Restoring aquatic habitats through dam removal

Katherine Abbott[1]
Allison Roy[2]
Keith Nislow[3]

1 Massachusetts Cooperative Fish and Wildlife Research Unit, University of Massachusetts, Amherst, MA
2 U.S. Geological Survey, Massachusetts Cooperative Fish and Wildlife Research Unit, University of Massachusetts, Amherst, MA
3 Northern Research Station, U.S.D.A. Forest Service, University of Massachusetts, Amherst MA

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For additional copies or information, contact:

Allison Roy
U.S. Geological Survey
Massachusetts Cooperative Fish and Wildlife Research Unit
E-mail: aroy@usgs.gov

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Katherine Abbott[1], Allison Roy[2], and Keith Nislow[3]

[1]Massachusetts Cooperative Fish and Wildlife Research Unit, University of Massachusetts Amherst
[2]U.S. Geological Survey, Massachusetts Cooperative Fish and Wildlife Research Unit, University of Massachusetts Amherst
[3]Northern Research Station, U.S.D.A. Forest Service, University of Massachusetts Amherst

Photo details: Top left: Brook trout (*Salvelinus fontinalis*) being held in water in the impoundment of Becker's Pond Dam. Top right: Looking upstream into the former impoundment of the Old Mill Dam on the Charles River, dam removed in 2017 and photo taken in 2021. Bottom left: Looking upstream into the former impoundment of the Sucker Brook Dam on Sucker Brook, dam removed in 2021 and photo taken in 2022. Bottom right: An adult dragonfly perched on emergent vegetation, with the exuviae (remains of the shed exoskeleton) of the dragonfly's aquatic larval stage below. Photos courtesy of K. Abbott.

Restoring Aquatic Habitats Through Dam Removal

Final Report

Funded by: The Massachusetts Division of Ecological Restoration (MassDER)†

Katherine Abbott[1], Allison Roy[2], and Keith Nislow[3]
[1]Massachusetts Cooperative Fish and Wildlife Research Unit, University of Massachusetts Amherst
[2]U.S. Geological Survey, Massachusetts Cooperative Fish and Wildlife Research Unit, University of Massachusetts Amherst
[3]Northern Research Station, U.S.D.A. Forest Service, University of Massachusetts Amherst

Executive Summary

This report presents results from a four-year project (2018–2022) to document the effects of small, run-of-river dams and dam removal on water quality (stream temperature and dissolved oxygen (DO)), aquatic macroinvertebrates, and fishes. Temperature and DO are critical water quality parameters that shape biogeochemical processes and biotic assemblages in streams. Macroinvertebrate and fish assemblages can be reflective of habitat and water quality due to their diversity and sensitivity to high temperatures and low DO and are often used as indicators of ecosystem health (e.g., Clean Water Act Section 401). This study aimed to better explain the responses of these important ecological parameters to small dam removals, which may support a more comprehensive understanding of the benefits of restoration to aquatic ecosystems.

We collected pre- and post-restoration water quality data and macroinvertebrate samples at 16 small dams in Massachusetts that have been removed (10 sites) or are currently being considered for removal (6 sites). General results from these monitoring efforts indicate that:

- 15 of 16 small dams increased impoundment water temperatures and warming persisted downstream at 11 of those sites, relative to upstream. Dam removal reduced summer impoundment warming at 7 of 10 removal sites and reduced downstream warming at 5 of 10 sites. These in-stream temperature improvements occurred within 5 years after dam removal.
- 13 of 16 small dams negatively impacted dissolved oxygen (DO) concentrations within the impoundments, but the magnitude of impact varied across sites. Negative impoundment DO impacts did not consistently translate downstream, and downstream responses to dam removal were generally minimal and variable across sites. Dam removal significantly reduced negative impoundment DO impacts within 1 year after removal at 7 of 10 sites, and sites with greater pre-removal impacts experienced the greatest magnitude of DO recovery after dam removal.
- Interannual variability in dam impacts on water quality across sites suggests periods of extreme weather (i.e., droughts or high precipitation) due to climate change may exacerbate adverse impacts from run-of-river dams.
- Macroinvertebrate assemblages within dam impoundments differed from assemblages in adjacent un-impounded stream sections and exhibited a loss of sensitive organisms (an average of 17% fewer). Dam removal led to more similar macroinvertebrate assemblages throughout most stream sections, and recovery of sensitive taxa occurred relatively quickly (1-3 years).
- Fish species richness increased upstream at 2 of 10 removal sites, suggesting potential increases in fish passage from downstream reaches. However, particular species, such as American Eel (*Anguilla rostrata*), exhibited both positive and negative responses to dam removal across study sites. Incorporating more sites with pre-and post-dam removal fish data could allow for better understanding factors explaining site-specific differences.

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Acknowledgements

We thank the dam owners, landowners, and conservation professionals from the Massachusetts Division of Ecological Restoration, U.S. Fish and Wildlife Service, The Nature Conservancy, and other organizations for providing permission and critical local knowledge to help establish and maintain sampling sites. Numerous undergraduate technicians at the University of Massachusetts Amherst supported the data collection under the direction of Peter Zaidel (MS student, 2015–2018), Sam Sillen (research technician, 2018), and Katherine Abbott (PhD student, 2019–present). Funding for this project was provided by the Massachusetts Division of Ecological Restoration, the Department of the Interior U.S. Fish and Wildlife Service through a grant from the National Fish and Wildlife Foundation's Hurricane Sandy Coastal Resiliency Competitive Grant Program (grant number 42671), Massachusetts Environmental Trust through the sale of their license plates, the University of Massachusetts Amherst Department of Environmental Conservation, and the U.S.D.A. Forest Service. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Data Accessibility

Temperature data (15-min) are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Daily water quality data (temperature and dissolved oxygen) are also available through ScienceBase (https://doi.org/10.5066/P9L2ATHV). Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

Background and Objectives

Small, run-of-river, surface-release dams (<15 m tall) are ubiquitous across northeastern U.S. watersheds and can fundamentally alter and degrade critical river ecosystems. Many of these dams were built during the 18th and 19th centuries and have exceeded their functional lifespan, posing a risk to communities and surrounding infrastructure should they fail due to high flows or disrepair (Pohl 2002). Often, the economic costs of repair, recurring maintenance, or retrofitting to meet federal licensing requirements can be prohibitive for dam owners (Chaffin and Gosnell 2017). Additionally, these aging structures can negatively impact stream ecology by altering hydrology, impairing sediment and nutrient transport, and impeding or preventing migratory fish passage (Poff and Hart 2002, Pohl 2002). To mitigate adverse ecological impacts, eliminate safety hazards, and reduce economic burdens, dam removal is becoming an increasingly favorable method of stream restoration, with over 1,600 dams removed in the U.S. since 1912 (American Rivers 2020) and between 4,000 and 36,000 total removals predicted by 2050 (Grabowski et al. 2018).

Dam owners, federal, tribal, and state agencies, non-profit organizations, and others have invested millions of dollars into dam removal projects with the expectation that they will improve stream ecosystems, but more information is needed regarding potential short-term adverse impacts of dam removals (Tullos et al. 2016). Compounding these concerns is the lack of information on stream ecosystem changes following removal; less than 10% of national dam removal projects include scientific study (Bellmore et al. 2017), raising questions about timing and extent of ecosystem recovery. Even within a single category of dams (e.g., small, surface-release dams), variability among dams has proven to be a consistent challenge to researchers quantifying the impacts of dam and dam removal (Poff and Hart 2002), with case studies demonstrating a range of dam impacts on temperature, dissolved oxygen (DO), macroinvertebrates, and fish assemblages. Given that each dam and dam removal is unique and nested within a discrete stream system and watershed, a case study approach (i.e., focusing on one or a few dam sites) may not be sufficient to define broader impacts and restoration responses across a state or region.

With more than 3,000 dams in Massachusetts (Division of Ecological Restoration 2022), more regionally relevant and timely information is needed to strategically plan restoration projects to maximize ecological benefits. A greater understanding of the factors influencing dam impacts and dam removal responses may help better predict restoration outcomes across the landscape, set expectations for stakeholders and regulatory agencies, and quantify the collective ecological services and societal benefits resulting from dam removal. In this project, we evaluated a suite of ecological metrics at 16 dam sites in Massachusetts across a range of dam, stream, and landscape characteristics, both before (n=16) and after (n=10) dam removal. This project broadly addresses the extent to which dam removal improves ecological integrity across varying stream and landscape characteristics, and the timeline of recovery of different ecological metrics. Specifically, our study objectives were to:

1) Quantify dam impacts and dam removal responses of in-stream temperature, dissolved oxygen and benthic macroinvertebrates,
2) Determine the dam, stream, and watershed characteristics that influence variability in dam impacts and dam removal responses, and
3) Examine the responses of fish assemblages to dam removals.[1]

This project is unique in both the temporal and spatial scope of our data collection, which is critical for understanding the variability among dams and stream/watershed size and condition, and for holistically quantifying multiple benefits of dam removal for stream ecosystems.

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[1] Fish sampling was conducted at these sites in collaboration with the Massachusetts Division of Fisheries and Wildlife (MassWildlife), although this objective was not part of the Massachusetts Division of Ecological Restoration (MassDER)-funded project.

Approach

Study Design

Our general study approach follows a modified Before-After-Control-Impact (BACI) design, which evaluates impacted (impoundment and downstream of dam) and reference (upstream of impoundment) stream conditions both before and after dam removal to differentiate the effects of the removal from natural variability within a stream system. For each site, data were collected in upstream, downstream, and impounded or formerly impounded stream sections, with each section defined as a ~100 m length of flowing water that is within 3 km of the dam. *Impoundment* refers to the lentic waterbody created by the dam and the upstream extent of the impoundment was determined by Google Earth Pro (version 7.3.4.8248) and field observations.

We conducted monitoring at 16 streams in Massachusetts with recent (2015–2021) or planned dam removals led by the Massachusetts Division of Ecological Restoration (MassDER; Table 1; Fig. 1). One additional dam site was monitored (Site 5; BVL) to better understand the potential effects of multiple dams on a single river. Site selection was primarily based on dam size and type (small, <15 m high, surface-release), authorized access, and the recent removal (2015-2021) or pursuit of removal by MassDER. Sites with recent removals have at least one summer of pre-removal data collection. Additionally, sites were selected to capture a range of dam, stream, and landscape characteristics to investigate how stream response to dam removal varies across these conditions (Table 2). Our overall approach and methods are detailed in the sections below, with individual, site-specific details and site maps located in Appendices 3-18, as listed on page 2.

Table 1 – Site information and coordinates for the 16 dam sites throughout Massachusetts, USA, monitored as a part of this study assessing water quality, macroinvertebrates, and fishes before and after dam removal. TBD = Date of dam removal to be determined. See Figure 1 for a map of all locations within Massachusetts.

Site No.	Site ID	Site Name	Latitude	Longitude	Stream Name	Major Watershed	Removal Year
1	BAL	Balmoral	42.6721	-71.1494	Shawsheen River	Merrimack	2017
2	BAR	Barstow's Pond	41.8824	-71.0486	Cotley River	Taunton	2018
3	BEC	Becker's Pond	42.0583	-73.4593	Unnamed tributary to Schenob Brook	Housatonic	TBD
4	BOS	Bostik/ S. Middleton	42.5699	-71.0310	Ipswich River	Ipswich	TBD
5	BVL	Ballardvale	42.6280	-71.1576	Shawsheen River	Merrimack	TBD
6	CGM	Cotton Gin Mill	42.0214	-70.9509	Satucket River	Taunton	2017
7	HUN	Hunter's Pond	42.2231	-70.7883	Bound Brook	South Coast	2017
8	IPS	Ipswich Mills	42.6776	-70.8378	Ipswich River	Ipswich	TBD
9	MAR	Marland Place	42.6623	-71.1468	Shawsheen River	Merrimack	2017
10	OLD	Old Mill	42.1309	-71.4443	Charles River	Charles	2017
11	RAT	Rattlesnake Brook	41.7809	-71.0858	Rattlesnake Brook	Taunton	2016
12	SUC	Sucker Brook	42.6853	-71.6101	Sucker Brook	Nashua	2021
13	TEL	Tel-Electric	42.4469	-73.2638	West Branch Housatonic River	Housatonic	2020
14	TUR	Millie Turner	42.6749	-71.5822	Nissitissit River	Nashua	2015
15	URM	Upper Roberts Meadow	42.3381	-72.7279	Roberts Meadow Brook	Connecticut	2018
16	WHE	Wheelwright	42.3524	-72.1370	Ware River	Chicopee	TBD

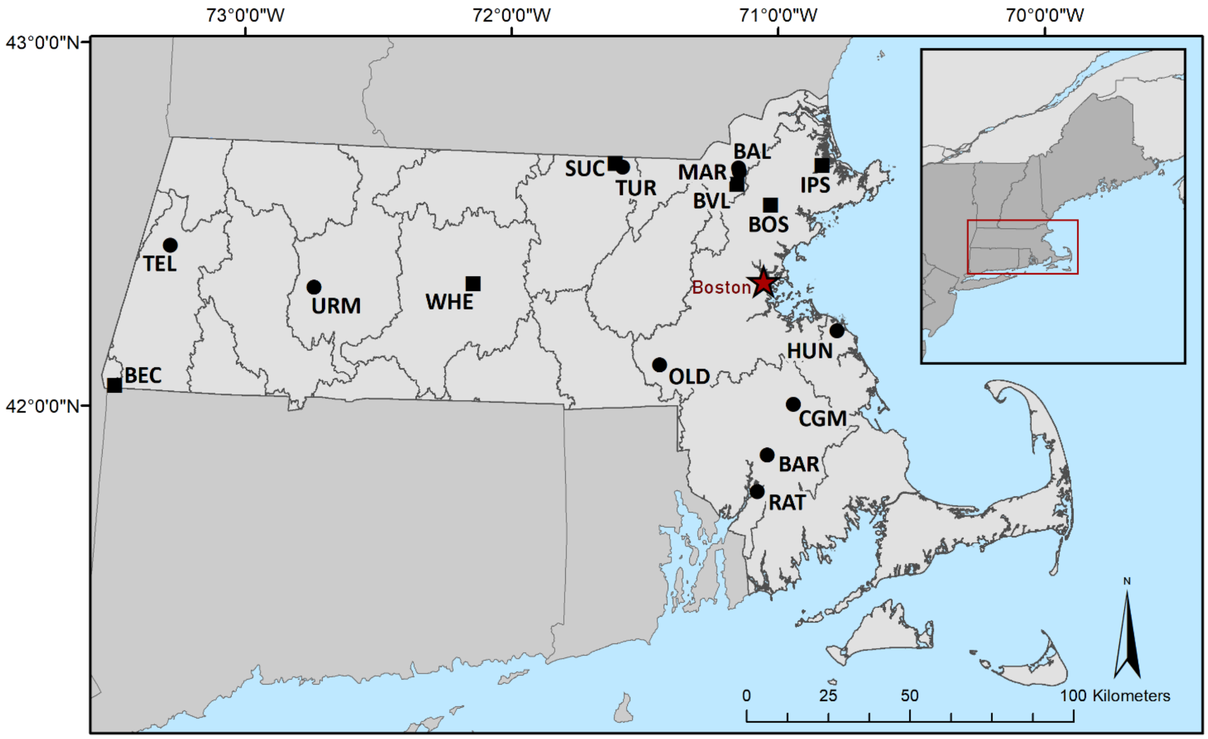

Figure 1. Map of the 16 sites in Massachusetts, USA, monitored in this project, of which 10 (circles) were removed over the course of this study and 6 (squares) remained standing. Dark grey lines represent subbasins (HUC-8) and the red star represents Boston, a major city. See Table 1 for site information corresponding to numbers. Map was prepared using ArcGIS 10.8 (ESRI, Redlands, California, USA).

Table 2 – Minimum, average, and maximum values of dam, impoundment, and watershed characteristics for 16 dam sites within this study.

