Freshwater Mollusk Biology and Conservation 22:1–11, 2019

REGULAR ARTICLE

BASELINE QUALITATIVE AND QUANTITATIVE MUSSEL SURVEYS OF THE MILL RIVER SYSTEM, MASSACHUSETTS, PRIOR TO FINAL DAM REMOVAL

Alan D. Christian[1]*, Amelia Atwood[1], Delilah Bethel[1], Thomas Dimino[2], Nate Garner[1,3], Julian R. Garrison[1,3], Laurissa Gulich[1], and Sean McCanty[2]

[1] *School for the Environment, University of Massachusetts Boston, 100 Morrissey Boulevard, Boston, MA 02125 USA*

[2] *Biology Department, University of Massachusetts Boston, 100 Morrissey Boulevard, Boston, MA 02125 USA*

[3]*Bowdoin College, 255 Maine Street, Brunswick, ME 04011 USA*

ABSTRACT

Dam removal is a common conservation tool that has many potential benefits for freshwater mussels. We conducted qualitative and quantitative mussel surveys in the Mill River system, Massachusetts, where four dams have been removed or modified to benefit aquatic organisms. These data represent a baseline for future monitoring of the effects of dam removal or modification. Mussel assemblages were composed of six species and were dominated by *Elliptio complanata*; *Lampsilis radiata* was the second most abundant species. Two species of Special Concern in Massachusetts, *Ligumia nasuta* and *Leptodea ochracea*, were rare, as were *Pyganodon cataracta* and *Utterbackiana implicata*. We conducted catch-per-unit-effort (CPUE) surveys at 77 sites; mussels occurred throughout much of the watershed except for the lower portion of the Mill River. The highest CPUE values were found immediately downstream of the two lakes in the system. We conducted quadrat-based surveys at nine sites, including one site in each of the lakes. Precision of estimates of total mussel density was ≥80% at most sites, which will allow detection of moderate to large changes over time. Monitoring of changes for rarer species may require a watershed-based approach based on CPUE because quantitative estimates had wide confidence intervals.

KEY WORDS: freshwater mussels, dam removal, population and assemblage size estimates, sampling adequacy and precision, stream habitat

INTRODUCTION

Dams are one of the major contributors to imperilment of freshwater mussels and their host fishes (Watters 1996; Vaughn and Taylor 1999; Gangloff et al. 2011). There are more than 75,000 dams in the United States and about 4,000 in New England (Graf 1999). Most Massachusetts dams were built in the 1700s and 1800s as small mill dams, and many are now obsolete and pose human and environmental risks (Division of Ecological Restoration 2018). The Massachusetts Department of Fish and Game Division of Ecological Restoration has removed at least 40 obsolete dams since 2005 (Division of Ecological Restoration 2018).

The Taunton River, a 1,295 km^2 watershed in southeastern Massachusetts, hosts one of the largest river herring runs (*Alosa* spp.) in New England and was designated a National Wild and Scenic River in 2009 (https://www.rivers.gov/rivers/taunton.php). The main stem of the Taunton River is free-flowing, but many tributaries are blocked by obsolete mill dams that impact river processes and habitat. Four such dams blocked the Mill River, a tributary of the Taunton River. The Mill River Restoration partnership is a collaboration of government agencies, nonprofit organizations, and others working to remove these dams and other fish passage barriers.

*Corresponding Author: alan.christian@umb.edu

Table 1. Site data for qualitative mussel survey sites in the Canoe (CR), Snake (SR), and Mill (MR) rivers. GPS coordinates indicate the upstream and downstream boundaries of each site. Sites with a single set of GPS coordinates were sampled with a transect-based approach, and coordinates indicate location of transect (see text). Macrohabitat codes: Gl = glide; Lsp = lateral scour pool; Mcp = midchannel pool; Po = pool; Ri = riffle; Ru = run. Substrate codes: Bo = boulder; Co = cobble; Fi = fines; Gr = gravel; Lwd = large woody debris; Sa = sand; Si = silt; Swd = small woody debris; Tra = trash. Vegetation codes: Av = aquatic vegetation; Ba = benthic algae.

