	2	0.032	3.353

62.4	0.04	6.00	2.100	0.109	2	0.032	3.434
62.4	0.04	6.00	2.125	0.112	2	0.032	3.517
62.4	0.04	6.00	2.150	0.114	2	0.032	3.600
62.4	0.04	6.00	2.175	0.117	2	0.032	3.684
62.4	0.04	6.00	2.200	0.120	2	0.032	3.769
62.4	0.04	6.00	2.225	0.123	2	0.032	3.856
62.4	0.04	6.00	2.250	0.125	2	0.032	3.943
62.4	0.04	6.00	2.275	0.128	2	0.032	4.031
62.4	0.04	6.00	2.300	0.131	2	0.032	4.120
62.4	0.04	6.00	2.325	0.134	2	0.032	4.210
62.4	0.04	6.00	2.350	0.137	2	0.032	4.301
62.4	0.04	6.00	2.375	0.140	2	0.032	4.393
62.4	0.04	6.00	2.400	0.143	2	0.032	4.486
62.4	0.04	6.00	2.425	0.146	2	0.032	4.580
62.4	0.04	6.00	2.450	0.149	2	0.032	4.675
62.4	0.04	6.00	2.475	0.152	2	0.032	4.771
62.4	0.04	6.00	2.500	0.155	2	0.032	4.867
62.4	0.04	6.00	2.525	0.158	2	0.032	4.965
62.4	0.04	6.00	2.550	0.161	2	0.032	5.064
62.4	0.04	6.00	2.575	0.164	2	0.032	5.164
62.4	0.04	6.00	2.600	0.167	2	0.032	5.265
62.4	0.04	6.00	2.625	0.171	2	0.032	5.366
62.4	0.04	6.00	2.650	0.174	2	0.032	5.469
62.4	0.04	6.00	2.675	0.177	2	0.032	5.573
62.4	0.04	6.00	2.700	0.180	2	0.032	5.677
62.4	0.04	6.00	2.725	0.184	2	0.032	5.783
62.4	0.04	6.00	2.750	0.187	2	0.032	5.890
62.4	0.04	6.00	2.775	0.191	2	0.032	5.997
62.4	0.04	6.00	2.800	0.194	2	0.032	6.106
62.4	0.04	6.00	2.825	0.198	2	0.032	6.215
62.4	0.04	6.00	2.850	0.201	2	0.032	6.326
62.4	0.04	6.00	2.875	0.205	2	0.032	6.437
62.4	0.04	6.00	2.900	0.208	2	0.032	6.550
62.4	0.04	6.00	2.925	0.212	2	0.032	6.663
62.4	0.04	6.00	2.950	0.215	2	0.032	6.777
62.4	0.04	6.00	2.975	0.219	2	0.032	6.893
62.4	0.04	6.00	3.000	0.223	2	0.032	7.009
62.4	0.04	6.00	3.025	0.226	2	0.032	7.126
62.4	0.04	6.00	3.050	0.230	2	0.032	7.245
62.4	0.04	6.00	3.075	0.234	2	0.032	7.364
62.4	0.04	6.00	3.100	0.238	2	0.032	7.484
62.4	0.04	6.00	3.125	0.242	2	0.032	7.605
62.4	0.04	6.00	3.150	0.246	2	0.032	7.728