Characteristic	Information Source	Minimum	Average	Maximum
Dam height (ft)	State Technical Reports/National Inventory of Dams	3.9	12.3	35.1
Impoundment surface area (acres)	MassDEP[*] Hydrography (1:25000)	0.2	13.0	53.0
Impoundment volume (acre-feet)	State Technical Reports/National Inventory of Dams	0.2	61.9	250.0
Impoundment widening (ratio)	Calculated in Google Earth Pro[†]	1.2	7.8	57.4
Residence time (hrs)	Calculated using available data[††]	0.4	224.8	733.0
Upstream slope (%)	Designing Sustainable Landscapes[†††]	0.0	0.3	1.2
Downstream slope (%)	Designing Sustainable Landscapes[†††]	0.0	0.4	1.3
Watershed area (sq-miles)	USGS StreamStats	1.1	44.6	150.0
Watershed forest cover (%)	NLCD[**] 2016; USGS StreamStats	25.3	54.3	89.7
Watershed impervious cover (%)	NLCD[**] 2016; USGS StreamStats	0.0	10.1	27.7
Watershed agriculture cover (%)	MassGIS Land Cover/Land Use (2016)	0.0	0.5	2.6
Watershed wetland cover (%)	NLCD[**] 2016; USGS StreamStats	4.3	12.2	21.8

[†] Calculated as the ratio of upstream width to average impoundment width

[††] Calculated using impoundment volume and median August discharge adjusted using the drainage-area ratio method

[†††] Designing Sustainable Landscapes: Stream gradient settings variable (McGarigal et al. 2020)

[*] MassDEP: Massachusetts Department of Environmental Protection

[**] NLCD: National Land Cover Database

Temperature

Continuous temperature data loggers (Onset© HOBO Pro V2 data loggers; Onset Computer Corporation, Bourne, MA; recording every 15 minutes) were installed at each site: deployed upstream (1 location), within the impoundment and former impoundment (1 location), and downstream of dam (multiple locations) (Fig. 2). All loggers were deployed in protective PVC housings with holes that allow water through-flow while minimizing sediment and debris accumulation that may interfere with readings. Loggers within flowing water sections (upstream, downstream, former impoundments) were placed at the stream bottom interface and anchored to a permanent bank structure via cabling or rebar. Within the impoundments, loggers were attached to a float to record surface water temperatures. Downstream of each dam site, a longitudinal array of 2 to 5 temperature loggers were deployed to assess the downstream extent of thermal impacts. The number of loggers and the distance deployed from the dam were dependent on site-specific conditions, with the furthest downstream logger constrained by inflowing tributaries, additional dams, or authorization and physical access limitations. Temperature data loggers were visited and downloaded bi-annually (May and October) and were swapped out with quality assured loggers each spring. Quality assurance (QA) tests of loggers were conducted using an ice bath (certified at 0 °C by a National Institute of Standards and Technology (NIST)-traceable thermometer) to confirm the loggers recorded 0 (± 0.2) °C every minute for one hour. Following each logger download, temperature data were plotted and visually inspected to identify anomalous points. Additionally, data were quantitatively examined using the *ContDataQC* package in R (R Studio 2019). Anomalous data points (i.e., extreme gross values, rates of change, or flat values) taken when the logger may have been frozen, fouled, or out of water were flagged and removed from analyses.

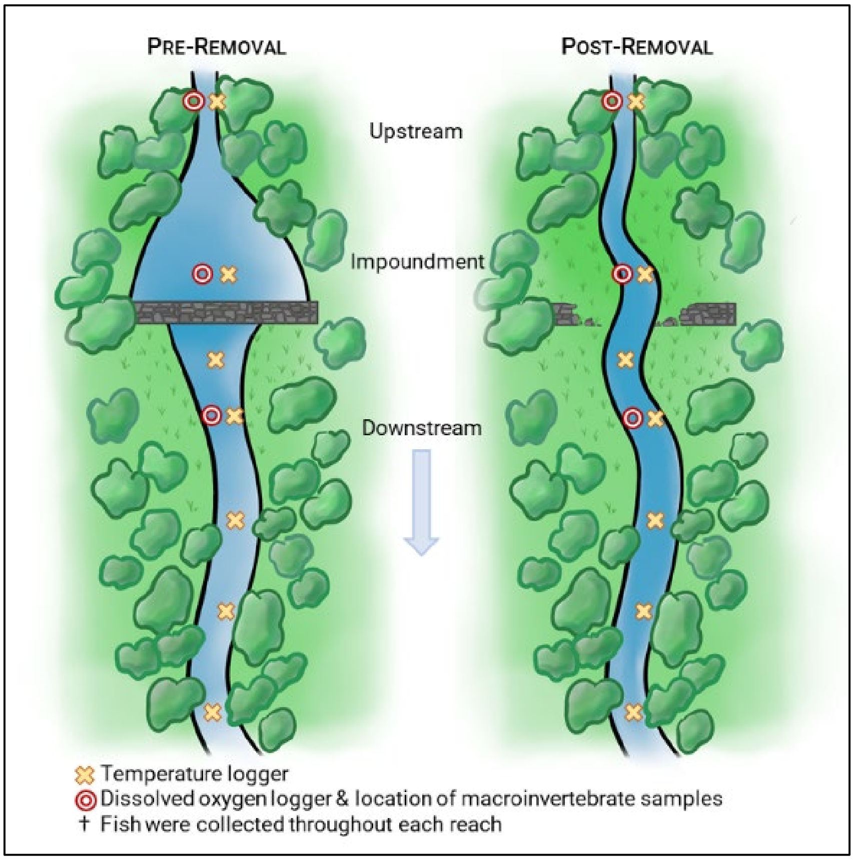

Figure 2. Schematic of data collection locations for each parameter (temperature, dissolved oxygen, macroinvertebrates) within study sites. Pre-removal data collection locations shown on left, and post-removal data collection locations shown on right.

We calculated daily minimum, maximum and mean temperatures for each logger at each site. *Impoundment warming* was calculated as the mean temperature of the impoundment logger minus the mean temperature of the upstream reference logger. Similarly, *downstream warming* was calculated as the mean temperature of a downstream logger minus the mean temperature of the upstream reference logger. To minimize temporal autocorrelation and associated inflated significance values, we aggregated the data by week. To statistically compare impoundment and downstream warming before and after dam removal at each site, we performed Welch's two-sample t-tests using an α level of 0.05 for statistical significance and controlling for multiple tests using the Benjamini-Hochberg adjustment. We calculated June-August mean temperatures and classified upstream and downstream sections of each site before and after dam removal to one of three thermal classes: coldwater (<18.29 °C), coolwater (18.29-21.7 °C) and warmwater (>21.7 °C; Beauchene et al. 2014).

Dissolved Oxygen

To assess the impacts of dams and dam removal on dissolved oxygen, dissolved oxygen loggers (Onset© U26-001 Onset Computer Corporation, Bourne, MA; recording every 15 min) were deployed upstream, within the impoundment, and downstream of each dam or former dam (Fig. 2) for week-long periods during July, August and September. Warm, summer months were targeted for data collection to capture the greatest effects of dams and dam removals when water levels are expected to be low, ambient temperatures are highest, and DO is likely to be lowest (Zaidel et al. 2021). The downstream logger was installed a minimum of 25 m from the dam site to reduce effects of spillway reoxygenation. Prior to deployment, each logger was calibrated to 100% oxygen saturation using a wetted sponge enclosure and to 0% oxygen saturation using a sodium sulfide solution. Logger values were compared to discrete measurements from a multiparameter sonde to ensure biofouling (algal growth on the logger during the deployment period) was not affecting data quality. All DO loggers were deployed in protective PVC housings, similar to the temperature loggers. After each week-long deployment, data were downloaded, plotted, and visually inspected to identify anomalous points. Data were quantitatively examined and corrected for data drift using the *ContDataQC* package in R (R Studio 2019). Anomalous data points (i.e., extreme gross values, rates of change, or flat values) taken when the logger may have been fouled or out of water were flagged and removed from analyses. At the retrieval visit for each impoundment DO logger before dam removal, we performed a vertical profile of each impoundment >0.5 m deep with a multiparameter sonde. During each vertical profile, temperature, DO (concentration and percent saturation), pH, and conductivity were measured at 0.5 m intervals from the surface down to the reservoir bottom. Data from vertical profiles are available upon request.

We calculated daily DO metrics (minimum, average, maximum, and diel range) for each stream section at each site. To quantify dam impacts on impoundment DO, *impoundment effect* was calculated for each metric as the daily difference between the impoundment and upstream values at each site, where negative values indicate a lower DO metric value within impoundments relative to upstream. Similarly, we quantified dam impacts on downstream DO by calculating the *downstream effect* as the daily difference between the downstream and upstream values at each site. To minimize temporal autocorrelation and associated inflated significance values, we subset the data by selecting the first and last days from each deployment period at each site before analysis. For statistical tests of differences of impoundment and downstream DO effect before and after dam removal at each site, we performed Welch's two-sample t-tests using an α level of 0.05 and controlling for multiple tests using the Benjamini-Hochberg adjustment. We calculated the average daily minimum DO concentrations within each stream section both before and after dam removal to assess whether stream sections met the Massachusetts Surface Water Quality Standards (SWQS; 314 Mass. Reg. 4.05). The SWQS designate inland waters based on their most sensitive uses, which are then prescribed minimum water quality criteria required to sustain such uses (MassDEP 2016). Class A and Class B coldwater streams must have DO > 6.0 mg/L, Class A and B warm water streams must have DO > 5.0 mg/L, and Class C streams must not have DO concentrations lower than 5.0 mg/L for at least 16 hours/day, and not less than 3.0 mg/L at any time (MassDEP 2016). All sites within this study are located in streams designated as Class B, or undesignated (BEC and URM). We use thresholds defined in the SWQS to provide a better understanding of the degree of DO impairment that is relevant to state regulations.

Macroinvertebrates

Benthic macroinvertebrates were sampled during summer months (July–September), both before and after dam removal from the upstream, impoundment, and downstream sections. To determine temporal changes in macroinvertebrate assemblages, samples were collected at least once prior to dam removal, and up to 5 years following removal. Within each flowing-water section (e.g., upstream, downstream, former impoundments), three replicate samples were taken using a Surber sampler (0.09 m^2 area) within riffle habitats. To capture taxa richness, a single multi-habitat sample was also collected from ~100 m of each flowing-water section using a D-frame net according to the Environmental Protection Agency's (EPA) Rapid Bioassessment Protocol (Barbour et al. 1999). Within impounded areas, three replicate sediment samples were collected using a Ponar grab sampler (0.0271 m^2 area) area. Along the impoundment margins, three replicate sweeps of submerged and emergent vegetation were completed using a rectangular net. All macroinvertebrate samples were preserved in 70% ethanol prior to sorting and identification by experts at Cole Ecological, Inc. or the University of Massachusetts Amherst. Up to 300 individuals were identified to the lowest practical taxonomic unit (usually genus or species, referred to as "taxa"). We assigned macroinvertebrate taxa to functional trait states according to their habit using the EPA Freshwater Biological Traits Database (US EPA 2012) and Vieira et al. (2006), assigned thermal classes based on Chalfin[2] (2022), and assigned feeding groups and tolerance values using Nuzzo (2003); See Table A2.1 in Appendix 2 for descriptions of traits).

We used the *BioMonTool* package in R (TetraTech; R Studio 2019) to calculate biotic metrics of richness, diversity, and biotic integrity (e.g., Shannon diversity, Hilsenhoff Biotic Index (HBI), percent coldwater taxa, Ephemeroptera/Plecoptera/Trichoptera (EPT) richness). We calculated the percent of taxa in each sample that were classified in functional trait groups (e.g., percent of coldwater taxa, percent of burrowers) to understand whether functional groups changed following removal. Non-metric, multi-dimensional scaling (NMDS) ordination, based on log abundances (excluding rare taxa), were conducted using the *vegan* package in R (R Studio 2019) to assess assemblage differences among sites and stream sections in both flowing-water and impoundments separately, and to assess the extent to which environmental characteristics influence macroinvertebrate assemblages.

Fishes

We collaborated with the Massachusetts Division of Fisheries and Wildlife (MassWildlife) to sample fishes upstream and downstream of dam and former dam sites and obtained additional data from their extensive fish sampling database (1998-present). Sites included the 16 intensively monitored streams that had pre- and post-removal data within at least one section upstream or downstream of a dam. Exact sampling dates and sites were dependent on MassWildlife staff goals and availability. Electrofishing surveys were generally conducted from July–October during the daytime to assess fish assemblages. Exact sampling locations were selected based on prior sampling efforts, available access, water conditions and habitat type. Within flowing water sections, backpack shocker(s) were used. Typically, one backpack was used in narrow (average width less than 8 m) and shallow streams (average depth less than 0.5 m), and in streams that are wider than 6 m on

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[2] Chalfin, E. Honor's Thesis. University of Massachusetts. Unpublished data. 2022.

average but shallow, two or more backpack units were used to increase efficiency. Sample sites included 100 m of stream length within 3 km of the dam or dam removal site. In situations where 100 m sections were not practical or possible, the length of stream sampled was recorded. Total counts were recorded to calculate relative abundances of species, and survey duration (seconds) was recorded to estimate effort.

Relative abundance and catch per unit effort (CPUE) were calculated using total counts of each species over the known effort (i.e., sampling time in seconds), where data were available. We focused on relative abundances here because effort was not recorded for a subset of samples. We also calculated total taxa richness and Shannon diversity index for each sample. Fishes were classified by habitat preference (e.g., fluvial specialist, habitat generalist), pollution tolerance (e.g., intolerant, tolerant), and by thermal tolerance (e.g., coldwater, coolwater, warmwater; Armstrong et al. 2011, Kashiwagi and Richards 2009; See Table A2.2 in Appendix 2 for descriptions of traits). NMDS ordination based on relative abundances was additionally used to summarize differences in fish assemblages following dam removal and identify important functional traits associated with those differences.

General Results and Discussion

Here, we share the collective results from across the 16 sites, including analyses examining factors that influence water quality impacts and responses across sites, and comparisons of macroinvertebrate and fish assemblages among stream sections and before and after dam removal.

Temperature

Prior to dam removal, 15 of the 16 dam impoundments in this study had warmer average summer temperatures than their upstream reference sections (Fig. 3), as in Zaidel et al. (2021). The magnitude of impoundment warming varied greatly across sites and has been shown to be driven by impoundment widening (ratio of upstream width to impoundment width), as well as upstream temperatures (Zaidel et al. 2021). That is, colder streams with wider impoundments will often experience greater in-stream warming due to dams. Downstream warming occurred at 11 of the 16 sites, with variable magnitudes (Fig. 3). The sites with the most impoundment warming also experienced the most downstream warming, suggesting that warm impoundment surface waters can spill over the dam and impact downstream temperatures as well.

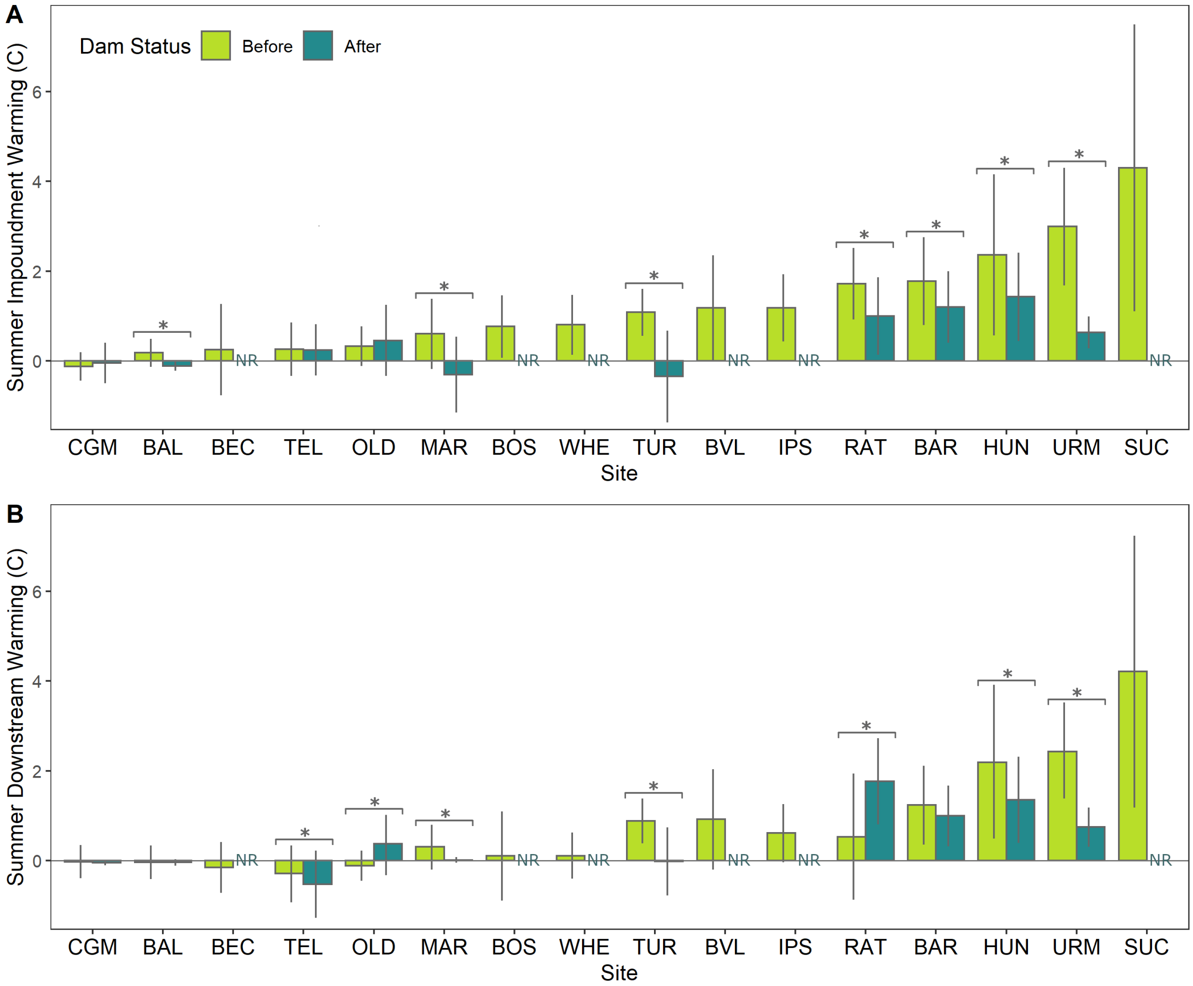

Figure 3. Summer mean A) impoundment warming (impoundment – upstream) and B) downstream warming (downstream – upstream) before and after dam removal (±1 standard deviation), with significant differences between warming before and after dam removal as determined by Welch's t-tests annotated (*p<0.05). Positive values indicate warmer temperatures than in the upstream section. NR indicates no dam removal as of summer 2021. Sites are ordered from least to most impoundment warming. See Table 1 and Figure 1 for more information on full site names and coordinates.