Stream	Site Number	Start GPS	End GPS	Mean Depth (m)	Mean Width (m)	Habitats	Substrates	Vegetation
CR	1	42.00266, −71.15771	42.00310, −71.15868	0.2	6	Ri, Ru, Po	Bo Co, Gr, Sa	
CR	2	42.00120, −71.15687	42.00266, −71.15771	0.2	8	Ri, Ru, Po, Gl	Gr, Sa, Co	
CR	3	42.00074, −71.15672	42.00129, −71.15687	0.3	5	Ri, Rn	Co, Gr, Sa, Si	
CR	4	41.99940, −71.15711	42.00074, −71.15672	0.3	2	Mcp, Ri	Sa, Si	Av
CR	5	41.99899, −71.15614	41.99940, −71.15711	0.5	3	Mcp	Sa, Si	Av
CR	6	41.99730, −71.15694	41.99899, −71.15614	1.0	5	Mcp	Sa, Si,	Av
CR	7	41.99578, −71.15881	41.99730, −71.15694	1.0	8	Mcp	Si, Fi, Sa	Av
CR	8	41.99534, −71.15958	41.99578, −71.15881	0.3	10	Mcp, Lsp	Sa, Gr, Co, Si	Av
CR	9	41.99507, −71.15953		0.2	5	Mcp	Co, Gr, Sa	Av
CR	10	41.99371, −71.16022		0.3	3	Gl	Sa, Co	Av on margin
CR	11	41.99262, −71.16052		0.4	3	Mcp	Sa, Si, Co	Av on margin
CR	12	41.99150, −71.16039		0.3	6	Mcp	Sa, Co	Ba, Av on margin
CR	13	41.99075, −71.16129		0.3	8	Lsp	Sa, Co, Si	
CR	14	41.98992, −71.16235		0.4	5	Mcp	Si, Swd	Av
CR	15	41.98959, −71.16331		0.3	4	Mcp	Sa, Si	Av
CR	16	41.98861, −71.16422		0.3	5	Lsp	Sa, Gr, Si	
CR	17	41.98774, −71.16481		0.6	5	Mcp	Gr, Si, Sa	
CR	18	41.98643, −71.16595		0.7	7	Mcp	Gr, Si, Sa	
CR	19	41.98648, −71.16786		0.4	5	Lsp	Sa, Si, Co	
CR	20	41.98541, −71.16941		0.3	4	Lsp	Sa, Si	Av on margin
CR	21	41.98436, −71.16940		0.2	6	Gl	Sa, Gr	Av on margin
CR	26	41.98249, −71.16341		0.2	7	Ru	Co, Sa, Si	
CR	27	41.98172, −71.16199		0.1	9	Ru	Co, Sa, Bo	
CR	28	41.98172, −71.16050		0.2	5	Mcp	Co, Sa	
CR	29	41.98214, −71.15871		0.3	5	Mcp	Co, Sa	
CR	30	41.98183, −71.15645		0.2	6	Mcp	Sa, Gr	
CR	31	41.98077, −71.15672		0.3	4	Mcp	Sa, Si	
CR	32	41.97949, −71.15527		0.2	6	Mcp	Sa, Si	
CR	33	41.98022, −71.15369		0.6	4	Mcp	Sa, Gr	
CR	34	41.98054, −71.15208		0.3	4	Ru	Sa	Av
CR	35	41.98024, −71.15084		0.3	2	Mcp	Sa, Si	Av
CR	36	41.97963, −71.14767		0.3	4	Mcp	Si	Av
CR	37	41.97794, −71.94449		0.4	4	Mcp	Sa, De	Av
SR	38	41.96706, −71.12579	41.96692, −71.12473	2.0	40	Mcp	Sa, Gr, Co	
SR	39	41.96760, −71.12251	41.96743, −71.12208	0.8	10	Mcp	Si, Swd	
SR	40	41.96743, −71.12208	41.96300, −71.11773	0.4	12	Ru	Sa, Si, Swd	
SR	41	41.96653, −71.12209		0.2	2	Mcp	Sa, Si, Fi	
SR	42	41.96624, −71.12072		0.4	3	Mcp, Lsp	Sa, Cl, Si	Av on margin
SR	43	41.96550, −71.11987		0.4	3	Mcp	Sa, Si, Swd	
SR	44	41.96475, −71.11873		0.5	8	Mcp, Lsp	Sa, Si, Fi	
SR	45	41.96429, −71.11772		0.4	6	Lsp	Sa, Si, Swd	
SR	46	41.96300, −71.11773	41.96264, −71.11718	0.3	7	Mcp	Sa, Si	Av
SR	47	41.96264, −71.11718	41.96286, −71.11581	0.4	6	Mcp	Sa, Si	Av
SR	48	41.96286, −71.11581	41.96497, −71.11355	0.4	7	Mcp	Sa, Cl,	Av
SR	49	41.96309, −71.11355	41.96497, −71.11153	0.8	7	Mcp	Sa, Si, Swd	
SR	50	41.96451, −71.11328	41.96497, −71.11530	0.4	5	Ru	Sa	Av
SR	51	41.96497, −71.11153	41.96533, −71.11010	0.9	5	Mcp	Sa, Si	Av
SR	52	41.96533, −71.11010	41.96595, −71.10915	0.3	5	Mcp	Sa,	Av
SR	53	41.96595, −71.10915	41.96667, −71.10719	0.7	6	Mcp	Sa, Si	Av

Table 1, continued.

Stream	Site Number	Start GPS	End GPS	Mean Depth (m)	Mean Width (m)	Habitats	Substrates	Vegetation
SR	54	41.96667, −71.10719	41.96612, −71.10533	0.6	4	Mcp	Sa, Si	Av
SR	55	41.96612, −71.10533	41.96473, −71.10483	1.5	5	Mcp	Sa, Si	Av
SR	56	41.96473, −71.10483	41.96392, −71.10565	0.4	6	Mcp	Sa, Si	Av
SR	57	41.96392, −71.10565	41.96252, −71.10279	1.3	7	Mcp	Sa, Si	Av
SR	58	41.96252, −71.10279	41.95989, −71.10010	1.5	10	Mcp	Sa, Si	Av
SR	59	41.95989, −71.10010	41.95840, −71.10017	1.5	10	Mcp	Sa, Si	Av
SR	60	41.95840, −71.10017		0.8	8	Mcp	Sa	Av
MR	61	41.92811, −71.10641	41.93374, −71.10789	0.5	8	Mcp, Lsp, Ri, Ru	Sa, Cl	Av
MR	62	41.92310, −71.10610	41.92811, −71.10641	0.5	10	Mcp, Ri, Ru, Gl	Bo, Co, Gr	
MR	63	41.92177, −71.10369	41.92310, −71.10610	0.5	10	Mcp, Ri, Ru	Co, Sa	
MR	64	41.92118, −71.10296	41.92177, −71.10369	0.5	10	Mcp	Co, Sa, Gr	
MR	65	41.91901, −71.10152	41.92118, −71.10296	1.5	15	Mcp	Sa, Co, Gr	
MR	66	41.91648, −71.10033	41.91902, −71.10142	0.4	10	Mcp, Ri, Ru	Co, Sa, Si, Bo	
MR	67	41.91460, −71.09669	41.91643, −71.10033	0.3	12	Mcp, Lsp, Gl, Ri, Ru	Co, Sa, Bo, Si	Av
MR	68	41.90996, −71.09785	41.91460, −71.09669	0.3	12	Mcp, Ri, Ru, Gl, Lsp	Sa, Gr, Co, Bo	
MR	69	41.90690, −71.09999	41.90996, −71.09785	1.0	12	Mcp, Lsp	Sa, Cl	
MR	70	41.90459, −71.09836	41.90690, −71.09999	0.25	15	Ri, Ru, Mcp, Lsp, Gl	Co, Sa, Gr, Si, Bo	
MR	71	41.90354, −71.09769	41.90459, −71.09836	0.25	15	Mcp, Ri, Ru	Co, Gr, Sa, Si	
MR	72	41.90009, −71.09267	41.90364, −71.09760	0.25	10	Ri, Ru, Lsp, Mcp	Co, Gr, Sa,	
MR	73	41.90014, −71.09113	41.90009, −71.09267	0.25	12	Ri, Ru	Co, Gr Sa,	
MR	74	41.89822, −71.08938	41.90014, −71.09113	0.5	8	Mcp, Lsp, Ri, Ru	Co, Gr, Sa,	
MR	75	41.89730, −71.08926	41.89822, −71.08938	0.25	8	Mcp	Sa, Co	
MR	76	41.89693, −71.08656	41.89730, −71.08926	0.5	10	Mcp, Lsp, Ri, Ru	Sa, Co, Gr, Lwd	
MR	77	41.89646, −71.08528	41.89693, −71.08656	0.5	9	Mcp, Lsp	Sa, Bo, Gr, Tra	