62.4	0.04	6.00	3.175	0.249	2	0.032	7.851
62.4	0.04	6.00	3.200	0.253	2	0.032	7.975
62.4	0.04	6.00	3.225	0.257	2	0.032	8.100
62.4	0.04	6.00	3.250	0.261	2	0.032	8.226
62.4	0.04	6.00	3.275	0.265	2	0.032	8.353
62.4	0.04	6.00	3.300	0.270	2	0.032	8.481
62.4	0.04	6.00	3.325	0.274	2	0.032	8.610
62.4	0.04	6.00	3.350	0.278	2	0.032	8.740
62.4	0.04	6.00	3.375	0.282	2	0.032	8.871
62.4	0.04	6.00	3.400	0.286	2	0.032	9.003
62.4	0.04	6.00	3.425	0.290	2	0.032	9.136
62.4	0.04	6.00	3.450	0.295	2	0.032	9.270
62.4	0.04	6.00	3.475	0.299	2	0.032	9.404
62.4	0.04	6.00	3.500	0.303	2	0.032	9.540
62.4	0.04	6.00	3.525	0.308	2	0.032	9.677
62.4	0.04	6.00	3.550	0.312	2	0.032	9.815
62.4	0.04	6.00	3.575	0.316	2	0.032	9.953
62.4	0.04	6.00	3.600	0.321	2	0.032	10.093
62.4	0.04	6.00	3.625	0.325	2	0.032	10.234
62.4	0.04	6.00	3.650	0.330	2	0.032	10.375
62.4	0.04	6.00	3.675	0.334	2	0.032	10.518
62.4	0.04	6.00	3.700	0.339	2	0.032	10.662
62.4	0.04	6.00	3.725	0.343	2	0.032	10.806
62.4	0.04	6.00	3.750	0.348	2	0.032	10.952
62.4	0.04	6.00	3.775	0.353	2	0.032	11.098
62.4	0.04	6.00	3.800	0.357	2	0.032	11.246
62.4	0.04	6.00	3.825	0.362	2	0.032	11.394
62.4	0.04	6.00	3.850	0.367	2	0.032	11.544
62.4	0.04	6.00	3.875	0.372	2	0.032	11.694
62.4	0.04	6.00	3.900	0.376	2	0.032	11.845
62.4	0.04	6.00	3.925	0.381	2	0.032	11.998
62.4	0.04	6.00	3.950	0.386	2	0.032	12.151
62.4	0.04	6.00	3.975	0.391	2	0.032	12.305
62.4	0.04	6.00	4.000	0.396	2	0.032	12.461
62.4	0.04	6.00	4.025	0.401	2	0.032	12.617
62.4	0.04	6.00	4.050	0.406	2	0.032	12.774
62.4	0.04	6.00	4.075	0.411	2	0.032	12.932
62.4	0.04	6.00	4.100	0.416	2	0.032	13.092
62.4	0.04	6.00	4.125	0.421	2	0.032	13.252
62.4	0.04	6.00	4.150	0.426	2	0.032	13.413
62.4	0.04	6.00	4.175	0.431	2	0.032	13.575
62.4	0.04	6.00	4.200	0.437	2	0.032	13.738
62.4	0.04	6.00	4.225	0.442	2	0.032	13.902