Dam removal significantly reduced impoundment warming within 5 years at 7 of the 10 removal sites (Fig. 3). Of the 3 sites where temperatures did not change, the Tel-Electric (TEL) and Old Mill (OLD) sites had relatively little warming prior to removal and have more open canopy cover after removal, potentially increasing solar radiation despite reduced water residence times. Due to an open water control gate at Cotton Gin Mill (CGM), both impoundment and downstream temperatures were minimally impacted by the dam and not expected to change after dam removal. After dam removal, downstream warming was significantly reduced at 5 of the 10 removal sites, increased at 2 sites, and unchanged at 3 sites (Fig. 3). At the 2 removal sites with the largest pre-removal dam impacts on downstream temperatures (HUN and URM), we observed significant decreases in temperature impacts after dam removal. Summer downstream temperatures before removal were 2.19 and 2.09 °C warmer than upstream references at HUN and URM, respectively. After dam removal, downstream temperatures at these sites were 1.13 and 0.76 °C warmer than upstream references. However, downstream temperatures were not significantly reduced at Barstow's Pond (BAR), and actually increased downstream of the former Rattlesnake Dam (RAT). At BAR, the Cotley River flows through a relatively open wetland complex between the upstream and downstream sections, which may reduce the apparent response to dam removal downstream. Prior to removal at RAT, we observed bifurcated flow within the river, with a large proportion of water flowing overland and not into the main channel downstream. The downstream section monitored consisted of stagnant water prior to removal instead of flow coming from over the dam. Flow was restored to the main channel after dam removal, and the open canopy post-restoration may contribute to the apparent increase in downstream warming at this site. A similar, though less extreme, mechanism may be influencing the apparent increase in warming at Old Mill.

Following thermal classification thresholds established by Beauchene et al. (2014), stream sections were designated as cold, cool, or warmwater (Table 3). Ten of 16 sites were designated as warmwater in both impoundment and downstream sections, and 9 of those remained unchanged after dam removal. Two sites were designated as coolwater throughout all sections (BEC and RAT), and 2 sites were designated as coolwater upstream and warmwater downstream (BAR and HUN). The two coldest sites—SUC and URM—were coldwater upstream and transitioned downstream to warmwater and coolwater, respectively. At a subset of sites, there were changes to the thermal classification after dam removal. For example, the downstream section of URM was restored from cool- to coldwater, and the downstream section of BAR improved from warm- to coolwater. At TUR, the stream appeared to change from warm- to coolwater throughout the study area after dam removal, but this response is likely due more to ambient weather conditions during the limited pre-removal sampling at this site (1 summer). This suggests that where stream thermal classifications are negatively impacted by the presence of dams (3 sites with removals), dam removal has the potential to restore downstream classifications (2 sites).

Table 3. Mean July temperatures (°C) upstream (US) and downstream (DS) of each of the 16 dams monitored within this study both before and after dam removal. Downstream temperatures provided are from the downstream logger closest to the dam (i.e., DS1). Blue shading represents coldwater, green shading represents coolwater, and pink shading represents warmwater classifications based on Beauchene et al. (2014). NR indicates no dam removal as of summer 2021. See Table 1 and Figure 1 for more information on full site names and coordinates.

Site ID	**Mean US temperature before removal** (°C)	**Mean DS temperature before removal** (°C)	**Mean US temperature after removal** (°C)	**Mean DS temperature after removal** (°C)
BAL	23.52	23.45	22.80	22.75
BAR	21.18	22.96	20.24	21.36
BEC	18.92	18.87	NR	NR
BOS	22.73	22.83	NR	NR
BVL	23.04	23.62	NR	NR
CGM	23.62	23.51	23.61	23.51
HUN	20.35	22.27	20.62	21.88
IPS	23.08	23.30	NR	NR
MAR	23.28	23.37	22.87	22.81
OLD	23.87	23.80	22.30	22.85
RAT	19.69	20.37	18.85	20.60
SUC	17.38	22.08	NR	NR
TEL	22.61	22.40	22.62	22.18
TUR	22.09	22.78	21.60	21.58
URM	17.34	19.44	17.51	18.18
WHE	22.25	22.40	NR	NR

Dissolved Oxygen

Prior to dam removal, impoundments had lower mean daily DO concentrations compared to their upstream reference reaches at 13 of 15 sites (Fig. 4). Two sites showed no difference between upstream and impoundment DO, including one site (CGM) that had been partially dewatered for several years. One site (BOS) had elevated mean daily impoundment DO relative to the upstream reach, likely due to the wetland complex upstream that may result in lower DO concentrations. Fluvial wetlands, either naturally occurring or influenced by humans (e.g., through undersized culverts), may decrease DO concentrations through increased residence time and oxygen demand from microbial processes, which may lead to low DO at the outflow of wetland complexes (Thoiun et al. 2009, Palmer 1997). The consistent impoundment DO changes did not translate to a widespread reduction in downstream DO concentrations relative to upstream. Downstream DO concentrations were slightly reduced at 10 sites and were elevated at 6 sites, but the magnitude of impact was highly variable (Fig. 4). The most extreme negative DO impacts in this study were found downstream of Rattlesnake Dam (RAT), where overland flow around the dam led to minimal water spilling, thus the downstream section was comprised of only standing pools of anoxic water. As such, the dam caused the downstream reach to experience far greater ecological impacts than just low DO concentrations. Sucker Brook (SUC), the Nissitissit River (TUR), and Roberts Meadow Brook (URM) also experienced reduced downstream DO concentrations, while the Shawsheen River (BVL) was not impacted downstream, likely due to high turbulence from water spilling over the dam. Of the 16 dam sites, 5 impoundments experienced average minimum DO concentrations lower than 5.0 mg/L, and 9 experienced at least one daily minimum DO concentration < 3.0 mg/L (Table 4). Some impoundments experienced long durations of low oxygen levels, with 3 impoundments (HUN, BOS, BAR) and 1 downstream section (RAT) averaging over 16 hours per day of low DO (Fig. 5).

Across the 10 sites where dams were removed, 7 experienced significant increases in mean impoundment DO relative to upstream reaches (Fig. 4). Impoundments that were most negatively impacted by dams also experienced the largest magnitude of recovery following dam removal. This recovery occurred at most sites within a year following dam removal, and a subset of sites that were monitored for >1 year appeared stable in impoundment DO concentrations relative to upstream, even after 2-3 years. After dam removal, downstream DO concentrations significantly increased at 5 of 10 sites relative to upstream, while 1 site experienced significantly decreased DO downstream relative to upstream (Fig 4). The magnitude and direction of downstream responses were less consistent across sites than the impoundment response (Fig. 4). After removal, impoundment DO at 9 of the 10 removal sites surpassed the 5 mg/L threshold for impaired DO, and the lowest minimum impoundment DO concentrations at these 9 sites were greater than 3.0 mg/L (Table 4). Dam removal also substantially reduced the average number of hours per day a site exhibited low DO (Fig. 5), with only 1 site still experiencing >4 hours of low DO per day (HUN), which may represent the natural conditions of the stream.

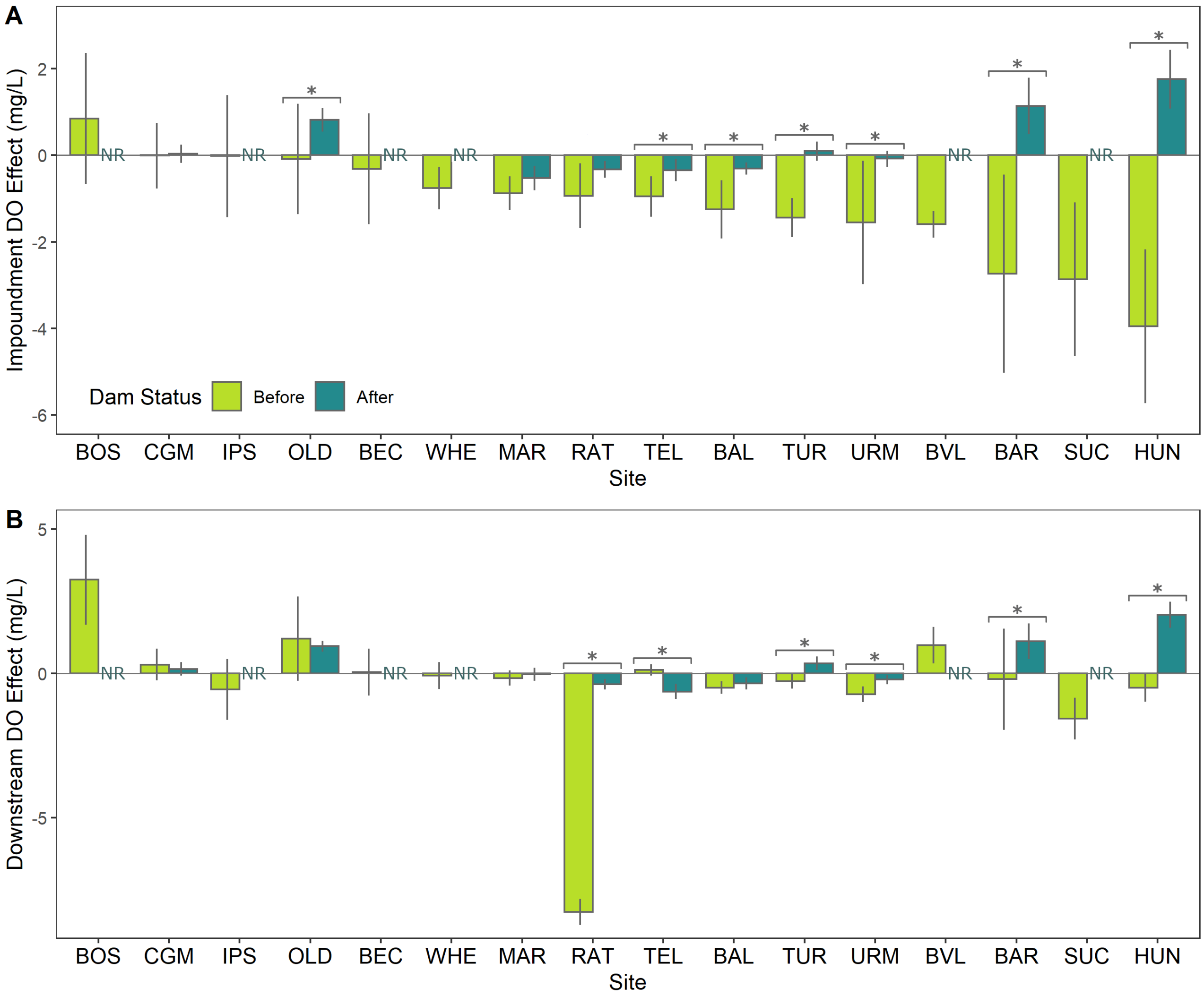

Figure 4. Summer mean A) impoundment dissolved oxygen (DO) effect (impoundment – upstream) and B) downstream DO effect (downstream – upstream) before and after dam removal (±1 standard deviation), with significant differences between DO effect before and after dam -removal as determined by Welch's t-tests annotated (*p<0.05). Negative values indicate reduced DO as compared to the upstream section. NR indicates no dam removal as of summer 2021. Sites are ordered from least to most impacted DO concentrations in the impoundment relative to upstream. See Table 1 and Figure 1 for more information on full site names and coordinates.

Table 4. Average daily minimum dissolved oxygen (DO) in upstream (US), impoundment (IMP), and downstream (DS) sections before and after dam removal, with overall minimum values (i.e., lowest values recorded) in parentheses. Purple shading represents >6 mg/L, teal shading represents >5 mg/L, and orange shading represents <5 mg/L, a threshold below which waters are considered impaired for DO (MassDEP 2016). NR indicates no dam removal as of summer 2021. See Table 1 and Figure 1 for more information on full site names and coordinates.

Site ID	Minimum DO Before US (mg/L)	Minimum DO Before IMP (mg/L)	Minimum DO Before DS (mg/L)	Minimum DO After US (mg/L)	Minimum DO After IMP (mg/L)	Minimum DO After DS (mg/L)
BAL	7.48 (6.54)	5.83 (4.71)	7.02 (5.93)	7.87 (6.49)	7.38 (5.57)	7.34 (5.55)
BAR	5.42 (3.30)	0.82 (0.00)	4.25 (2.81)	6.21 (4.66)	6.66 (5.73)	6.79 (5.84)
BEC	7.24 (3.01)	6.93 (3.85)	7.37 (3.37)	NR	NR	NR
BOS	2.58 (0.00)	3.34 (0.30)	6.14 (0.06)	NR	NR	NR
BVL	4.53 (3.82)	2.26 (1.67)	6.91 (4.75)	NR	NR	NR
CGM	5.67 (2.86)	5.66 (2.14)	6.31 (4.26)	5.67 (4.47)	6.03 (5.18)	5.93 (4.92)
HUN	4.11 (0.25)	0.55 (0.00)	4.65 (1.28)	4.77 (4.30)	4.13 (2.52)	5.18 (4.24)
IPS	5.17 (3.34)	5.53 (3.19)	2.17 (0.26)	NR	NR	NR
MAR	7.09 (6.42)	6.01 (5.01)	7.63 (6.55)	7.61 (6.47)	7.07 (6.05)	7.74 (6.4)
OLD	6.13 (3.60)	6.05 (4.33)	7.72 (6.12)	6.32 (5.46)	7.17 (6.33)	7.31 (6.4)
RAT	7.83 (7.14)	5.66 (0.46)	0.00 (0.00)	8.29 (7.42)	7.79 (6.71)	7.6 (6.27)
SUC	8.37 (7.28)	4.06 (0.00)	6.44 (4.37)	NR	NR	NR
TEL	7.53 (6.59)	5.27 (3.00)	7.78 (6.89)	7.35 (5.15)	7.05 (6.47)	6.77 (4.96)
TUR	8.32 (7.39)	7.00 (6.02)	8.06 (6.88)	8.06 (6.80)	7.54 (6.25)	8.11 (6.93)
URM	9.19 (8.80)	6.85 (2.88)	8.35 (7.32)	9.11 (8.46)	8.95 (8.23)	8.63 (6.92)
WHE	7.07 (5.18)	6.41 (4.22)	7.26 (5.44)	NR	NR	NR

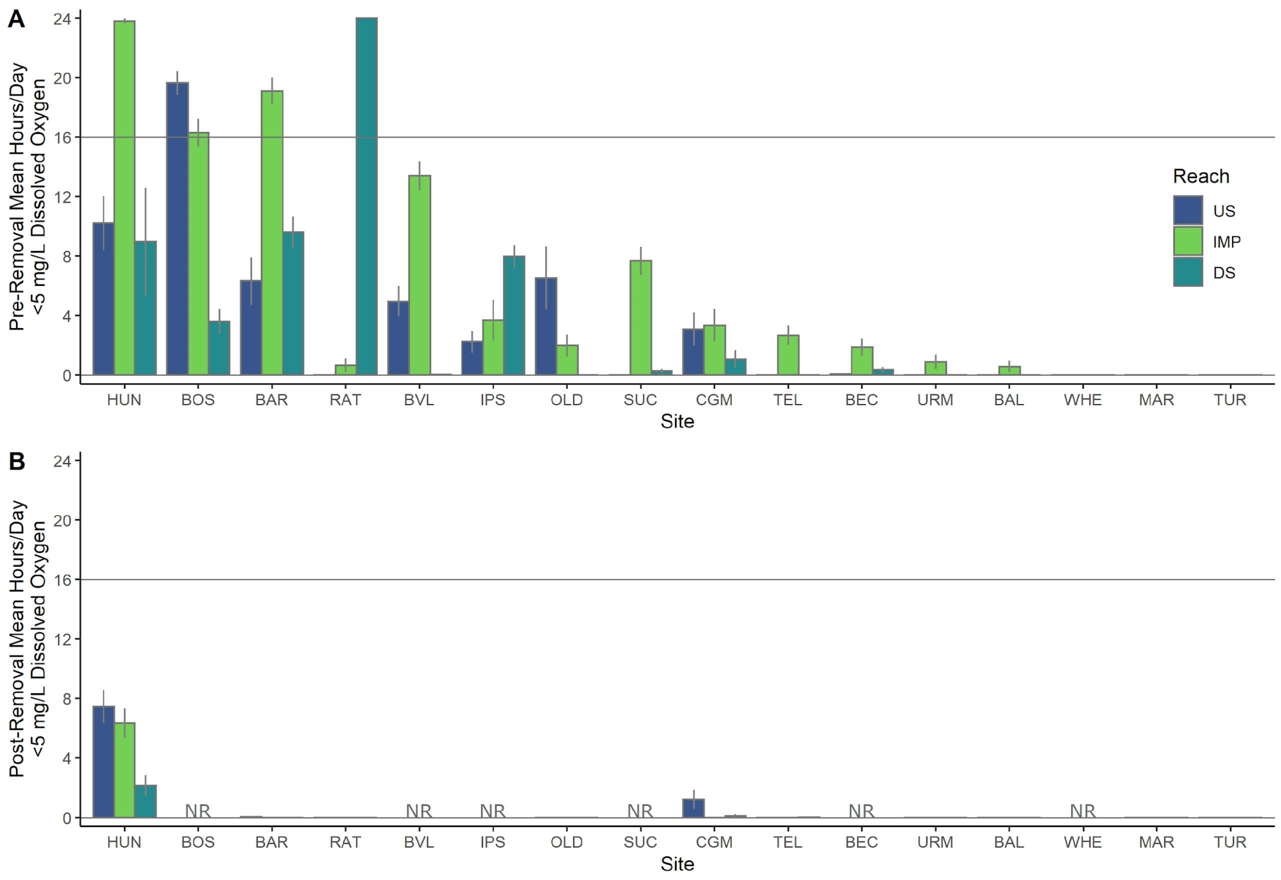

Figure 5. Mean hours per day (± standard error) that each stream section spent below 5.0 mg/L, a threshold below which waters may be considered impaired for dissolved oxygen (DO). The Massachusetts Department of Environmental Protection Surface Water Quality Standards prescribe minimum DO criteria as ≥5.0 mg/L for inland waters designated as Class A and Class B. Inland waters designated as Class C must not have DO concentrations lower than 5.0 mg/L for at least 16 hours/day, a value indicated by the horizontal line (MassDEP 2016). See Table 1 and Figure 1 for more information on full site names and coordinates.