The partnership is dedicated to monitoring the impacts of dam removals on stream habitats and on fish and invertebrate populations, including mussels. From 2012 to 2013, two dams were removed on the Mill River (Hopewell Dam, 2012; Whittenton Dam, 2013), and a fish ladder and eelway were installed at a third dam (Morey's Bridge Dam, 2013), and the last and most downstream dam in the system (West Britannia Street Dam) was removed in January 2018.

Coincident with the above partnership activities, the Massachusetts Chapter of the Nature Conservancy, the Massachusetts Division of Ecological Restoration, and the Massachusetts Natural Heritage and Endangered Species Program evaluated approaches to monitoring the effects of dam removal on mussel assemblages in the Mill River (Hazelton 2014). They considered two major questions. (1) How does dam removal alter habitat for the Eastern Pondmussel (*Ligumia nasuta*)? The Eastern Pondmussel is listed as a species of Special Concern in Massachusetts and occurs in low gradient and lotic habitats such as those present in impounded areas (Natural Heritage and Endangered Species Program 2015a). (2) Will dam removal allow recolonization by the Alewife Floater (*Utterbackiana implicata*; no state status) as increased passage and rearing habitat become available for migratory hosts such as river herring and shad (Natural Heritage and Endangered Species Program 2015b)? Hazelton (2014) concluded that both questions are best answered by a long-term monitoring scheme, to be conducted every four years, that includes an initial qualitative survey of the Mill River system and the establishment of permanent quantitative monitoring sites. Hazelton (2014) also recommended establishing a quantitative monitoring site in Winnecunnet Pond and Lake Sabbatia, two natural lakes within the watershed.

Our goal was to conduct baseline qualitative and quantitative surveys of mussel assemblages in the Mill River system as recommended by Hazelton (2014). The resulting baseline data will allow monitoring of areas affected by dam removal or modification in 2012 and 2013 (Hopewell, Whittenton, and Morey's Bridge dams), and they provide a pre-dam-removal baseline for West Britannia Street Dam, which was removed after this study was completed. In addition to evaluating the effects of dam removal or modification on *U. implicata* and *L. nasuta*, these data also provide information on *Leptodea ochracea*, the Tidewater Mucket, a species of Special Concern in Massachusetts that occurs in the region (Natural Heritage and Endangered Species Program 2015c). We identified two specific objectives associated with the study goal. Our first objective was to conduct qualitative mussel surveys in 2015 throughout the Mill River system from the upstream sections of the Canoe River to the confluence of the Mill River with the Taunton River (17 river km) to document species composition, mussel abundance (catch per unit effort),

Table 2. Results of 2016 qualitative mussel surveys in the Canoe, (CR), Snake (SR), and Mill (MR) rivers. EC = *Elliptio complanata*; LN = *Ligumia nasuta*; LO = *Leptodea ochracea*; LR = *Lampsilis radiata*; PC = *Pyganodon cataracta*; UI = *Utterbackiana implicata*. CPUE = catch-per-unit-effort.

Site	Species						Time Searched (min.)	Species Richness	Total Number of Mussels	CPUE (number/min.)
	EC	LR	LO	LN	PC	UI				
CR1	0	0	0	0	0	0	51	0	0	0.0
CR2	41	1	0	0	0	0	84	2	42	0.5
CR3	29	0	0	0	0	0	48	1	29	0.6
CR4	9	1	0	0	0	0	24	2	10	0.4
CR5	6	0	0	0	0	1	24	1	7	0.3
CR6	17	3	0	1	0	0	41	3	21	0.5
CR7	16	11	0	1	0	1	54	3	29	0.5
CR8	29	0	0	0	0	0	75	1	29	0.4
CR9	0	0	0	0	0	0	5	0	0	0.0
CR10	0	0	0	0	0	0	2	0	0	0.0
CR11	0	0	0	0	0	0	2	0	0	0.0
CR12	25	1	0	0	0	0	4	2	26	6.5
CR13	2	0	0	0	0	0	3	1	2	0.7
CR14	0	0	0	0	0	0	3	0	0	0.0
CR15	5	0	0	0	0	0	3	1	5	1.7
CR16	2	0	0	0	0	0	4	1	2	0.5
CR17	3	0	0	0	0	0	3	1	3	1.0
CR18	0	0	0	0	0	0	3	0	0	0.0
CR19	11	0	0	0	0	0	2	1	11	5.5
CR20	9	0	0	0	0	0	3	1	9	3.0
CR21	6	1	0	0	0	0	4	2	7	1.8
CR22	0	0	0	0	0	0	2	0	0	0.0
CR23	4	2	0	0	0	1	2	2	7	3.5
CR24	5	1	0	0	0	0	4	2	6	1.5
CR25	9	0	0	0	0	0	19	1	9	0.5
CR26	0	0	0	0	0	0	2	0	0	0.0
CR27	0	0	0	0	0	0	4	0	0	0.0
CR28	0	0	0	0	0	0	4	0	0	0.0
CR29	0	0	0	0	0	0	4	0	0	0.0
CR30	19	0	0	0	0	0	5	1	19	3.8
CR31	1	0	0	0	0	0	3	1	1	0.3
CR32	0	0	0	0	0	0	1	0	0	0.0
CR33	21	2	0	0	0	0	4	2	23	5.8
CR34	0	1	0	1	0	0	2	2	2	1.0
CR35	0	0	0	0	0	0	3	0	0	0.0
CR36	1	0	0	0	0	0	3	1	1	0.3
CR37	0	0	0	0	0	0	3	0	0	0.0
SR38	100	10	0	5	0	5	18	3	120	6.7
SR39	3	1	0	0	0	1	4	2	5	1.3
SR40	12	4	0	0	0	0	4	2	16	4.0
SR41	0	0	0	0	0	0	2	0	0	0.0
SR42	0	0	0	0	0	0	5	0	0	0.0
SR43	0	0	0	0	0	0	2	0	0	0.0
SR44	1	0	0	0	0	0	3	1	1	0.3
SR45	11	2	0	0	0	0	3	2	13	4.3
SR46	6	0	0	0	0	0	3	1	6	2.0
SR47	3	0	0	0	0	0	4	1	3	0.8
SR48	3	1	0	0	0	0	4	2	4	1.0
SR49	6	1	0	0	0	2	4	2	9	2.3

Table 2, continued.