62.4	0.04	6.00	4.250	0.447	2	0.032	14.067
62.4	0.04	6.00	4.275	0.452	2	0.032	14.233
62.4	0.04	6.00	4.300	0.458	2	0.032	14.400
62.4	0.04	6.00	4.325	0.463	2	0.032	14.568
62.4	0.04	6.00	4.350	0.468	2	0.032	14.737
62.4	0.04	6.00	4.375	0.474	2	0.032	14.907
62.4	0.04	6.00	4.400	0.479	2	0.032	15.077
62.4	0.04	6.00	4.425	0.485	2	0.032	15.249
62.4	0.04	6.00	4.450	0.490	2	0.032	15.422
62.4	0.04	6.00	4.475	0.496	2	0.032	15.596
62.4	0.04	6.00	4.500	0.501	2	0.032	15.771
62.4	0.04	6.00	4.525	0.507	2	0.032	15.946
62.4	0.04	6.00	4.550	0.512	2	0.032	16.123
62.4	0.04	6.00	4.575	0.518	2	0.032	16.301
62.4	0.04	6.00	4.600	0.524	2	0.032	16.479
62.4	0.04	6.00	4.625	0.529	2	0.032	16.659
62.4	0.04	6.00	4.650	0.535	2	0.032	16.839
62.4	0.04	6.00	4.675	0.541	2	0.032	17.021
62.4	0.04	6.00	4.700	0.547	2	0.032	17.204
62.4	0.04	6.00	4.725	0.553	2	0.032	17.387
62.4	0.04	6.00	4.750	0.558	2	0.032	17.572
62.4	0.04	6.00	4.775	0.564	2	0.032	17.757
62.4	0.04	6.00	4.800	0.570	2	0.032	17.943
62.4	0.04	6.00	4.825	0.576	2	0.032	18.131
62.4	0.04	6.00	4.850	0.582	2	0.032	18.319
62.4	0.04	6.00	4.875	0.588	2	0.032	18.508
62.4	0.04	6.00	4.900	0.594	2	0.032	18.699
62.4	0.04	6.00	4.925	0.600	2	0.032	18.890
62.4	0.04	6.00	4.950	0.606	2	0.032	19.082
62.4	0.04	6.00	4.975	0.613	2	0.032	19.276
62.4	0.04	6.00	5.000	0.619	2	0.032	19.470
62.4	0.04	6.00	5.025	0.625	2	0.032	19.665
62.4	0.04	6.00	5.050	0.631	2	0.032	19.861
62.4	0.04	6.00	5.075	0.637	2	0.032	20.058
62.4	0.04	6.00	5.100	0.644	2	0.032	20.256
62.4	0.04	6.00	5.125	0.650	2	0.032	20.455
62.4	0.04	6.00	5.150	0.656	2	0.032	20.656
62.4	0.04	6.00	5.175	0.663	2	0.032	20.857
62.4	0.04	6.00	5.200	0.669	2	0.032	21.059
62.4	0.04	6.00	5.225	0.676	2	0.032	21.262
62.4	0.04	6.00	5.250	0.682	2	0.032	21.465
62.4	0.04	6.00	5.275	0.689	2	0.032	21.670
62.4	0.04	6.00	5.300	0.695	2	0.032	21.876
62.4	0.04	6.00	5.325	0.702	2	0.032	22.083
62.4	0.04	6.00	5.350	0.708	2	0.032	22.291
62.4	0.04	6.00	5.375	0.715	2	0.032	22.500
62.4	0.04	6.00	5.400	0.722	2	0.032	22.710
62.4	0.04	6.00	5.425	0.728	2	0.032	22.920
62.4	0.04	6.00	5.450	0.735	2	0.032	23.132
62.4	0.04	6.00	5.475	0.742	2	0.032	23.345
62.4	0.04	6.00	5.500	0.749	2	0.032	23.558
62.4	0.04	6.00	5.525	0.755	2	0.032	23.773
62.4	0.04	6.00	5.550	0.762	2	0.032	23.989
62.4	0.04	6.00	5.575	0.769	2	0.032	24.205
62.4	0.04	6.00	5.600	0.776	2	0.032	24.423
62.4	0.04	6.00	5.625	0.783	2	0.032	24.641
62.4	0.04	6.00	5.650	0.790	2	0.032	24.861
62.4	0.04	6.00	5.675	0.797	2	0.032	25.082
62.4	0.04	6.00	5.700	0.804	2	0.032	25.303
62.4	0.04	6.00	5.725	0.811	2	0.032	25.525
62.4	0.04	6.00	5.750	0.818	2	0.032	25.749
62.4	0.04	6.00	5.775	0.825	2	0.032	25.973
62.4	0.04	6.00	5.800	0.833	2	0.032	26.199
62.4	0.04	6.00	5.825	0.840	2	0.032	26.425
62.4	0.04	6.00	5.850	0.847	2	0.032	26.652
62.4	0.04	6.00	5.875	0.854	2	0.032	26.881
62.4	0.04	6.00	5.900	0.861	2	0.032	27.110
62.4	0.04	6.00	5.925	0.869	2	0.032	27.340
62.4	0.04	6.00	5.950	0.876	2	0.032	27.571
62.4	0.04	6.00	5.975	0.884	2	0.032	27.803
62.4	0.04	6.00	6.000	0.891	2	0.032	28.037
62.4	0.04	6.00	6.025	0.898	2	0.032	28.271
62.4	0.04	6.00	6.050	0.906	2	0.032	28.506
62.4	0.04	6.00	6.075	0.913	2	0.032	28.742
62.4	0.04	6.00	6.100	0.921	2	0.032	28.979
62.4	0.04	6.00	6.125	0.928	2	0.032	29.217
62.4	0.04	6.00	6.150	0.936	2	0.032	29.456
62.4	0.04	6.00	6.175	0.944	2	0.032	29.696
62.4	0.04	6.00	6.200	0.951	2	0.032	29.937
62.4	0.04	6.00	6.225	0.959	2	0.032	30.179
62.4	0.04	6.00	6.250	0.967	2	0.032	30.422
62.4	0.04	6.00	6.275	0.974	2	0.032	30.665
62.4	0.04	6.00	6.300	0.982	2	0.032	30.910
62.4	0.04	6.00	6.325	0.990	2	0.032	31.156
62.4	0.04	6.00	6.350	0.998	2	0.032	31.403