Macroinvertebrates

Prior to dam removal, macroinvertebrate assemblages differed among sites and among stream sections (Fig. 6A). A pre-removal NMDS ordination suggests that impoundment macroinvertebrate communities are dramatically different than flowing-water stream sections, which is expected due to the large differences in habitat (pond vs. stream), water quality, and substrate type. For these plots, each point represents one sample, and the distance between 2 points indicates how similar the assemblages are within those samples. Vectors on these plots indicate which thermal and tolerance metrics are most associated with different assemblages. These data suggest that impoundment assemblages were generally dominated by tolerant taxa, while upstream assemblages contained more coldwater and sensitive taxa. After dam removal, assemblages in the former impoundment became much more similar to each other, and natural differences between sites largely accounted for differences in assemblages, rather than being driven by within-site dam impacts (Fig. 6B).

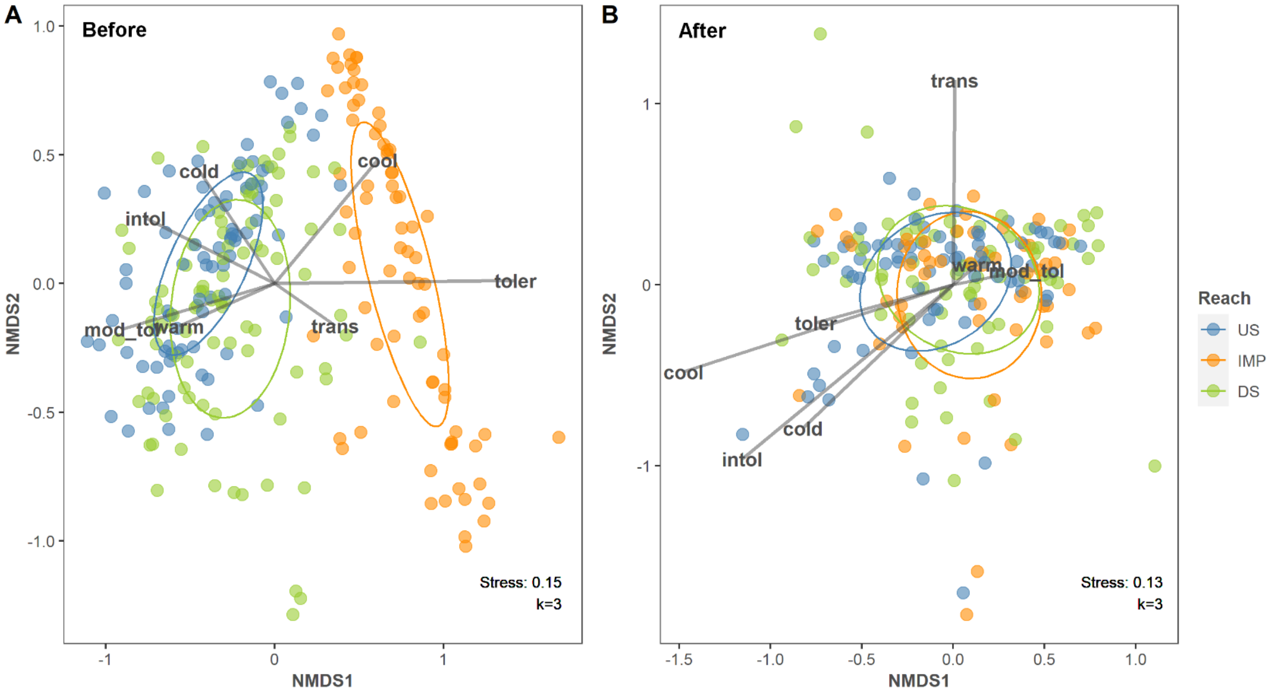

Figure 6. Macroinvertebrate community assemblages A) before dam removals, and B) after dam removals in upstream (US), impoundment (IMP) and downstream (DS) sections as determined by non-metric multidimensional scaling (NMDS) using Bray-Curtis distance (k=3). Ellipses indicate a 95% confidence interval around the mean. Each point represents one sample, and a smaller distance between points indicates more similar assemblages between samples. Lines from the center point toward higher abundances of macroinvertebrates with that trait. See Table A2.1 in Appendix 2 for functional trait descriptions.

In all of the 16 dam impoundments sampled, the percent of sensitive macroinvertebrate taxa was much less than upstream (Table 5), with the greatest differences between stream sections found in the 4 sites with the coldest upstream temperatures (URM, RAT, SUC, BEC; Table 3). This result suggests dams in colder, high water quality stream systems may lead to more fragmented biotic assemblages by creating different habitat types than would naturally be present. Downstream impacts were more variable, with 4 sites containing a greater percent of sensitive taxa downstream (TEL, BEC, BOS, WHE). These 4 sites have abundant riffle habitat downstream of the dams, with minimal downstream warming and little, if any, negative DO impacts. In contrast, the upstream sections at these sites are generally influenced by wetlands, with finer substrates and lower quality habitat. The remaining 11 sites exhibited the same pattern with fewer sensitive taxa (%) downstream as compared to upstream (average of 6 % fewer), but some sites exhibited larger difference between sections than others (range: 17% fewer to 2% more) Of the 2 sites with the most negative apparent downstream impact on sensitive macroinvertebrate taxa (IPS and RAT), one is tidally influenced downstream (IPS) and the other had minimal water flow to the downstream channel, severely reducing habitat availability (RAT).

After dam removal, all 10 former impoundments exhibited an increase in the percent of sensitive taxa present (average 13% more), though the timeline of improvement varied across sites. Channel development within the former impoundment can be relatively rapid (a few months to years), from a geomorphic perspective. These data suggest that sensitive macroinvertebrates can quickly (1-5 years) utilize this newly available habitat, providing important ecological functions to support other sensitive taxa, such as brook trout (*Salvelinus fontinalis*). Some sites exhibited fully recovered sensitive taxa similar to or exceeding the upstream sections (OLD, CGM, TEL, and MAR), and recovery occurred within 1 year (OLD, CGM, and TEL) up to 5 years (MAR).

Of concern with some dam removal projects is the potential for negative impacts of sediment release on sensitive downstream biota. At one site with passive sediment release (URM), we observed no reduction in downstream macroinvertebrate densities 1 year after dam removal, and concomitant increases in the percent of sensitive taxa (from 26.2 to 35.3%), suggesting negative impacts with sediment releases are not imminent. Other sites showed similar improvements in sensitive taxa downstream but did not fully recover to reach upstream levels (RAT, BAL, and CGM). This variability among sites may be due to natural differences in habitat availability which constrain recovery within a stream section; for example, downstream of the former Balmoral Dam is heavily channelized with little to no riparian zone, which may limit sensitive taxa regardless of a dam or dam removal.

Table 5. Average percent of sensitive macroinvertebrate taxa in upstream (US), impoundment (IMP), and downstream (DS) sections before and 1, 3, and 5 years after dam removal. NR is used to indicate sites in which the dam was not removed, and a dash symbol (-) is used to identify years in which samples were not collected. See Table 1 and Figure 1 for more information on full site names and coordinates.

Site ID	US Before	US 1-year	US 3-years	US 5-years	IMP Before	IMP 1-year	IMP 3-years	IMP 5-years	DS Before	DS 1-year	DS 3-years	DS 5-years
BAL	13.8	10.5	13.1	13.4	2.6	7.0	11.9	12.9	6.6	8.1	8.4	8.6
BAR	15.1	14.9	16.4	-	0.8	2.9	15.6	-	12.0	10.7	16.0	-
BEC	26.4	NR	NR	NR	1.9	NR	NR	NR	33.7	NR	NR	NR
BOS	2.8	NR	NR	NR	1.3	NR	NR	NR	7.9	NR	NR	NR
BVL	17.5	NR	NR	NR	0.6	NR	NR	NR	15.6	NR	NR	NR
CGM	14.9	11.2	-	-	6.6	13.2	-	-	13.1	9.1	-	-
HUN	8.9	18.1	17.3	-	0.4	7.3	14.6	-	7.9	12.7	9.4	-
IPS	24.9	NR	NR	NR	1.7	NR	NR	NR	8.8	NR	NR	NR
MAR	18.0	13.7	22.6	13.8	2.4	12.3	15.8	15.4	15.0	12.4	16.1	12.5
OLD	8.9	6.3	14.5	7.9	0.3	9.6	16.1	12.4	6.0	14.6	11.5	14.8
RAT	37.5	30.5	32.7	40.4	5.2	22.0	28.7	25.3	20.1	24.4	19.7	26.0
SUC	32.0	NR	NR	NR	1.9	NR	NR	NR	24.5	NR	NR	NR
TEL	7.2	8.5	-	-	0.5	8.7	-	-	17.7	13.0	-	-
TUR	30.0	26.9	32.2	32.6	-	-	-	-	31.9	20.7	31.9	24.4
URM	40.8	47.2	46.5	-	6.5	41.6	38.0	-	26.2	44.2	42.8	-
WHE	23.7	NR	NR	NR	3.6	NR	NR	NR	26.8	NR	NR	NR

Fishes

Across the 10 dam removal sites, we sampled a total of 34 fish species (Table 6). Of these, the most commonly sampled species were Fallfish (*Semotilus corporalis*), Blacknose Dace (*Rhinichthys atratulus*), Common Shiner (*Luxilus cornutus*), American Eel (*Anguilla rostrata*), and Longnose Dace (*Rhinichthys cataractae*). Preliminary results of fish sampling data from the 10 dam removal sites in this study suggest that like other ecological parameters, fish assemblages exhibit variability in dam impacts and dam removal response across sites. Fish species also responded differently to dam removals in different systems, likely due to site-specific changes in habitat, food, and water quality. For example, in the 7 streams where American Eel were present, relative abundances increased upstream at 4 of those sites after dam removal (RAT, MAR, CGM, and BAL) but decreased upstream at 3 sites (TUR, HUN, and BAR). Bluegill (*Lepomis macrochirus*) responded negatively to dam removal in most upstream and downstream sections sampled. These fish are considered habitat generalists (Armstrong et al. 2011) and are typically found in more pond-like environments, and thus are expected to be outcompeted in the transition to more riverine conditions after dam removal (Jones et al. 2022).

Species richness (total number of unique organisms), also varied across sites and stream sections (Fig. 7). BAR and TUR exhibited similar patterns after dam removal, where upstream richness increased and downstream richness decreased, which resulted in greater species richness similarity across stream sections. Based on NMDS ordinations, both before and after dam removal, fish assemblages were more influenced by differences between sites than by differences between upstream (US) and downstream (DS) sections (Fig. 8); thus, responses to dam removal may be obscured by these site-specific differences. Vectors included on Figure 8 indicate which thermal (C=Cold, CW=Cool, W=Warm), habitat use (MG=Macrohabitat generalist, FD=Fluvial dependent, FS=Fluvial specialist) and tolerance (I=Intolerant, M=Moderately tolerant, T=Tolerant) categories are most associated with different assemblages. These data suggest that certain sites (BAR, BAL, MAR) were generally dominated by tolerant, warmwater, and habitat generalist taxa, while other sites (URM, TUR) contained more sensitive, coldwater, fluvial specialist taxa.

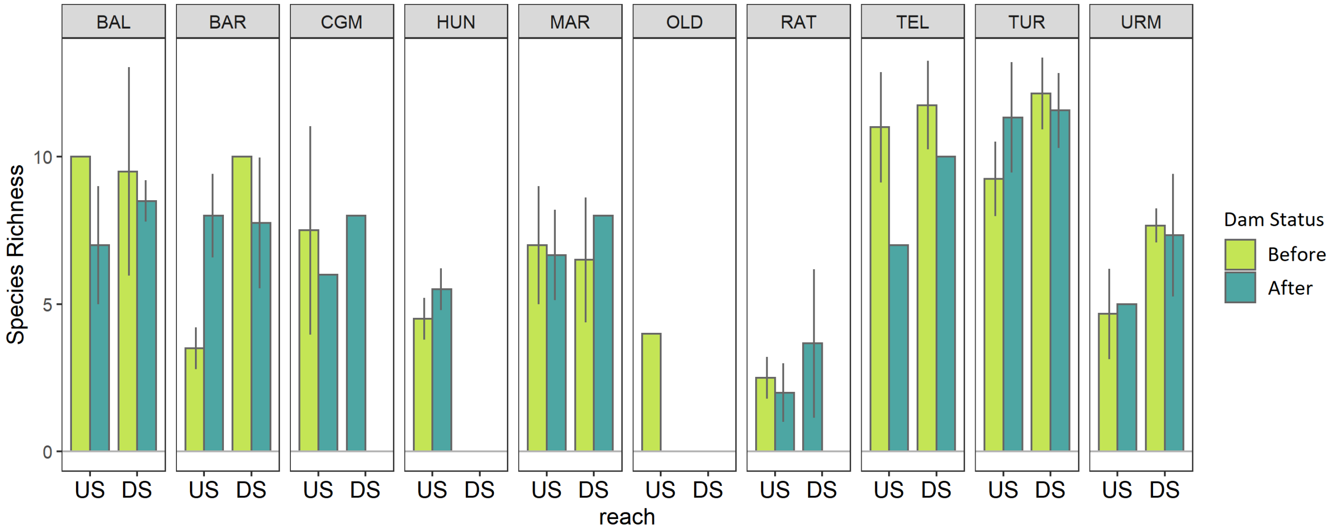

Figure 7. Average species richness (±1 standard deviation) in upstream (US) and downstream (DS) sections at the 10 dam removal sites both before (pre) and after (post) dam removal. 34 total species were included in analysis, see Table 6 for fish species and their common and scientific names. See Table 1 and Figure 1 for more information on full site names and coordinates.