Site	Species						Time Searched (min.)	Species Richness	Total Number of Mussels	CPUE (number/min.)
	EC	LR	LO	LN	PC	UI				
SR50	8	0	0	0	0	0	2	1	8	4.0
SR51	9	0	0	0	0	0	2	1	9	4.5
SR52	3	0	0	0	0	0	2	1	3	1.5
SR53	1	2	0	0	0	0	3	2	3	1.0
SR54	1	0	0	0	0	0	3	1	1	0.3
SR55	0	0	0	0	0	0	3	0	0	0.0
SR56	8	1	0	0	0	0	4	2	9	2.3
SR57	7	0	0	0	0	1	4	1	8	2.0
SR58	2	0	0	0	0	2	4	1	4	1.0
SR59	1	0	0	0	0	0	4	1	1	0.3
SR60	3	0	0	0	0	0	2	1	3	1.5
MR61	885	228	0	2	2	0	80	4	1,117	14.0
MR62	782	10	0	0	0	0	144	2	792	5.5
MR63	264	1	0	1	0	0	16	3	266	16.6
MR64	132	2	0	0	0	0	62	2	134	2.2
MR65	52	4	0	0	0	0	112	2	56	0.5
MR66	0	0	0	0	0	0	50	0	0	0.0
MR67	0	2	0	0	0	0	56	1	2	0.0
MR68	31	2	0	0	0	0	112	2	33	0.3
MR69	12	1	0	0	0	2	84	2	15	0.2
MR70	0	0	0	0	0	0	58	0	0	0.0
MR71	0	0	0	0	0	0	24	0	0	0.0
MR72	0	0	0	0	0	0	114	0	0	0.0
MR73	0	0	0	0	0	0	22	0	0	0.0
MR74	0	0	0	0	0	0	88	0	0	0.0
MR75	0	0	0	0	0	0	24	0	0	0.0
MR76	0	0	0	0	0	0	70	0	0	0.0
MR77	0	1	0	0	0	0	44	1	1	0.0
Totals	2,616	297	0	11	2	16	1,756	5	2,942	1.7

and distributions of freshwater mussel assemblages relative to existing (i.e., West Britannia) and historical dams. Our second objective was to establish nine long-term quantitative mussel-monitoring sites in the Mill River system, including one site each in Winnecunnet Pond and Lake Sabbatia. We quantitatively sampled these nine sites in 2016.

METHODS

Study Area

The Mill River watershed is located within the Taunton River watershed in the Northeastern Coastal Zone Ecoregion of southeastern Massachusetts (Fig. 1). The Mill River watershed drains 113 km^2 and is covered by 49% forest, 17% wetlands, 3% lakes and ponds, and 33% developed land, of which 12% is considered impervious (United States Geological Survey 2018, based on NLCD 2011 data). The Mill River system is made up of three segments, the Mill, Snake, and Canoe rivers, which are delineated by Lake Sabbatia and Winnecunnet Pond. Both are natural lakes, but water level in Lake Sabbatia is raised substantially and regulated by Morey's Bridge Dam. Most of the Canoe and Snake rivers are associated with extensive wetlands. These sections have abundant aquatic vegetation, and there is no defined stream channel in some places. In contrast, the Mill River is more consistently riverine and characterized by typical riffle/run/pool development. Morey's Bridge Dam is upstream of site 61 at the outflow of Lake Sabbatia, Whittenton Dam was located near site 61, West Britannia Street Dam was located near site 65, and Hopewell Dam was located near site 67 (see subsequent discussion for information about site selection).

Objective 1: Qualitative Mussel Survey

We conducted qualitative surveys between July 1, 2015, and August 15, 2015, on approximately 17 km of the Mill