Memo

To: **Turners Falls Hydroelectric Project Mussel Delphi Panel**
From: **Jason George, Gomez and Sullivan Engineers**
Date: **April 12, 2016**
RE: **Approach to Shear Stress (SS), Relative Shear Stress (RSS), and Mussel Habitat Suitability**

Evidence suggests that complex hydraulic and substrate parameters are important to freshwater mussels. Among the parameters that have been studied, shear stress (SS) and relative shear stress (RSS) have shown the most promise for understanding mussel habitat quality, especially at high flows, although their predictive power is still low. Through review of existing literature and expert opinion from the Delphi panel, we have been attempting to develop SS and RSS habitat suitability criteria (HSC) for three species (yellow lampmussel, eastern pondmussel, tidewater mucket) that occur in the Holyoke Dam impoundment ("Reach 5" of FirstLight's IFIM study area). The primary objective of this exercise is to use the HSC in the IFIM study to model the potential effects of flow operations on these three species' habitat. The process of developing HSC for SS and RSS has generally yielded more questions than answers, and in some cases points toward fine-scale hydraulic, substrate, and mussel distribution data that are not available for HSC development, IFIM modeling, or analyses.

The relatively coarse-scale data that are available suggest that yellow lampmussels exist in areas of Reach 5 with "high" RSS ("high" compared to values reported in other studies; Morales et al. 1996, Allen and Vaughn 2010, Glover 2013) based on hydraulic and substrate parameters (i.e., water depth, water velocity, and substrate). The high RSS is due mainly to prevalence of fine-grained material (i.e., sand) that is easily mobilized. The presence of larger substrate types or other bed-stabilizing elements (physical or biological) in these areas are not well described in qualitative terms, but more importantly, they are not quantified or easily modeled. Such features may allow long-term persistence of mussel beds even in areas where overall RSS is high but there are localized areas with lower RSS. Eastern pondmussels exist in complex, nearshore habitats where SS is low due to low water velocities. Modeled RSS in these nearshore areas would likely be high because of fine particle sizes, but the streambed is likely more stable than models would predict due to cohesion of the fine-grained particles, presence of rooted aquatic vegetation and coarse woody debris that increase stability, and dense mussel beds that may also increase stability. Overall, it seems that effective substrate stability in areas where mussels do and do not occur, and how mussels respond to varying levels of substrate stability, are unknown. Some of these challenges were outlined in a document prepared for the second round of the Delphi process.

Mussel distribution is influenced by many factors. Physical habitat is just one.

Quote from Allen and Vaughn (2010): "Strayer (2008) argued that many factors in addition to hydraulic and substrate characteristics influence freshwater mussel distributions. These other factors include fish host distributions, food quality and quantity, water quality, and temperature. Therefore, even if substrate and hydraulic conditions were optimal, overall mussel habitat quality could be quite poor if these other requirements were not met (e.g., fish hosts not abundant or food quality low). Consequently, substrate and hydraulic variables should be analyzed as constraints or limiting factors rather than predictive variables because, at best, they can only partially explain mussel distributions."

Substrate stability is complex…

…some of these complexities are biological and never adequately captured in hydraulic/substrate modeling, and some of these complexities are too spatially or temporally variable to ever adequately describe. The SS and RSS summary provided as part of Round 2 of the Delphi described some of the challenges with using these parameters to describe/model habitat suitability, and also with the implications of SS and RSS on mussels given species-specific morphologies, behaviors, and microhabitat selection. Allen and Vaughn (2010) reached some conclusions that reinforce some of the challenges we face:

> "Our estimates of substrate stability at high flows suggest that mussels might be able to tolerate some substrate movement. Mussel abundance and mussel species richness were high when HF [high flow] RSS was >1, but dropped sharply when HF RSS was >2 (RSS >1 indicates substrate movement). However, our estimates of RSS used a typical sized particle (D50) to estimate substrate movement. Therefore, RSS >1 does not necessarily mean that the entire stream bed is in motion because D50 could represent just a small fraction of the larger materials sampled from the bed surface (Gordon et al. 2004). <u>Thus, mussels might be able to tolerate movement of smaller substrate particles during high flows, but not movement of larger particles or the entire stream bed.</u> Furthermore, we omitted substrate particles >63.5 mm from our substrate analysis to reduce the bias larger particles can have on substrate variables (Church et al. 1987). Omitting the largest substrate particles reduces D50 values and could have caused overestimation of substrate movement. Alternatively, if mussels themselves stabilize substrates as other authors have suggested (Johnson and Brown 2000, Vaughn and Spooner 2006, Strayer 2008), all substrates might have remained stable at RSS >1. Mussels increase sediment compaction and cohesion (Zimmerman and de Szalay 2007), which should decrease the ability of substrate particles to become entrained (Gordon et al. 2004). <u>Estimates of substrate stability based on RSS use substrate and hydraulic variables, so biological influences on substrate stability are not taken into account.</u> We think in-depth study of the influence of mussels on substrate stability is warranted."