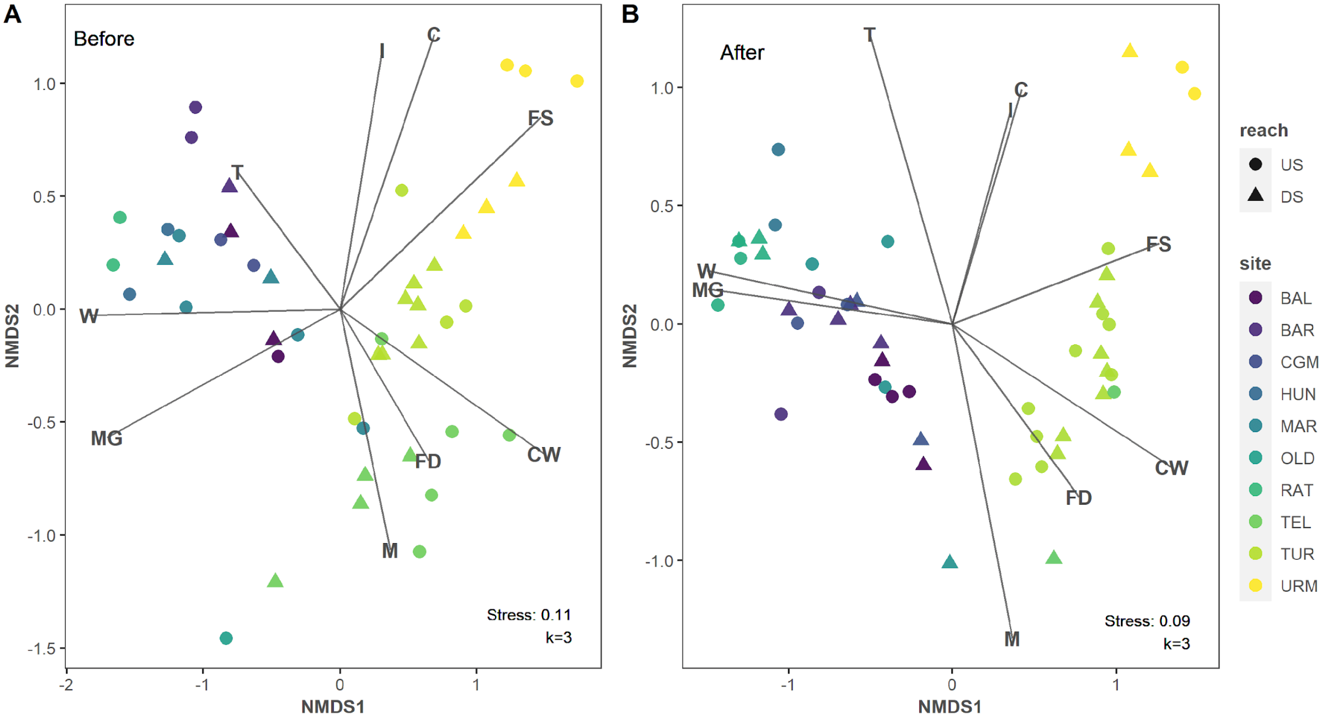

Figure 8. Fish assemblages A) before and B) after dam removals in upstream (US) and downstream (DS) sections as determined by non-metric multidimensional scaling (NMDS) using Bray distance (k=3). Each point represents a sampling event, and a smaller distance between points indicates more similar fish assemblages between samples. Functional groups associated with different assemblages are indicated by vectors (MA habitat use categories: "FS"=Fluvial specialist, "FD"=Fluvial dependent, "MG"=Macrohabitat generalist; thermal classification: "C"=Coldwater, "CW"=Coolwater, "W"=Warmwater; and tolerance classification: "I"=Intolerant, "M"=Moderately tolerant, "T"=Tolerant). See Table 1 and Figure 1 for more information on full site names and coordinates.

Table 6. List of the 34 fish included in analysis of fish assemblages before and after dam removals at 10 sites in Massachusetts, including fish abbreviation codes, common names, and scientific names.

Fish Code	Common Name	Scientific Name
AE	American Eel	*Anguilla rostrata*
B	Bluegill	*Lepomis macrochirus*
BB	Brown Bullhead	*Ameiurus nebulosus*
BC	Black Crappie	*Pomoxis nigromaculatus*
BND	Blacknose Dace	*Rhinichthys atratulus*
BNM	Bluntnose Minnow	*Pimephales notatus*
BS	Banded Sunfish	*Enneacanthus obesus*
BT	Brown Trout	*Salmo trutta*
C	Common Carp	*Cyprinus carpio*
CCS	Creek Chubsucker	*Erimyzon oblongus*
CP	Chain Pickerel	*Esox niger*
CRC	Creek Chub	*Semotilus atromaculatus*
CS	Common Shiner	*Luxillus cornutus*
EBT	Brook Trout	*Salvelinus fontinalis*
F	Fallfish	*Semotilus corporalis*
GS	Golden Shiner	*Notemigonus crysoleucas*
GSF	Green Sunfish	*Lepomis cyanellus*
K	Banded Killifish	*Fundulus diaphanus*
LMB	Largemouth Bass	*Micropterus salmoides*
LND	Longnose Dace	*Rhinicthys cataractae*
NP	Northern Pike	*Esox lucius*
P	Pumpkinseed	*Lepomis gibbosus*
RB	Rock Bass	*Ambloplites rupestris*
RBS	Redbreast Sunfish	*Lepomis auritus*
RP	Redfin Pickerel	*Esox americanus americanus*
RT	Rainbow Trout	*Oncorhynchus mykiss*
SC	Slimy Sculpin	*Cottus cognatus*
SD	Swamp Darter	*Etheostoma fusiforme*
SMB	Smallmouth Bass	*Micropterus dolomieu*
SS	Spottail Shiner	*Notropis hudsonius*
TD	Tesselated Darter	*Etheostoma olmstedi*
WS	White Sucker	*Catostomus commersoni*
YB	Yellow Bullhead	*Ameiurus natalis*
YP	Yellow Perch	*Perca flavescens*

Conclusions

In this study, we found that small dams can negatively impact stream ecological parameters both within the dam impoundment and extending downstream, although the magnitude of impact varies across sites. Additionally, we found that dam removal can reduce or eliminate these negative impacts, but only where impairments to stream ecology have been identified before dam removal. For example, some dams caused no or only minimal downstream warming; at these sites, we generally did not find substantial thermal recovery after dam removal. Conversely, where dams induced relatively high downstream in-stream temperatures, dam removal greatly reduced or eliminated negative thermal impacts within 5-years. This type of variation in dam impact and removal response highlights the need for practitioners to set expectations for restoration (Beechie et al. 2010). These results also support the use of dam removal as a tool to restore more natural thermal regimes, and in some cases, improve the thermal designation of a stream section (Beauchene et al. 2014). Previous research at the dam sites monitored within this study has shown that dams creating wider impoundments (relative to upstream widths) located in colder stream systems are more susceptible to warming, likely due to increased solar radiation (Zaidel et al. 2021). These results suggest that information about impoundment width and upstream temperatures may also inform the extent of thermal recovery after dam removal.

Results also suggest that sites with the most negative DO impacts in both impounded and downstream sections also experienced the most recovery after dam removal, with most reaches recovering to meet or exceed upstream reference DO concentrations within 1 year after dam removal. Removing a dam can increase localized flow velocities and water column mixing, reduce hydraulic residence time, reduce sediment and nutrient trapping, (Bednarek 2001), and reduce temperatures (this study); all of these factors can lead to a more natural, riverine DO regime and increased similarity between formerly impounded and upstream reaches. Within the 5 stream sections that were previously considered impaired for DO (< 5 mg/L), dam removal eliminated impairment in all but 1 section, suggesting the potential for dam removal to improve water quality to meet State-specific surface water criteria (e.g., 314 CMR 4.05). These results suggest DO may be one of the first critical water quality parameters to recover following dam removal, setting the stage for re-colonization by more oxygen-sensitive macroinvertebrate and fish taxa.

Due to taxon-specific preferences and sensitivities, macroinvertebrate assemblages often reflect changes in hydrology and physical substrate and habitat caused by damming. Studies have found macroinvertebrate assemblages in impoundments dominated by lentic taxa (i.e., Chironomidae (midges), Oligochaeta (worms), and Ephemeridae (burrowing mayflies); Stanley et al. 2002, Santucci et al. 2005). In downstream reaches, a restricted sediment supply may lead to sediment-starved conditions and coarser substrates, which can impact macroinvertebrate taxa that depend on finer-grained sediment, such as burrowers. This study indicates that these patterns are also found across a variety of Massachusetts dam sites, with impoundments containing different assemblages than those found in adjacent undammed stream sections. After removal, we generally observed a relatively rapid change in impoundment and downstream assemblages to become similar to upstream reaches (within 1-3 years). At a site that had a substantial sediment release downstream during the removal process, we observed increases in macroinvertebrate densities, diversity, and percent sensitive taxa 1-3 years after removal, which may ease concerns regarding perceived negative removal impacts (Tullos et al. 2016). Fish assemblages and particular fish species exhibited highly variable responses both within and between study sites, and generally, assemblages were driven more by stream system than by stream section.

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APPENDICES

Restoring Aquatic Habitats Through Dam Removal: Final Report

Funded by: The Massachusetts Division of Ecological Restoration (MassDER)

Prepared by: Katherine Abbott[1], Allison Roy[2], and Keith Nislow[3]
[1]Massachusetts Cooperative Fish and Wildlife Research Unit, University of Massachusetts Amherst
[2]U.S. Geological Survey, Massachusetts Cooperative Fish and Wildlife Research Unit, University of Massachusetts Amherst
[3]Northern Research Station, U.S.D.A. Forest Service, University of Massachusetts Amherst

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Data Accessibility

Temperature data (15-min) are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Daily water quality data (temperature and dissolved oxygen) are also available through ScienceBase: https://doi.org/10.5066/P9L2ATHV. Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

APPENDIX 1: Definitions and Abbreviations

MassDER: Massachusetts Division of Ecological Restoration

MassWildlife: Massachusetts Division of Fisheries and Wildlife

MassDEP: Massachusetts Department of Environmental Protection

UMass: University of Massachusetts Amherst

USGS: United States Geological Survey

NID: National Inventory of Dams

PVC: Polyvinyl chloride. Used to make pipes (or lengths of pipes) able to withstand long periods underwater without deteriorating. Used for temperature and dissolved oxygen logger housings.

QA: Quality assurance. The steps taken to ensure that accurate data are collected.

DO: Dissolved oxygen

NLCD: National Land Cover Database

Surber sampler: A square frame placed on riffle substrate to delineate a 0.09-m^2 area, with a net attached to a vertical section that captures dislodged macroinvertebrates from the sampling area. Use restricted to water depths of less than 0.3 m.

Ponar grab sampler: A sediment-sampling device consisting of two opposing semi-circular jaws held open by a trigger, which closes upon contact with bottom sediment. Fine screen covers the top of the device jaws so material remains trapped.

Shannon Diversity: Shannon-Weiner Species Diversity Index. A metric that estimates taxonomic diversity based on the number of species and the evenness of their abundance.

Hilsenhoff Biotic Index (HBI): A metric that estimates the overall organic pollution tolerance of the macroinvertebrate community based on the relative abundance of taxonomic groups and their associated pollution tolerance values. Often used as a proxy for water quality.

Functional Feeding Group (FFG): Refers to the primary process used by macroinvertebrate group to acquire food resources. Categories include: PR = Predator, SC = Scraper, CG = Collector-Gatherer, CF = Collector-Filterer, and SH = Shredder. See Table A2.1 for definitions of each category.

Tolerance Value: Value indicating the relative sensitivity of a macroinvertebrate group to pollution and disturbance. Ranges from 0 (most sensitive) to 10 (least sensitive).

Habit: Identifies the primary mechanism by which a macroinvertebrate group uses for maintaining position and moving in an aquatic environment. Categories include: SP = Sprawler, SW = Swimmer, CN = Clinger, CB = Climber, and BU = Burrower. See Table A2.1 for definitions of each category.

APPENDIX 2: Macroinvertebrate and Fish Trait Descriptions

Table A2.1. Descriptions of macroinvertebrate functional traits and trait states (modalities) applied and analyzed within this study.

Trait	Trait State	Abbreviation	Description
Feeding Group	Predator	PR	Feed on other macroinvertebrates or consumers
Feeding Group	Scraper	SC	Consume algae and associated material
Feeding Group	Collector-Gatherer	GC	Collect fine particulate organic matter (FPOM) from the stream bottom
Feeding Group	Filterers	CF	Collect fine particulate organic matter (FPOM) from the water column
Feeding Group	Shredder	SH	Consume leaf litter or coarse particulate matter
Habit	Sprawler	SP	Dwell primarily on surfaces of leaves, fine sediments, or other substrates
Habit	Swimmer	SW	Benthic dwellers that often exhibit "minnow-like" swimming behavior in the water column
Habit	Clinger	CN	Have behavioral or morphological adaptations for attachment to surfaces in water current of riffles or erosional habitats
Habit	Climber	CB	Climb up stems and leaves of roots, debris, and submerged or emergent plants
Habit	Burrower	BU	Dwell primarily in fine sediments or tunnel into plant stems, leaves or roots
Thermal Category	Transitional	Trans	Weighted average optima of 18 to 21 °C and maximum probability of occurrence in stream temperatures < 18 °C
Thermal Category	Eurythermal	Eury	Able to tolerate a wide range of stream temperatures
Thermal Category	Coldwater	Cold	Weighted average optima of 16 to 18 °C and maximum probability of occurrence in stream temperatures < 21 °C
Thermal Category	Coolwater	Cool	Weighted average optima of 18 to 20 °C and maximum probability of occurrence in stream temperatures < 23 °C
Thermal Category	Warmwater	Warm	Weighted average optima of over 20 °C and maximum probability of occurrence in stream temperatures > 23 °C
Tolerance values	Sensitive	I	Pollution tolerance value from 0 to 3, intolerant of pollution
Tolerance values	Moderately Tolerant	M	Pollution tolerance values between 3 and 7
Tolerance values	Tolerant	T	Pollution tolerance value from 7 to 10, tolerant of pollution

Table A2.2. Descriptions of fish functional traits and trait states (modalities) applied and analyzed within this study.

Trait Name	**Trait State**	**Abbreviation**	**Description**
Habitat-Use	Macrohabitat Generalist	MG	Use a broad range of habitats and can meet all of their life history requirements in lentic habitats
Habitat-Use	Fluvial Specialist	FS	Require flowing-water habitats throughout their life cycles
Habitat-Use	Fluvial Dependent	FD	Require access to flowing-water habitat for at least some portion of their life history
Temperature Class	Coldwater	C	Associated with cold water
Temperature Class	Coolwater	CW	Associated with cool water
Temperature Class	Warmwater	W	Associated with warm water
Pollution Tolerance	Tolerant	T	Tolerant to environmental degradation
Pollution Tolerance	Moderately Tolerant	M	Moderately tolerant to environmental degradation
Pollution Tolerance	Intolerant	I	Intolerant to environmental degradation, sensitive to water quality impairments

APPENDIX 3: Balmoral Dam (BAL)

Sampling Overview

Balmoral Dam, a 6.9 ft tall (2.1 m) surface-release dam forming a 5.7-acre (2.3 ha) impoundment, was removed in early 2017. This structure was the first of three remaining barriers on the Shawsheen River, which is a tributary of the Merrimack River in Andover, MA. This dam was concurrently removed with the adjacent upstream dam, the Marland Place Dam. This site is located in a 72.9 mi^2 (188.8 km^2) watershed that is 25% forest cover, 28% impervious cover, and 0.3% cultivated land, with a mean elevation of 146 ft (44.5 m) above sea level. This site was monitored for temperature, dissolved oxygen, benthic macroinvertebrates, and fishes both before and after dam removal.

Figure A3.1. Map of temperature and dissolved oxygen logger locations in the Shawsheen River, Andover, MA. Macroinvertebrates were sampled in approximately 100m sections around BALUS, BALIMP, and BALDS1 loggers. See Figure 1 in Study Design section for location within Massachusetts. Esri World Imagery Basemap accessed 10/18/2022.

One temperature data logger was deployed upstream (BALUS), one within the impoundment (BALIMP), and four deployed downstream (BALDS1-BALDS4) of the dam, covering 0.37 mi (0.6 km) of the river downstream (Fig. A3.1). At this site, the BALUS logger is the same as the furthest downstream logger of the Marland Place site (MARDS4; See Appendix 11). Temperature loggers were deployed in July 2015 and remained in the field until October 2021, capturing 2 years of pre-removal stream temperature and 5 years of post-removal stream temperature. Dissolved oxygen (DO) loggers were deployed upstream (BALUS), within the impoundment (BALIMP), and downstream (BALDS1) of Balmoral Dam or former dam location (Fig. A3.1) for approximately week-long deployments during summer months (July, August, and September) from 2015 to 2017. Summer DO was monitored for 2 years before removal and 1 year after dam removal.

Macroinvertebrates were sampled once per summer from 2015 to 2019, and again in 2021, capturing 2 years of pre-removal and up to 5 years of post-removal assemblages. Within impounded areas, 3 replicate Ponar sediment grab samples were collected from randomly selected locations, and along impoundment margins, 3 replicate sweeps of submerged and emergent vegetation were conducted using a rectangular net. In flowing stream sections (e.g., upstream, downstream, and former impoundment), 3 replicate Surber samples were taken in separate riffle habitats and a single representative multihabitat sample was collected throughout ~100 m of stream. All samples were preserved in 70% ethanol prior to sorting and identification by Cole Ecological, Inc. or a trained UMass researcher. Up to 300 individuals were identified to the lowest practical taxonomic unit (usually genus or species, referred to as “taxa”).

Fish sampling was also conducted in upstream and downstream sections by MassWildlife intermittently prior to removal (1998-2015) and after removal in 2018 and 2020; data summaries are provided in the General Results section of this final report. Temperature data are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Water quality data (temperature and dissolved oxygen) are also available through ScienceBase (https://doi.org/10.5066/P9L2ATHV). Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

Results

Temperature

Prior to dam removal, mean summer temperatures within the impoundment (22.9 °C) were slightly cooler than the upstream reference temperatures (23.0 °C; Fig. A3.2) and downstream temperatures were consistent across all loggers at 22.6 °C. Downstream warming—the mean difference between upstream and downstream (DS1) daily temperatures—was highest during October and November, and this site actually exhibited a slight cooling downstream in August (Fig. A3.3). Summer downstream warming was on average -0.04 °C, with high variability (SD= 0.37; Fig. A3.4), indicating a negligible effect of the dam on downstream summer temperatures. Summer stream temperatures cooled slightly with increasing distance downstream from the dam with a slope of -0.15 °C/km (Fig. A3.5). These results suggest that Balmoral Dam had a small impact on Shawsheen River stream temperatures within the dam's impoundment and downstream.