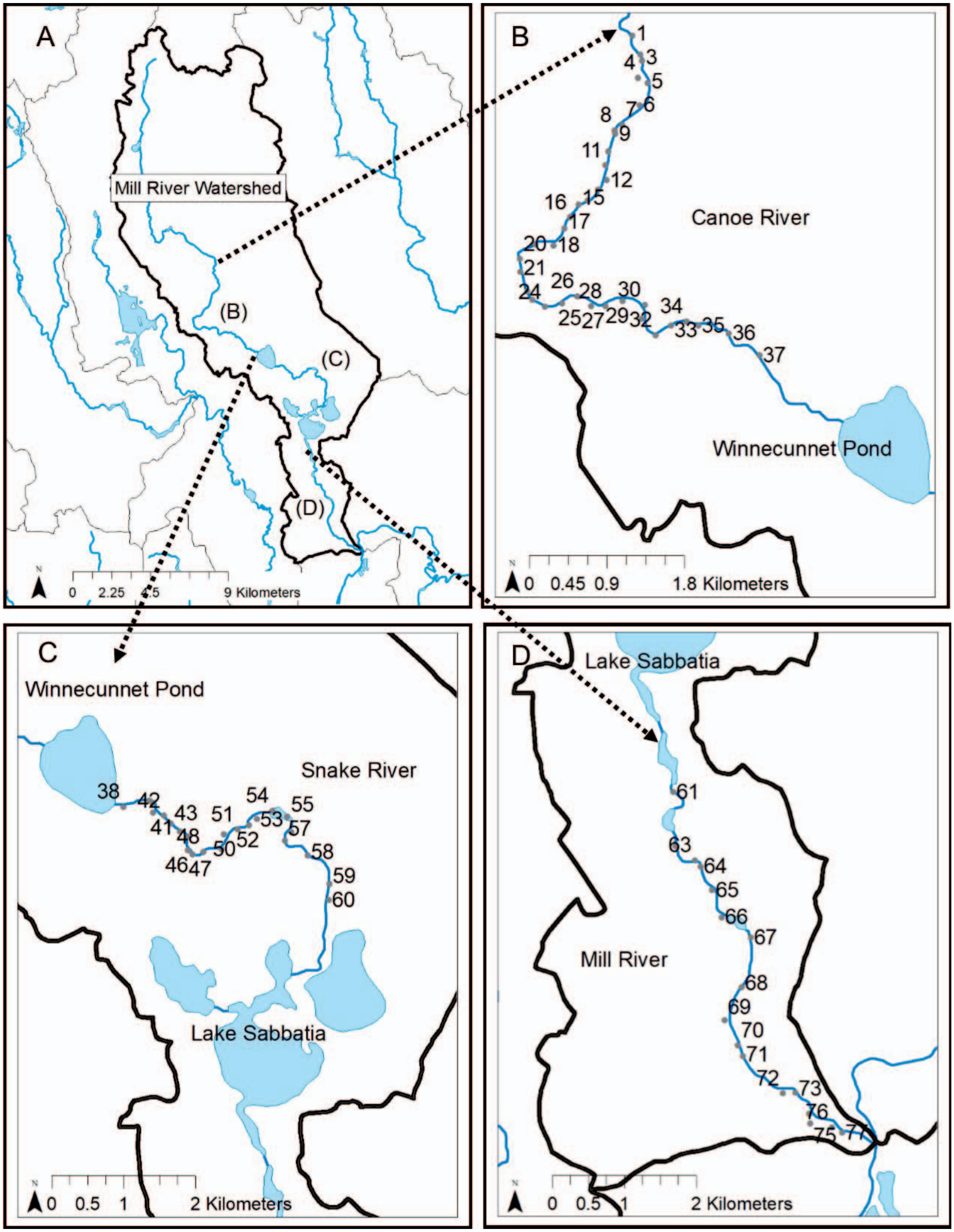

Figure 1. (A) Map of the Mill River watershed showing location of the Canoe (B), Snake (C), and Mill River (D) segments. Numbers on panels B–D indicate 2015 qualitative sampling sites. Some site numbers are not shown due to overlapping labeling format rules in ArcMap. Dams and dam removal areas are in the Mill River (D) segment: Morey's Bridge Dam is located at the outflow of Lake Sabbatia upstream of site 61; Whittenton Dam was located near site 61; West Britannia Street Dam was located near site 65; and Hopewell Dam was located near site 67.

Table 3. Site data and sampling precision for quantitative mussel sampling sites in the Mill River system. Site codes for streams represent the dam-removal effect category (e.g., USRS; see text) followed by the site number (see Table 1). Site codes for lakes are WP = Winnecunnet Pond; LS = Lake Sabbatia. GPS coordinates represent the upstream (US) and downstream (DS) boundaries of the 100-m reach at each stream site or the location of transects at lake sites. The columns "*n* required" indicate the number of samples necessary to achieve 80% and 90% precision (Downing and Downing 1992). NA = not applicable, cannot be calculated.

Site	Location	Coordinates	Area (m^2)	Samples (*n*)	% Area Sampled	*n* Required for 80% Precision	*n* Required for 90% Precision
USRS 07	US	−71.15877, 41.99578	700	25	3.6	11.0	43.9
	DS	−71.15950, 41.99530					
WP	Transect 1	−71.12676, 41.97088	3,100	21	0.7	8.2	32.6
	Transect 2	−71.12680, 41.97056					
	Transect 3	−71.12682, 41.97020					
USRS 38	US	−71.12597, 41.96706	2,000	13	0.7	4.2	16.7
	DS	−71.12479, 41.96695					
LS	Transect 1	−71.11089, 41.93848	3,100	21	0.7	23.8	95.3
	Transect 2	−71.11095, 41.93739					
	Transect 3	−71.10915, 41.93452					
DRRS 61	US	−71.10748, 41.93129	1,200	25	2.1	9.3	37.1
	DS	−71.10708, 41.93078					
DRRS 65	US	−71.10288, 41.92183	1,000	25	2.5	25.0	100.0
	DS	−71.10304, 41.92110					
DRRS 67	US	−71.09820, 41.91566	1,200	25	2.1	NA	NA
	DS	−71.09738, 41.91540					
DSRS 70	US	−71.09836, 41.90459	1,000	25	2.5	79.1	316.2
	DS	−71.09766, 41.90355					
DSRS 76	US	−71.08647, 41.89680	1,100	25	2.3	NA	NA
	DS	−71.08530, 41.89664					

River system from the mouth of the Mill River upstream into the Snake and Canoe rivers (Fig. 1). We examined the entire study section for suitable mussel habitat and the presence of live mussels or relic shells. We delineated qualitative sample sites based on changes in habitat or the spatial extent of mussel aggregations (Table 1). At each qualitative site, we conducted timed searches for mussels with view scopes and snorkeling and by touch. Timed searches were from 1 to 144 minutes (Table 2); in general, we spent more time at sites with higher mussel abundance and at larger sites. At riverine sites, we attempted to search the entire sample area. In sections of the Canoe and Snake rivers associated with extensive wetlands (sites 9–37 and 39–60), it was impractical to delineate and sample sites as for lotic sections because much of the stream was a complex mosaic of terrestrial and aquatic habitats. In these sections, we established sites in areas of localized lotic habitat and conducted timed searches at each site within a single haphazardly placed transect that traversed the stream width. We calculated catch-per-unit-effort (CPUE) for each site based on total search time. We recorded GPS coordinates and macrohabitats (riffle, run, pool, glide, mid-channel pool, lateral scour pool), substrate (boulder, cobble, gravel, sand, silt, fines), and vegetation (rooted aquatic vegetation, benthic algae) at each site. We identified and counted all live mussels and then returned them to the substrate.