Limitations of binary HSC

The FERC-approved study plan for this study calls for development of binary HSC for key parameters through review of existing data, literature, and the Delphi panel of experts. The binary criteria idea was developed from the Delaware River dwarf wedgemussel habitat persistence study described in Maloney et al. (2012) and Bovee et al. 2007 which used a single suitable vs. unsuitable range for each hydraulic parameter. The binary HSC is relatively simplistic, and uses a single threshold (for each species and life stage) above which is modeled as "unsuitable" and below which is modeled as "suitable". Given all the complexities described above and that have been emphasized by Delphi panelists, such a threshold does not exist. Mussels can, and do, tolerate a wide range of depth, velocity, substrate, waterbody types, and stream sizes. With a binary HSC, the "threshold" between suitable and unsuitable will necessarily be at the very high end of SS and RSS values in the study area.

Focus on high flows

Based on the narrative in the document that was developed for the second round of the Delphi panel, and supporting literature such as Allen and Vaughn (2010), the most sensible area to focus on is high-flow SS and RSS. Allen and Vaughn (2010) concluded that, "hydraulic variables estimated at high flows outperformed the same variables estimated at low flows. This result supports our hypothesis that hydraulic characteristics are more important to mussel habitat at high than at low flows, a conclusion that has been suggested by other authors (Hardison and Layzer 2001, Howard and Cuffey 2003, Gangloff and Feminella 2007)."

At the USGS streamgage in Montague (MA), long-term flow data indicate a wide range of discharge, from <500 cfs to >140,000 cfs, with an annual mean of 15,840 cfs based on the period October 1940 to December 2014. On an annual basis, the 80, 90, and 95 percentiles (or 20, 10, and 5 exceedance percentiles) are approximately 20,800, 32,400, and 44,700 cfs, respectively. These percentiles are commonly used to define "high flow" events. Its not unreasonable to assume that at flows above these thresholds, especially the highest-end flows that approach or exceed 100,000 cfs, will mobilize large amounts of sediments and have the largest effect on mussel distributions.

The high end of FirstLight's operating range, or the discharge above which they have no control over water levels downstream from Cabot Station, is approximately 15,938 cfs[1]. This corresponds to approximately the 71 percentile, or the 29 exceedance percentile. This is less than half of the 90 percentile (or 10 exceedance percentile) of 32,400 cfs. Existing studies and feedback from Delphi panelists seem to concur that high-flow SS and RSS are the most relevant for mussel habitat, and based on Connecticut River flow data, these high-flows occur well outside of the operating range of the Turners Falls Project. If we were to establish a binary HSC for SS and RSS, the threshold would likely be based on conditions at a discharge at least 15,000 cfs higher than FirstLight's operating range. Although this does not discount the validity of the HSC development process, it does suggest that binary HSC for SS and RSS will provide no insight into the effects of FirstLight's flow operations on mussels or mussel habitat, at least on the coarse scale that we are currently working on. Also, since direct measurements of key parameters (water depth, flow velocity, etc.) are impossible to obtain at highest flows, they must be modeled, and there are limits to how well and at what resolution hydraulic models can reliably predict these parameters at the highest end of the flow range.

Moving forward

Based on information presented in this summary and in the summary document circulated as part of the second round of the Delphi process, and feedback from Delphi panelists, we do not think the objective of establishing an evidence-based and biologically meaningful HSC for SS or RSS is achievable at this time with the previously stated data limitations. At this point, we propose to use the HSC for which we have reached consensus from Delphi panelists (water depth, flow velocity, and substrate). These will be used in the IFIM study in the same way that the HSC for fish species are used. Based on the outputs of the IFIM, we plan to analyze the potential effects of flow operations on the three target mussel species and their habitat. At that point, we will consider the SS and RSS parameters as potential constraints or limiting factors in key areas (e.g., certain higher-gradient reaches of the Connecticut River may be exposed to extreme SS or RSS values at high flows, so it may not be meaningful to assess habitat in such an area).

[1] The hydraulic capacity of Cabot and Station No. 1 are 13,728 and 2,210 cfs, respectively for a total of 15,938 cfs.

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