We observed minimal temperature response following the removal of Balmoral Dam in 2017, likely because of the small effect of Balmoral Dam on stream temperature. Mean summer temperatures across all stream sections were lower in the years following dam removal, which may be due to the removal of the upstream dam (Marland Place Dam) or to ambient weather conditions in those years. In the former impoundment, temperatures were reduced from 22.9 °C to 21.9 °C (1.0 °C difference); during the same years, upstream reference temperatures averaged 23.0 °C before removal to 22.1 °C after removal (0.9 °C difference). In 2020, a relatively warm and dry summer, several loggers were out-of-water, leading to the inconsistent longitudinal pattern that year. Downstream warming was highest in winter months (November and December), but with high variability within months (Fig. A3.3). Mean summer downstream warming was not changed following dam removal, but variability was reduced (before: SD= 0.37, after: SD=0.07), indicating downstream temperatures became more consistently similar to upstream reference temperatures. After removal, summer stream temperatures continued to decrease slightly with increasing distance downstream (-0.11 °C/km; (Fig. A3.5). A previous study found temperature impacts of small dams were related to the impoundment widths, where wider impoundments allow for more solar radiation and a longer residence time of water (Zaidel et al. 2021). The former impoundment and downstream sections of this site are heavily channelized, and this constraint on channel width likely contributed to the small impact and response to the dam and dam removal, respectively.

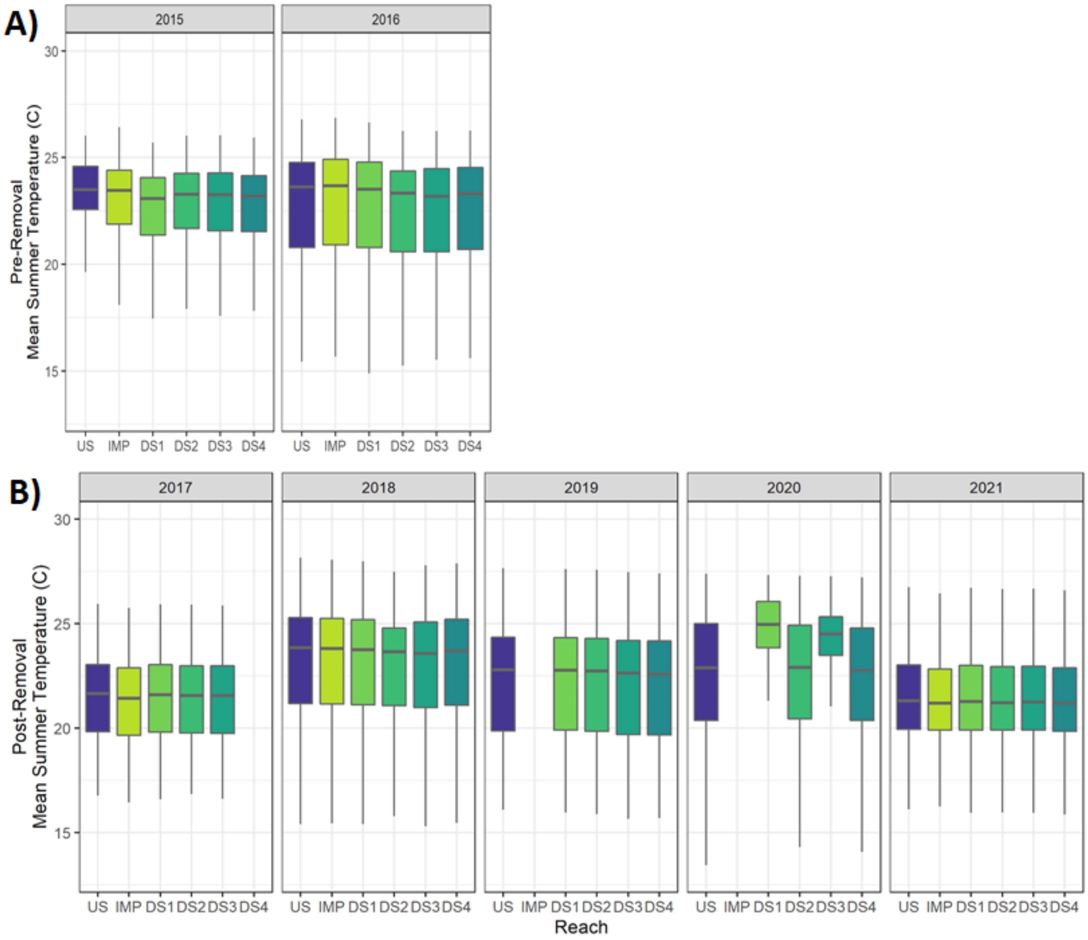


Figure A3.2) Mean summer (July-September) in-stream temperatures at each logger location A) before dam removal (2015-2016) and B) after dam removal (2017-2021). Logger locations are indicated by the following abbreviations: US = upstream, IMP = Impoundment, DS1-DS4 = Downstream 1 through Downstream 4.

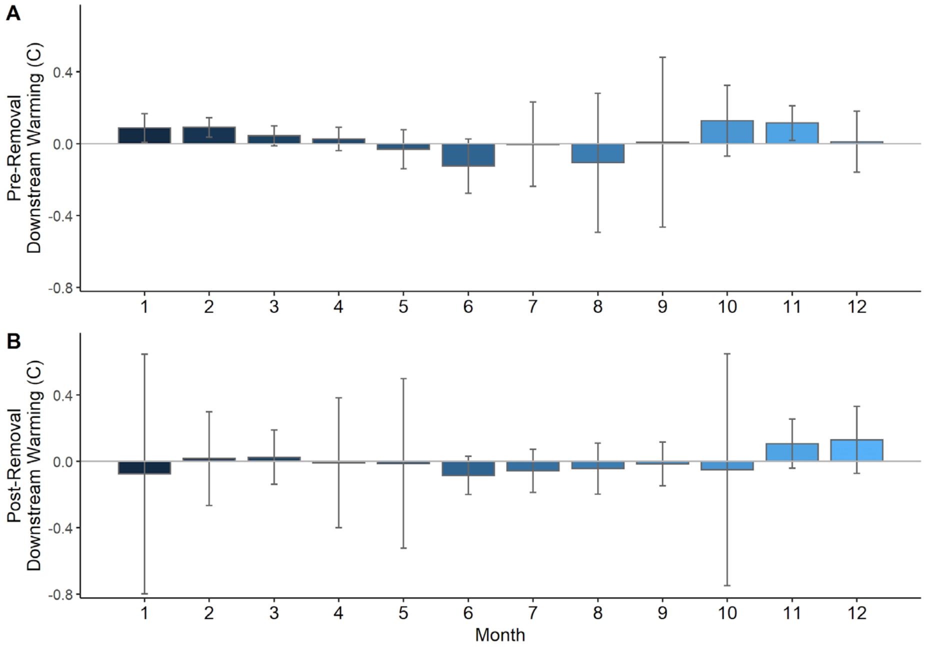


Figure A3.3) Downstream warming by month A) before (2015-2016) and B) after dam removal (2017-2021).

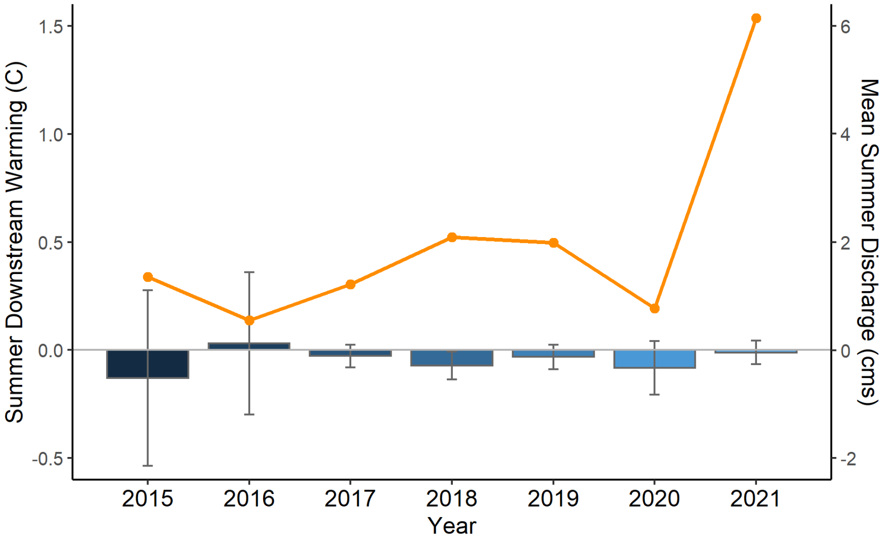


Figure A3.4) Summer (July-September) downstream warming (i.e., the difference between upstream and downstream temperatures ± SD; blue bars) and estimated mean summer discharge (orange line).

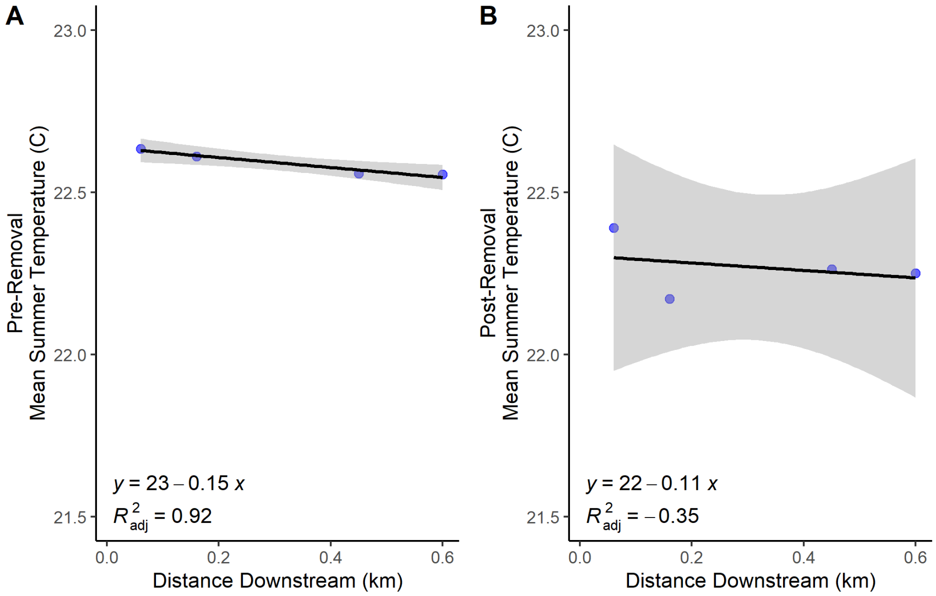


Figure A3.5) Mean summer temperature for each downstream logger (DS1-DS4) relative to the distance from the dam A) before and B) after dam removal. The black line represents the mean slope of linear temperature decay downstream of the dam and the shaded grey area represents the 95% confidence interval.

Dissolved oxygen (DO)

Prior to removal in 2017, Balmoral Dam had moderate negative impacts on DO concentrations within the impoundment and downstream. Surface DO within the impoundment was consistently lower than either of the upstream or downstream sections (mean daily DO concentration of 6.68 mg/L; Figure A3.6), and the daily range was larger (mean daily range: 1.79 mg/L; Fig. A3.7). The downstream section had slightly lower DO than the upstream reference (DS: 7.45 mg/L; US: 7.93 mg/L). Daily ranges downstream were generally smaller than upstream (Fig. A3.7). Most reaches did not experience periods of DO less than 5 mg/L (Fig. A3.8), a threshold below which waters may be considered impaired for DO (MassDEP 2016). The impoundment experienced occasional periods of low DO only in 2016, a summer with relatively low precipitation and high air temperatures.

Following dam removal in early 2017, DO concentrations within the former impoundment experienced an increase of 1.4 mg/L, from 6.68 to 8.08 mg/L. Downstream DO also increased by 0.6 mg/L, while upstream DO increased by 0.5. Dissolved oxygen concentrations of the impoundment and downstream sections became more similar following dam removal. Daily ranges within the former impoundment did not change following removal, but downstream ranges increased to be more similar to the formerly impounded section, although both sections maintained slightly smaller ranges than upstream. After removal, DO impairment (i.e., concentrations less than 5 mg/L) did not occur in any stream section (Figure A3.8).

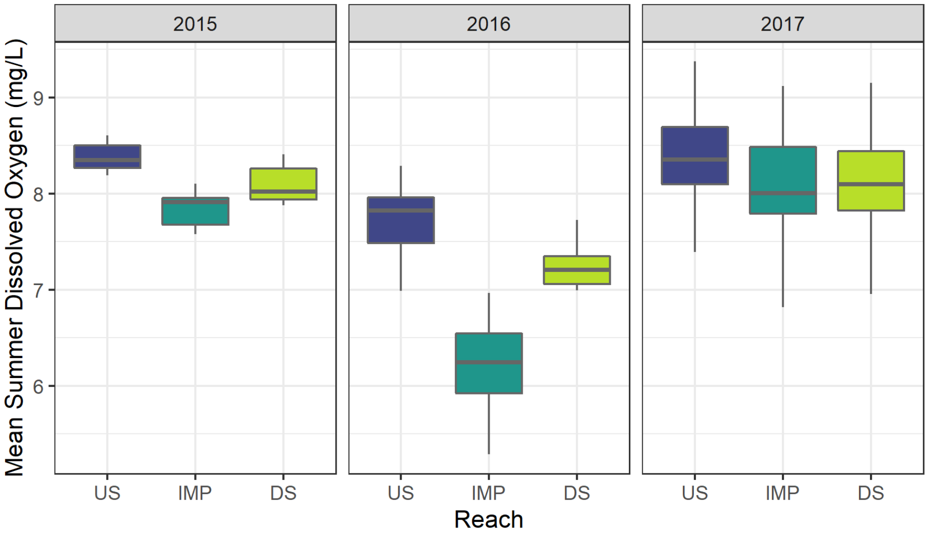


Figure A3.6) Mean summer (July-September) dissolved oxygen concentrations in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2017. Dam removal occurred in early 2017, prior to the summer deployment.

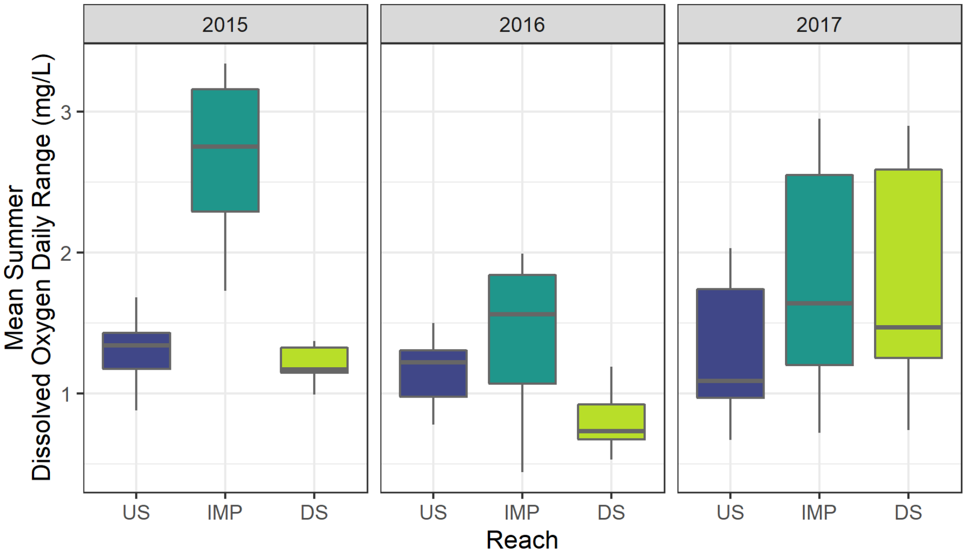


Figure A3.7) Mean summer (July-September) daily range of dissolved oxygen levels in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2017. Dam removal occurred in early 2017, prior to the summer deployment.

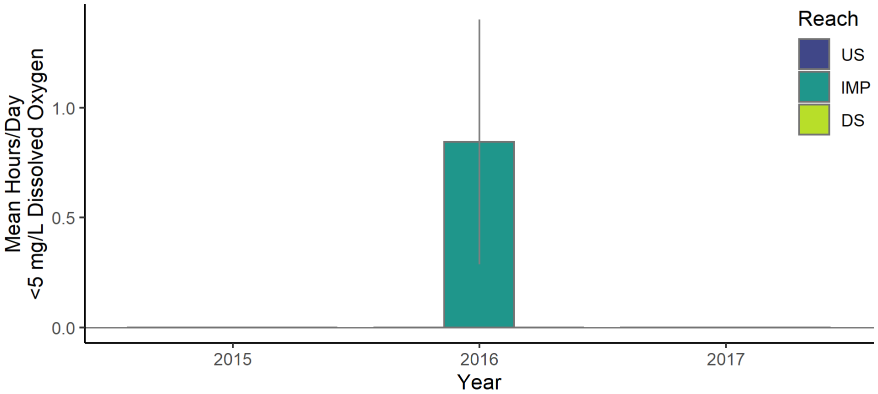


Figure A3.8) Mean and standard error (SE) hours per day that upstream (US), impoundment (IMP) and downstream (DS) stream sections spent below 5.0 mg/L, a threshold below which waters may be considered impaired for DO, prior to dam removal (MassDEP 2016). At this site, only the impoundment in 2016 experienced any time of DO < 5 mg/L.