Objective 2: Quantitative Sampling Sites

Site selection.—We selected nine long-term quantitative mussel sampling sites to encompass the range of potential effects likely associated with dam removal. These effects were categorized as follows: (1) upstream reference sites (USRS), representing conditions upstream of direct dam effects; (2) dam removal and restoration sites (DRRS), representing conditions directly influenced by dam removal; and (3) downstream of dam removal and restoration (DSRS), representing conditions downstream of dam removal. We grouped all qualitative sites into one of these three categories. We selected sites in each category based in part on the occurrence of diverse and abundant mussel assemblages identified in the qualitative samples (Table 2), but because all sites in the DRRS and DSRS categories had low mussel CPUE, we were forced to select sites with low mussel abundance so that these categories were represented. As a result, we had two USRS sites, three DRRS sites, and two DSRS sites (Table 3). In addition, we selected one site each in Winnecunnet Pond (WP) and Lake Sabbatia (LS).

Quantitative mussel survey methods.—At each quantitative stream site, we established a 100-m reach representative of the site. In May and June 2016, we sampled 13–25 1-m^2 quadrats at randomly selected X,Y coordinates within each reach (Table 3). At quantitative lake sites, we established a 100-m reach of

Table 4. Results of 2016 quantitative mussel sampling in the Mill River system. See Table 3 for site code definitions. Number = number of individuals; % = percentage of total mussels at the site; Density = number of individuals/m^2; SD = standard deviation of density estimates; Population = estimated number of individuals at site; ±95% CI = ±95% confidence interval around the population estimate. EC = *Elliptio complanata*; LN = *Ligumia nasuta*; LO = *Leptodea ochracea*; LR = *Lampsilis radiata*; PC = *Pyganodon cataracta*; UI = *Utterbackiana implicata*.

		Species						
Site	Parameter	EC	LR	LO	LN	PC	UI	Total
USRS 07	Number	127	3	0	0	0	0	130
	%	97.7	2.3	0.0	0.0	0.0	0.0	100.0
	Density	5.1	0.1	0.0	0.0	0.0	0.0	5.2
	SD	4.8	0.3	0.0	0.0	0.0	0.0	5.0
	Population	3,556	84	0	0	0	0	3,640
	±95% CI	1,169	76	0	0	0	0	1,204
WP	Number	187	9	1	0	3	0	200
	%	93.5	4.5	0.5	0.0	1.5	0.0	100.0
	Density	8.8	0.4	0.0	0.0	0.1	0.0	9.4
	SD	6.9	0.9	0.2	0.0	0.4	0.0	7.2
	Population	27,605	1,329	148	0.	443	0	29,524
	±95% CI	8,177	1,066	119	0	377	0	8,616
USRS 38	Number	406	54	2	5	0	0	467
	%	86.9	11.6	0.4	1.1	0.0	0.0	100.0
	Density	31.2	4.2	0.2	0.4	0.0	0.0	35.9
	SD	34.5	5.0	0.4	1.1	0.0	0.0	40.2
	Population	62,462	8,308	308	769	0	0	71,846
	±95% CI	34,404	4,948	315	1,137	0	0	40,129
LS	Number	15	4	0	2	2	0	23
	%	65.2	17.4	0.0	8.7	8.7	0.0	100.0
	Density	0.7	0.2	0.0	0.1	0.1	0.0	1.1
	SD	1.3	0.4	0.0	0.3	0.3	0.0	1.7
	Population	2,214	590	0	295	295	0	3,395
	±95% CI	1,553	533	0	377	377	0	1,194
DRRS 61	Number	166	6	0	3	0	1	176
	%	94.3	3.4	0.0	1.7	0.0	0.6	100.0
	Density	6.9	0.3	0.0	0.1	0.0	0.0	7.3
	SD	9.8	0.5	0.0	0.4	0.0	0.2	10.3
	Population	7,968	288	0	144	0	48	8,448
	±95% CI	4,073	229	0	187	0	42	4,284
DRRS 65	Number	22	2	1	0	0	0	25
	%	88.0	8.0	4.0	0.0	0.0	0.0	100.0
	Density	0.9	0.1	0.0	0.0	0.0	0.0	1.0
	SD	4.3	0.5	0.3	0.0	0.0	0.0	4.9
	Population	880	80	40	0	0	0	1,000
	±95% CI	439	155	35	0	0	0	466
DRRS 67	Number	0	0	0	0	0	0	0
	%	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Density	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	SD	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Population	0	0	0	0	0	0	0
	±95% CI	0	0	0	0	0	0	0
DSRS 70	Number	2	0	0	0	0	0	2
	%	100.0	0.0	0.0	0.0	0.0	0.0	100.0
	Density	0.1	0.0	0.0	0.0	0.0	0.0	0.1
	SD	0.3	0.0	0.0	0.0	0.0	0.0	0.3
	Population	80	0	0	0	0	0	80
	±95% CI	110	0	0	0	0	0	110

Table 4, continued.

Site	Parameter	Species						Total
		EC	LR	LO	LN	PC	UI	
DSRS 76	Number	0	0	0	0	0	0	0
	%	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Density	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	SD	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Population	0	0	0	0	0	0	0
	±95% CI	0	0	0	0	0	0	0

shoreline and used a weighted line to demarcate three transects running perpendicular to the shoreline at 25, 50, and 75 m. We sampled a 1-m^2 quadrat every 5 m beginning 1 m from shore along each transect.

We collected mussels from quadrats by excavating the substrate to about 10 cm depth and placing all individuals into a nylon mesh dive bag. We identified all individuals and returned them to the substrate. We calculated mean mussel density and standard deviation for each species based on simple random sampling and extrapolated total population size (and 95% confidence intervals) based on site area (Huebner et al. 1990; Harris et al. 1993; Christian and Harris 2005). We calculated the precision of our estimates (total mussel abundance, all species) and the number of samples needed for 80% and 90% precision at each of our sites (Downing and Downing 1992).

RESULTS

Objective 1: Qualitative Mussel Survey

We found five mussel species and a total of 2,942 individuals across all 77 qualitative sites (Table 2). Mean CPUE across all sites was 1.7 individuals/min. The highest CPUE values were found in the Mill River (14.0 and 16.6), but the Canoe and Snake rivers each had sites with CPUE >5.0 individuals/min. We found no mussels at 26 sites, which occurred in all three stream segments. Across all sites, the relative abundance of the five species was *Elliptio complanata* (89%), *Lampsilis radiata* (10%), *U. implicata* (0.5%), *L. nasuta* (0.4%), and *Pyganodon cataracta* (<0.1%). *Ligumia nasuta* was observed at six sites and represented by 11 individuals. *Utterbackiana implicata* was observed at nine sites and represented by 16 individuals. We did not detect *Le. ochracea* in qualitative samples.

We found four species and 300 individuals in the Canoe River (Table 2). Mean CPUE across all sites was 1.1 individuals/min. Mussel CPUE showed no clear upstream to downstream pattern, and sites with higher CPUE were scattered throughout the stream. Species relative abundance was *E. complanata* (90%), *La. radiata* (8%), *U. implicata* (1%), and *L. nasuta* (1%). We found a total of three *L. nasuta*, one each at sites 6, 7, and 34. We found a total of three *U. implicata*, one each at sites 5, 7, and 23.

We found four species and 226 individuals in the Snake River (Table 2). Mean CPUE across all sites was 1.8 individuals/min. Mussel CPUE showed no clear upstream to downstream pattern, and sites with higher CPUE were scattered throughout the Snake River segment. Species relative abundance was *E. complanata* (83%), *La. radiata* (10%), *U. implicata* (5%), and *L. nasuta* (2%). We found five *L. nasuta* at a single site (38). We found a total of 11 *U. implicata* distributed across sites 38, 39, 49, 57, and 58.

We found five species and 2,416 individuals in the Mill River (Table 2). Mean CPUE across all sites was 2.3 individuals/min. The highest CPUE was found at sites immediately downstream of Lake Sabbatia (sites 61 and 63), but mussels were conspicuously absent or rare downstream of site 69. Species relative abundance was *E. complanata* (89%), *La. radiata* (10%), *L. nasuta* (<1%), *U. implicata* (<1%), and *P. cataracta* (<1%). We found a total of three *L. nasuta* at sites 61 and 63 and one *U. implicata* at site 69.

Objective 2: Quantitative Sampling Sites—Mussels

Estimates of mean mussel density across quantitative sites ranged from 0.0 to 35.9 individuals/m^2 (Table 4). Population estimates at sites where mussels were detected ranged from 1,000 mussels at DRRS65 to 71,846 mussels at USRS38. Species richness ranged from zero at DRRS67 and DSRS76 to four at WP, USRS38 and LS, and we observed a total of six species across all quantitative sites. As with qualitative samples, *E. complanata* dominated mussel assemblages at all quantitative sites, but we found *Le. ochracea* only in quantitative sampling; we found a total of four individuals of *Le. ochracea* at three sites. Precision of mussel density estimates at sites where mussels were detected was ≥80% except at USRS38 and DSRS70, where precision was 69% and 40%, respectively (Table 3). At site DSRS38, only six additional samples were required to achieve 80% precision (31 samples); in contrast, a large number of samples (225) were required at DSRS70 because of the low mussel density at this site. The number of samples required to achieve 90% precision was 316 at DSRS70 and between 17 and 100 at the other sites where mussels were detected.

DISCUSSION

Mussel assemblages in the Mill River system were dominated by *E. complanata*, which is typical of New England streams (e.g., Raithel and Hartenstine 2006). *Ligumia nasuta*, *Le. ochracea*, and *U. implicata* were rare throughout the system. *Utterbackiana implicata* appears to be a specialist on anadromous fishes such as herrings and Striped Bass (Kneeland and Rhymer 2008). The rarity of this species is probably related to the fact that dams formerly blocked the movement of these fishes into the system. Improved fish passage for anadromous fishes after dam removal and installation of fish ladders at Morey's Bridge Dam may result in increased abundance of *U. implicata* (see Smith 1985). It is more difficult to predict the response of *L. nasuta* and *Le. ochracea* to dam removal. These species typically occur in low-gradient streams and lakes, and *Le. ochracea* appears able to parasitize a number of nonmigratory fishes; hosts of *L. nasuta* are unknown (Kneeland and Rhymer 2008; Nedeau 2008). The rarity of *P. cataracta* in the Mill River was surprising because this species appears able to adapt to a wide range of habitats, including impounded streams, and it is a host generalist (Nedeau 2008).

Mussel CPUE showed no clear upstream to downstream pattern in the Canoe or Snake rivers, and substantial mussel aggregations occurred irregularly throughout these streams. Typical riffle/run/pool stream habitats occurred in these streams only in the upper reaches of the Canoe River (sites 1–8) and in the Snake River immediately downstream of Winnecunnet Pond (site 38). Riverine sites in the Canoe River were not associated with conspicuously higher mussel CPUE than wetland-influenced sites, but the highest CPUE in the Snake River was observed at site 38. Similarly, the highest CPUE in the Mill River was observed immediately downstream of Lake Sabbatia. Higher abundance at these sites may be due to increased food availability associated with high primary productivity in the lakes and geomorphological stability of the sites (Ward and Stanford 1983; Gangloff et al. 2011). The rarity or absence of mussels in the Mill River downstream of site 69 may be due to the effects of urban development associated with the city of Taunton (Walsh et al. 2005). The former presence of four dams near this section and backwater effects from the confluence with the Taunton River also may be factors in reducing mussel abundance (Ward and Stanford 1983; Ashmore 1993; Christian et al. 2005).

We were unable to directly examine the effects of former dam presence or recent dam removal on mussel assemblages because of the heterogeneous nature of the system, the concentration of dams in a relatively short stretch of the Mill River, and the recent removal of dams. Quantitative sites associated with West Britannia Dam site (DRRS65), Hopewell Dam site (DRRS67), and the downstream-most sites (DSRS70 and DSRS76) all had low mussel density and species richness. Similar to qualitative sites, we cannot specify the factors that limit mussel occurrence at these sites, but future monitoring will be valuable for examining mussel responses in these areas.