Macroinvertebrates

Prior to dam removal, we found that macroinvertebrate taxa differed between upstream and downstream sections, as well as between flowing water and impounded sections. For example, the percent of taxa (unique organisms) classified as coldwater (thermal optimum <18 °C) was higher downstream (3.7%) as compared to upstream (2.6%), while the percent of warmwater (>20 °C) taxa was higher upstream (11.3%) as compared to downstream (9.0%). In general, coolwater (18-20 °C) and warmwater taxa comprised most taxa at this site. We observed a smaller percentage of sensitive taxa within the impoundment (2.6%) than the upstream section (13.8%) and a much greater percentage of pollution-tolerant taxa (39%) than upstream (14.5%; Fig. A3.9). Before dam removal, the Hilsenhoff Biotic Index (HBI), which estimates the overall pollution tolerance weighted by the relative abundance of each taxa (Hilsenhoff 1988), also indicated more pollution tolerant taxa within the impoundment relative to flowing water sections. The total number of taxa (taxa richness) was slightly lower in impoundment and downstream sections compared to the upstream section, and diversity, which incorporates both richness and abundance of taxa, followed a similar pattern.

After dam removal, the former impoundment exhibited an increase in sensitive taxa, and a corresponding decrease in tolerant taxa (Fig. A3.9), which may reflect an improvement in water quality and habitat with the shift from stagnant to flowing water. However, thermal classes reflect a general decrease in coldwater taxa and an increase in warmwater taxa in the former impoundment and downstream. The downstream section also exhibited a slight increase in the percent sensitive taxa after dam removal (Fig. A3.9). HBI scores in the former impoundment decreased to become more similar to adjacent flowing water sections. Taxa richness and diversity in both the former impoundment and downstream sections were not substantially altered after dam removal (Fig. A3.10). Functional traits—feeding behavior and movement habits, for example—allow us to link environmental conditions to the abundance and diversity of the different functional groups sampled. In the former impoundment, we observed an increase in taxa that feed by filtering water, like Hydropsychidae caddisflies, which may reflect increased water flow. We also observed a reduction in taxa that burrow and an increase in taxa that cling to rocks in the former impoundment after removal, reflecting the shift in habitat from stagnant to flowing water and from fine sediment and organic matter to coarser substrate (Fig. A3.11). We also observed recovery of sensitive taxa over time in the most impacted stream sections, particularly within the impoundment (Fig. A3.12). Due to the close proximity of the Marland Place Dam removal project upstream, it is possible that some macroinvertebrate responses are related to downstream effects of that removal, rather than effects of the Balmoral Dam removal.

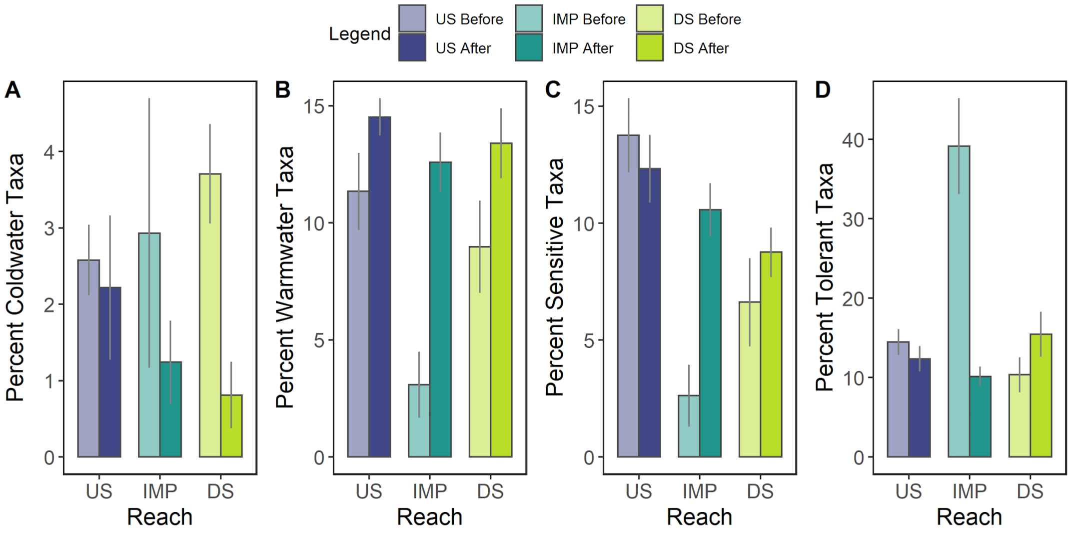


Figure A3.9) Mean percent of macroinvertebrate taxa by A) coldwater, B) warmwater, C) sensitive, and D) pollution-tolerant found within each sample in upstream (US), impoundment (IMP), and downstream (DS) stream sections before (2015-2016) and after dam removal (2017-2021).

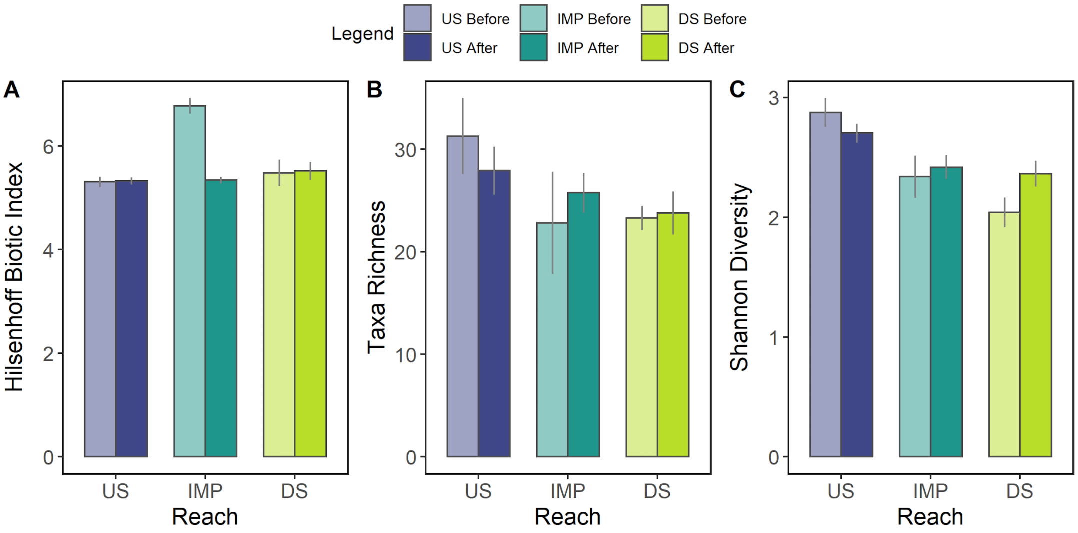


Figure A3.10) Mean macroinvertebrate biotic metric A) Hilsenhoff Biotic Index, B) total taxa richness, and C) Shannon diversity found in upstream (US), impoundment (IMP), and downstream (DS) sections before (2015-2016) and after dam removal (2017-2021).

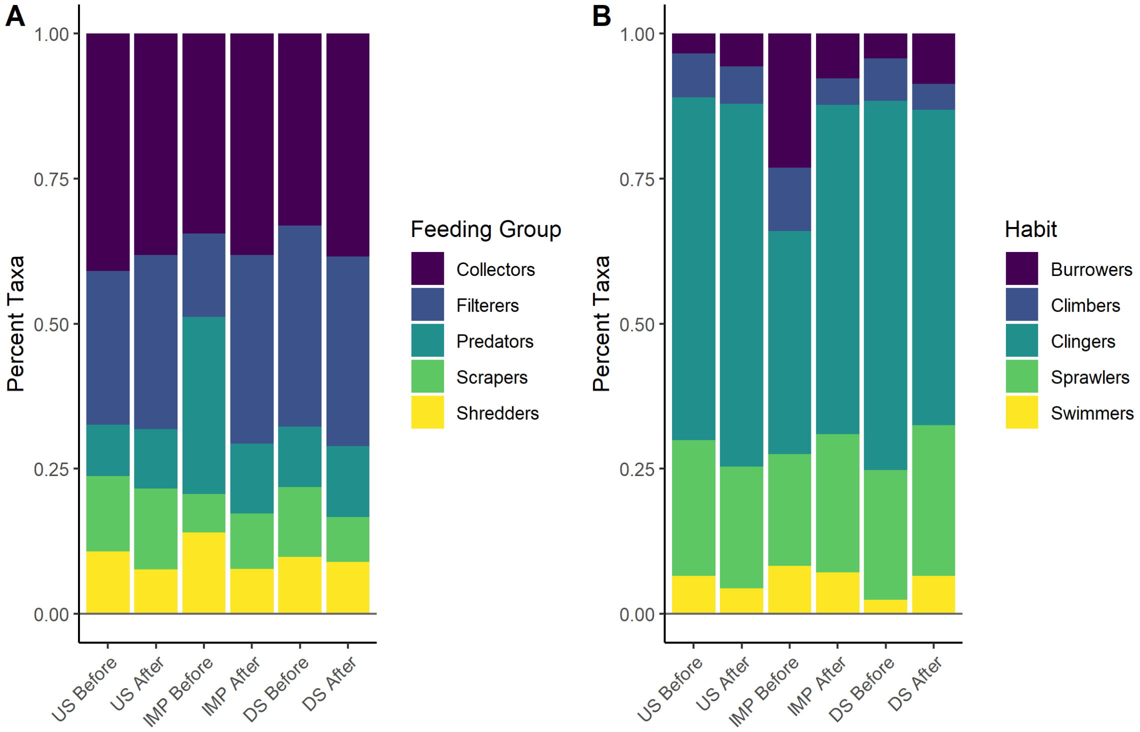


Figure A3.11) Percent of macroinvertebrate taxa by functional trait groups A) feeding guild, and B) habit guild in upstream (US), impoundment (IMP), and downstream (DS) stream sections before (2015-2016) and after dam removal (2017-2021). See Table A2.1 in Appendix 2 for information on feeding groups and habit categories.

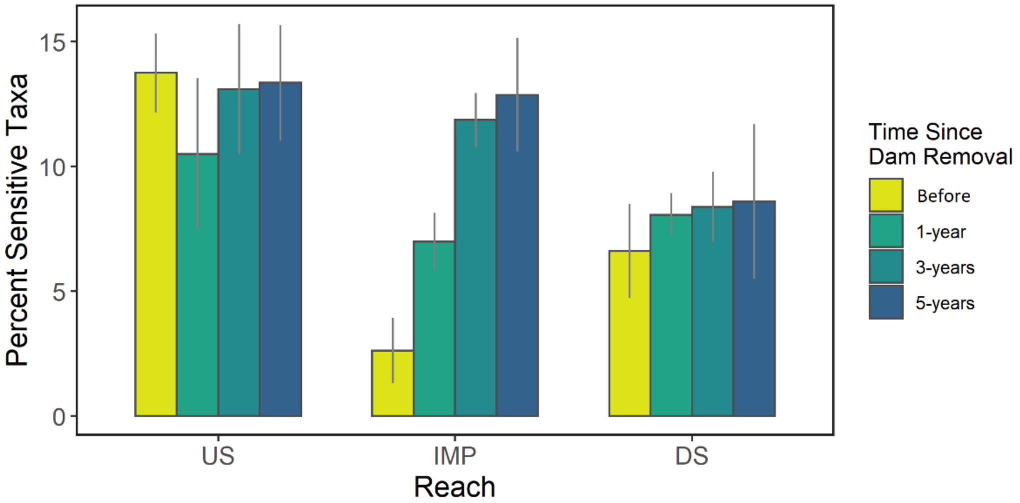


Figure A3.12) Percent of sensitive macroinvertebrate taxa in upstream (US), impoundment (IMP), and downstream (DS) stream sections before and in the years after dam removal (1-, 3-, and 5-years after removal).

Table A3.1. Averages of key ecological parameters before and after dam removal in each stream section (± 1 standard deviation).

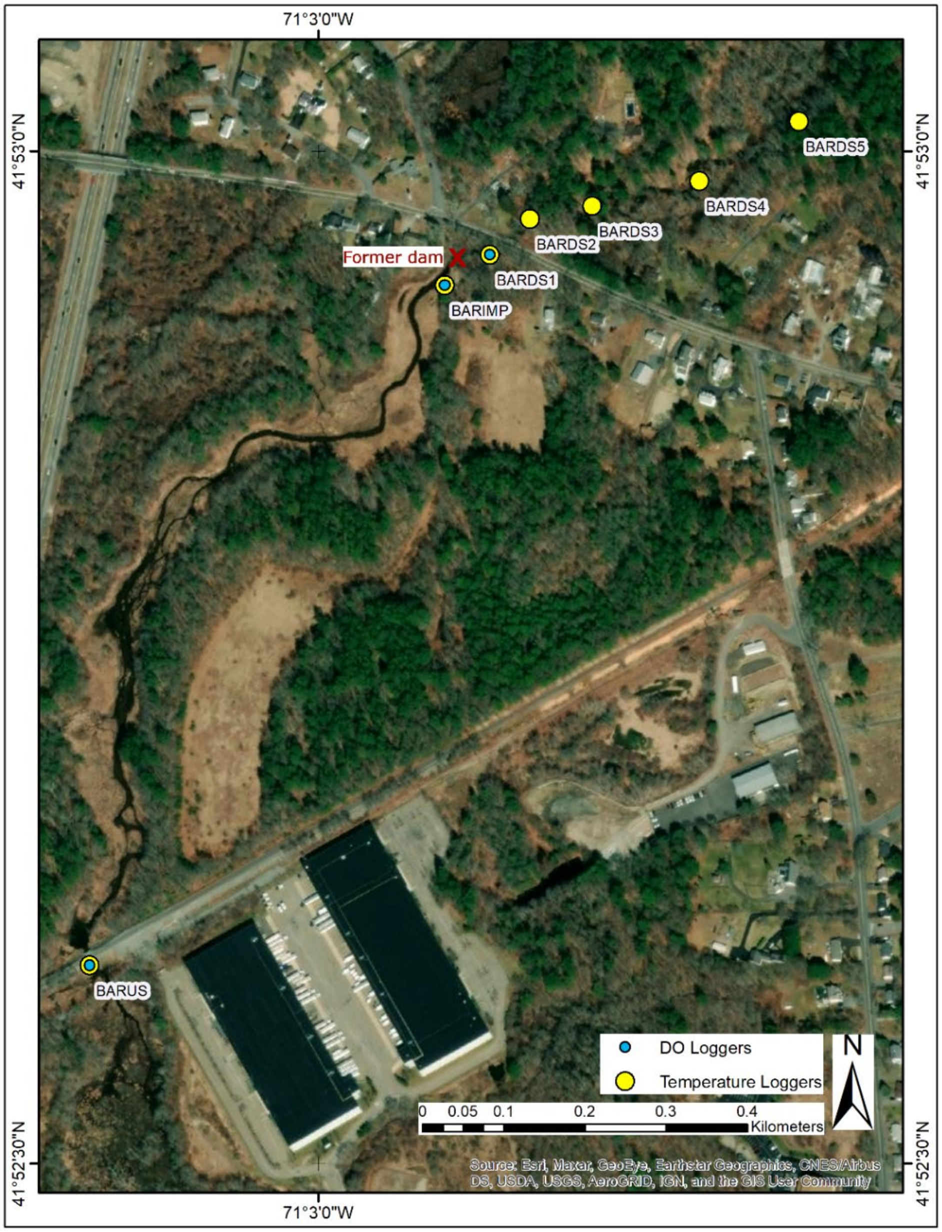
Ecological Parameter	**Upstream Before**	**Upstream After**	**Impoundment Before**	**Impoundment After**	**Downstream[†] Before**	**Downstream After**
Stream Temperature (C)	23.0 ± 2.3	22.1 ± 2.9	22.9 ± 2.6	21.9 ± 2.6	22.6 ± 2.5	22.3 ± 2.7
Dissolved Oxygen (mg/L)	7.9 ± 0.4	8.4 ± 0.5	6.7 ± 0.9	8.1 ± 0.6	7.4 ± 0.5	8.0 ± 0.7
Hilsenhoff Biotic Index[††] (HBI)	5.3 ± 0.3	5.3 ± 0.2	6.8 ± 0.4	5.3 ± 0.2	5.5 ± 0.7	5.6 ± 0.6

†Temperature from first downstream logger (DS1) only. ††Higher HBI indicates a greater relative abundance of pollution-tolerant macroinvertebrate taxa and suggests poorer water quality.

APPENDIX 4: Barstow's Pond Dam (BAR)

Sampling Overview

Barstow's Pond Dam, an 8.5 ft tall (2.6 m) surface-release dam forming a 10.1-acre (4.1 ha) impoundment, was removed in early 2018. This structure was the first barrier to upstream migrating fish on the Cotley River, which is a tributary to the Taunton River, in Taunton, MA. This site is located in a 7.3 mi^2 (19 km^2) watershed that is 67% forest cover, 12% impervious cover, and 1% cultivated land, with a mean elevation of 78.0 ft (23.8 m) above sea level. This site was monitored for temperature, dissolved oxygen, benthic macroinvertebrates, and fishes both before and after dam removal.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure A4.1. Map of temperature and dissolved oxygen logger locations in the Cotley River, Taunton, MA. Macroinvertebrates were sampled in approximately 100m sections around BARUS, BARIMP, and BARDS1 loggers. See Figure 1 in Study Design section for location within Massachusetts. Esri World Imagery Basemap accessed 10/18/2022.