Most of our quantitative estimates of total mussel density had precision sufficient to allow detection of moderate changes in density over time. Because of low mussel density at site DSRS70, a prohibitively large number of samples were required to achieve 80% precision. However, changes may be statistically detectable if mussel abundance increases dramatically at this site. Except for DSRS70, achieving 90% precision required up to a 10-fold increase in sample effort above our effort, but 90% precision could be achieved at some sites with a more modest increase in effort. Future monitoring efforts will need to weigh study goals against resources available for sampling at those times. Although our samples were adequate to detect moderate changes in total mussel density, the power to detect changes in density of target species such as *L. nasuta*, *Le. ochracea*, and *U. implicata* will be very low because of their rarity and the wide confidence intervals associated with their density estimates. Such changes might be detectable at quantitative sites if restoring access for migratory host fishes of *U. implicata* results in dramatic increases in the abundance of this mussel. Detecting more modest changes in abundance or distribution of rarer species may require a watershed-scale approach based on CPUE (e.g., Strayer and Smith 2003).

ACKNOWLEDGMENTS

Field assistance was provided by Cathy Bozek, Sophie Cash, Anne Mae Maillet, Marie Hendrik, Mary Rose Larges, Sean Sears, Felicia Horton, Lindsey Lloyd, Brianna Shaughnessy, and Ted Lyman. Laboratory assistance was provided by Sophie Cash and Barbara Araya. Early drafts of this manuscript benefited from a review by Marea Gabriel and Sara Burns of the Massachusetts Chapter of the Nature Conservancy and Catherine Colliton of the University of Massachusetts Boston. This paper also benefited from feedback provided by two anonymous reviewers. Funding was provided by the Massachusetts Chapter of the Nature Conservancy and by the National Science Foundation through its support of the Coastal Research in Environmental Science and Technology, Research Experiences for Undergraduate Programs, University of Massachusetts Boston School for the Environment (NSF awards 1359242 and 1658901).

LITERATURE CITED

Ashmore, P. 1993. Anabranch confluence kinetics and sedimentation processes. Pages 129–146 *in* J. L. Best and C. S. Bristow, editors. Braided rivers. Special Publications 1993, Volume 75. Geological Society, London, England.

Christian, A. D., and J. L. Harris. 2005. Development and assessment of a sampling design for mussel assemblages in large streams. American Midland Naturalist 153:284–292.

Christian, A. D., J. L. Harris, W. R. Posey, J. F. Hockmuth, and G.L. Harp. 2005. Freshwater mussel (Bivalvia: Unionidae) assemblages of the Lower Cache River, Arkansas. Southeastern Naturalist 1:487–512.

Division of Ecological Restoration. 2018. River restoration and dam removal.

Commonwealth of Massachusetts, Boston. Available at https://www.mass.gov/river-restoration-dam-removal (accessed July 29, 2018).

Downing, J. A., and W. L. Downing. 1992. Spatial aggregation, precision, and power in surveys of freshwater mussel populations. Canadian Journal of Fisheries and Aquatic Sciences 49:985–991.

Gangloff, M. M., E. E. Hartfield, D. C. Werneke, and J. W. Feminella. 2011. Associations between small dams and mollusk assemblages in Alabama streams. Journal of the North American Benthological Society 30:1107–1116.

Graf, W. L. 1999. Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. Water Resources Research 35:1305–1311.

Harris, J. L., P. J. Rust, S. W. Chordas III, and G. L. Harp. 1993. Distribution and population structure of freshwater mussels (Unionidae) in Lake Chicot, Arkansas. Proceedings of the Arkansas Academy of Science 47:38–43.

Hazelton, P. D. 2014. Effects of dam removals on freshwater mussel habitat and assemblages in a Southeastern New England River. Unpublished report prepared for Mill River Restoration Group. Massachusetts Division of Fisheries and Wildlife, Natural Heritage and Endangered Species Program, Boston.

Huebner, J. D., D. F. Malley, and K. Donkersloot. 1990. Population ecology of the freshwater mussel *Anodonta grandis grandis* in a Precambrian Shield lake. Canadian Journal of Zoology 68:1931–1941.

Kneeland, S. C., and J. M. Rhymer. 2008. Determination of fish host use by wild populations of rare freshwater mussels using a molecular identification key to identify glochidia. Journal of the North American Benthological Society 27:150–160.

Natural Heritage and Endangered Species Program. 2015a. Eastern Pondmussel *Ligumia nasuta* fact sheet. Massachusetts Division of Fisheries & Wildlife, Westborough. Available at www.mass.gov/nhesp (accessed August 8, 2018).

Natural Heritage and Endangered Species Program. 2015b. Alewife Floater *Anodonta implicata* fact sheet. Massachusetts Division of Fisheries & Wildlife, Westborough. www.mass.gov/nhesp (accessed August 8, 2018).

Natural Heritage and Endangered Species Program. 2015c. Tidewater Mucket *Leptodea ochracea* fact sheet. Massachusetts Division of Fisheries & Wildlife, Westborough. www.mass.gov/nhesp (accessed August 8, 2018).

Nedeau, E. J. 2008. Freshwater mussels and the Connecticut River watershed. Connecticut River Watershed Council, Greenfield, Massachusetts.

Raithel, C. J., and R. H. Hartenstine. 2006. The status of freshwater mussels in Rhode Island. Northeastern Naturalist 13:103–116.

Smith, D. G. 1985. Recent range expansion of the freshwater mussel *Anodonta implicata* and its relationship to clupeid fish restoration in the Connecticut River system. Freshwater Invertebrate Biology 4:105–108.

Strayer, D. L., and D. R. Smith. 2003. A guide to sampling freshwater mussel populations. American Fisheries Society Monograph 8, Bethesda, Maryland.

United States Geological Survey. 2018. StreamStats Version 4. Department of Interior, Washington, DC. Available at https://water.usgs.gov/osw/streamstats/ (accessed August 14, 2018).

Vaughn, C., and C. M. Taylor. 1999. Impoundments and the decline of freshwater mussels: A case study of an extinction gradient. Conservation Biology 13:912–920.

Walsh, C. J., A. H. Roy, J. W. Feminella, P. D. Cottingham, P. M. Groffman, and R. P. Morgan II. 2005. The urban stream syndrome: Current knowledge and the search for a cure. Journal of the North American Benthological Society 24:706–723.

Ward, J. V., and J. A. Stanford. 1983. The serial discontinuity concept of lotic ecosystems. Dynamics of Lotic Ecosystems 10:29–42.

Watters, G. T. 1996. Small dams as barriers to freshwater mussels (Bivalvia, Unionoida) and their hosts. Biological Conservation 75:79–85.