One temperature data logger was deployed upstream (BARUS), one within the impoundment (BARIMP), and five deployed downstream (BARDS1-BARDS5) of the dam, covering the 0.25 mi (0.4 km) of the river between Barstow's Pond Dam and its confluence with the Taunton River (Fig. A4.1). Temperature loggers were deployed in June 2015 and remained in the field until October 2021, capturing 3 years of pre-removal stream temperature and 4 years of post-removal stream temperature. Dissolved oxygen (DO) loggers were deployed upstream (BARUS), within the impoundment (BARIMP), and downstream (BARDS1) of Barstow's Pond Dam or former dam location (Fig. A4.1) for approximately week-long deployments during summer months (July, August, and September) from 2015 to 2019. Summer DO was monitored for 3 years before removal and 2 years after dam removal.

Macroinvertebrates were sampled once per summer from 2015 to 2020, capturing 3 years of pre-removal and 3 years of post-removal assemblages. Within impounded areas, 3 replicate Ponar sediment grab samples were collected from randomly selected locations, and along impoundment margins, 3 replicate sweeps of submerged and emergent vegetation were conducted using a rectangular net. In flowing stream sections (e.g., upstream, downstream, and former impoundment), 3 replicate Surber samples were taken in separate riffle habitats and a single representative multihabitat sample was collected throughout ~100 m of stream. All samples were preserved in 70% ethanol prior to sorting and identification by Cole Ecological, Inc. or a trained UMass researcher. Up to 300 individuals were identified to the lowest practical taxonomic unit (usually genus or species, referred to as "taxa").

Fish sampling was also conducted in upstream and downstream sections by MassWildlife from 2017 to 2020; data summaries are provided in the General Results section of this final report. Temperature data are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Water quality data (temperature and dissolved oxygen) are also available through ScienceBase (https://doi.org/10.5066/P9L2ATHV). Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

Results

Temperature

Prior to dam removal, mean summer temperatures within the impoundment and at the downstream loggers closest to Barstow's Pond Dam (DS1-DS4) were consistently warmer than the upstream reference and the furthest downstream logger (DS5; Fig. A4.2). Downstream warming—the mean difference between upstream and downstream (DS1) daily temperatures—was highest during June, July, and August, and negligible during winter months (Fig. A4.3). Summer downstream warming was on average 1.23 °C, with high variability (SD= 0.9; Fig. A4.4). Summer stream temperatures cooled with increasing distance downstream from the dam with a slope of -2.6 °C/km (Fig. A4.5). These results suggest that Barstow's Pond Dam had a large effect on Cotley River stream temperatures within the dam's impoundment and downstream.

This temperature impact was reduced, but not eliminated following dam removal in 2018. Mean summer temperatures in the former impoundment were reduced from 22.9 °C to 21.5 °C (1.4 °C difference); during the same years, upstream reference temperatures averaged 21.1 °C before removal to 20.4 °C after removal (0.7 °C difference). Downstream warming remained highest in June, July, and August, but with high variability within months (Fig. A4.3). Overall, downstream warming was reduced following dam removal (before: 1.23 °C; after: 1.0 °C; $t=-3.32$; $p=0.001$), indicating downstream temperatures became more similar to upstream reference temperatures. This response was highly variable from year to year (Fig. A4.4) and appears to be somewhat related to discharge. For example, downstream warming was exacerbated in 2020 due to very low summer flows and warming was reduced in 2021 due to higher-than-average summer precipitation. Summer stream temperatures cooled with increasing distance downstream, with a slightly steeper slope (-2.9 °C/km) than before dam removal (Fig. A4.5). Some downstream warming may persist after dam removal due to the relatively open canopy and wetland area surrounding the former impoundment, contrasted with the denser forested canopy of the downstream section. It is possible that the former impoundment will experience more shading and more consistent, cooler temperatures as woody riparian vegetation develops.

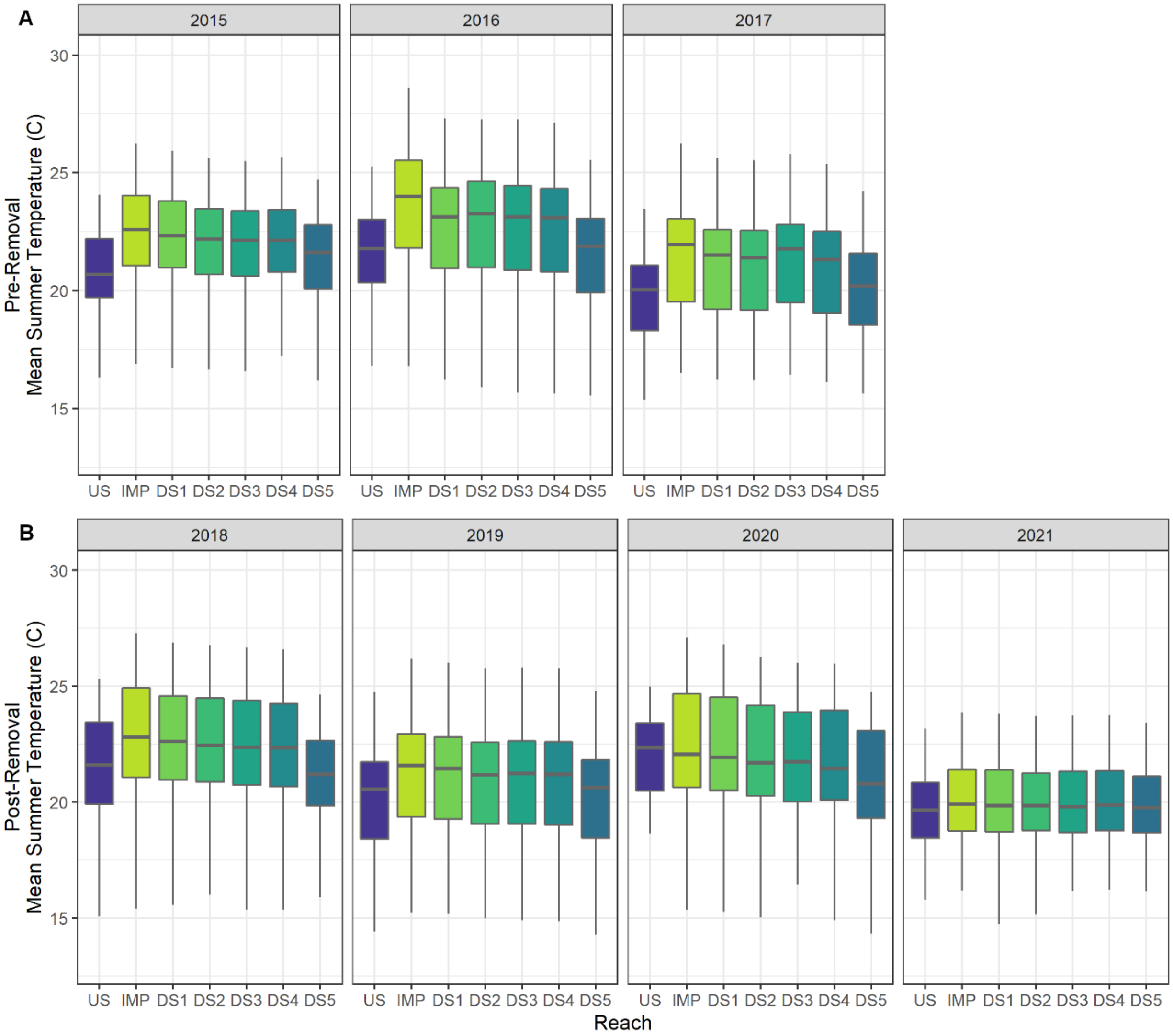


Figure A4.2) Mean summer (July-September) in-stream temperatures at each logger location A) before dam removal (2015-2017) and B) after dam removal (2018-2021). Logger locations are indicated by the following abbreviations: US = upstream, IMP = Impoundment, DS1-DS5 = Downstream 1 through Downstream 5.

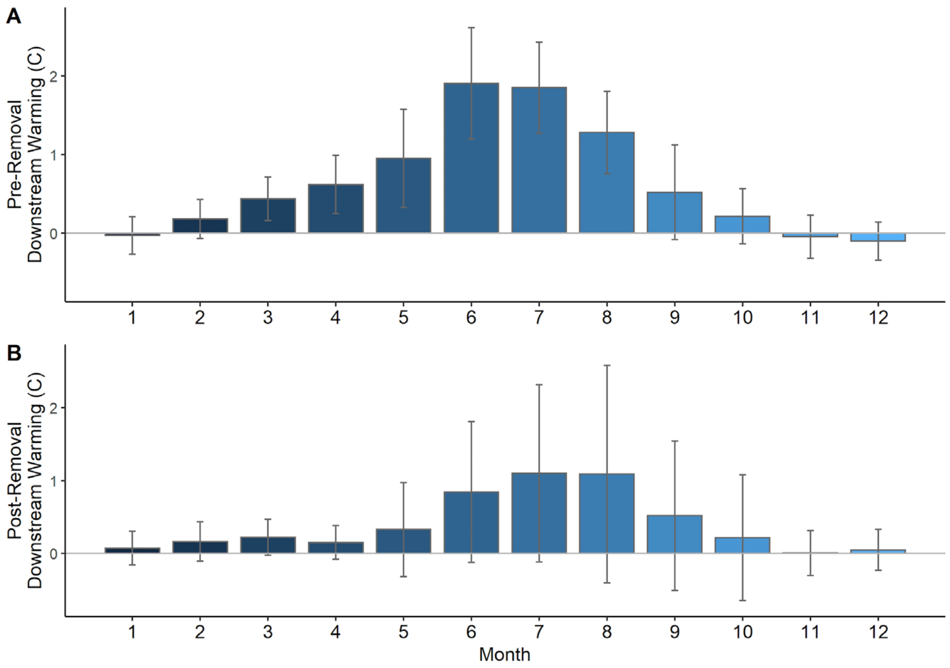


Figure A4.3) Downstream warming by month A) before (2015-2017) and B) after dam removal (2018-2021).

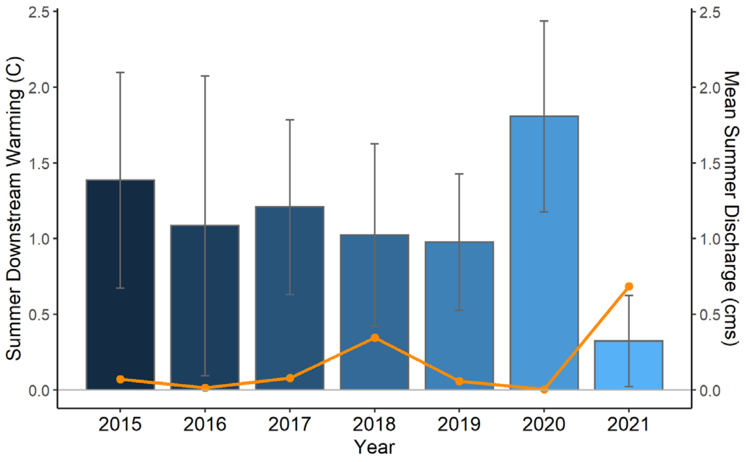


Figure A4.4) Summer (July-September) downstream warming (i.e., the difference between upstream and downstream temperatures ± SD; blue bars) and estimated mean summer discharge (orange line).

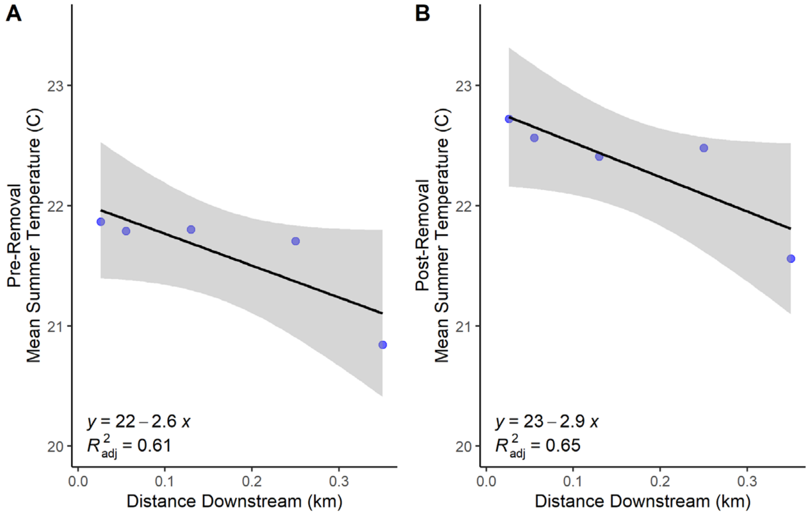


Figure A4.5) Mean summer temperature for each downstream logger (DS1-DS5) relative to the distance from the dam A) before and B) after dam removal. The black line represents the mean slope of linear temperature decay downstream of the dam and the shaded grey area represents the 95% confidence interval.

Dissolved oxygen (DO)

Prior to removal in 2018, Barstow's Pond Dam had some of the most negative impacts on DO concentrations among the sites studied. Surface DO within the impoundment was consistently lower than either of the upstream or downstream sections (mean daily DO concentration of 3.06 mg/L; Fig. A4.6), and the daily range was consistently larger (mean daily range: 5.04 mg/L; Fig. A4.7). The downstream section generally had lower DO than the upstream reference, except in 2017. In 2017, field observations indicate a blockage in the culvert immediately upstream of the upstream logger location (BARUS) seemed to cause flow to bypass the culvert and flow over a path west of the monitoring location and flow may have been fed by more wetland contributions rather than the mainstem Cotley River. This may explain the relatively low upstream DO observed this year, which did not persist in the following years. Daily ranges downstream were generally higher than upstream and lower than impoundment ranges. The impoundment and downstream sections experienced periods of hypoxia and anoxia on several occasions, with the impoundment consistently experiencing over 15 hours/day of DO less than 5 mg/L (Fig. A4.8), a threshold below which waters may be considered impaired for DO (MassDEP 2016).

Following dam removal in early 2018, DO concentrations within the former impoundment and downstream experienced a marked increase (over 7.8 mg/L), surpassing upstream reference concentrations in both 2018 and 2019. Dissolved oxygen concentrations were similar between impoundment and downstream sections and among both years post-removal. Impoundment daily ranges decreased following removal to be more similar to downstream sections, but both downstream and impoundment daily ranges remained larger (>2.5 mg/L) than the upstream reference (avg: 0.8 mg/L). In both years monitored after removal, DO impairment (i.e., concentrations less than 5 mg/L) was eliminated in both impoundment and downstream sections (Fig. A4.8). This suggests DO concentrations in previously impaired stream sections can recover to natural conditions within less than a year following dam removal.

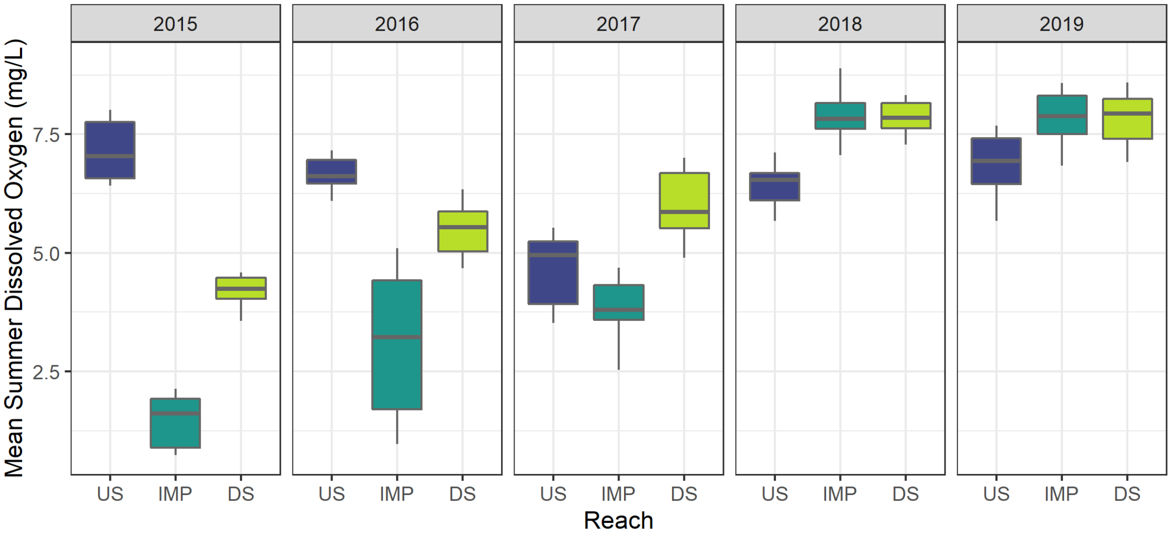


Figure A4.6) Mean summer (July-September) dissolved oxygen concentrations in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2019. Dam removal occurred in early 2018, prior to the summer deployment.

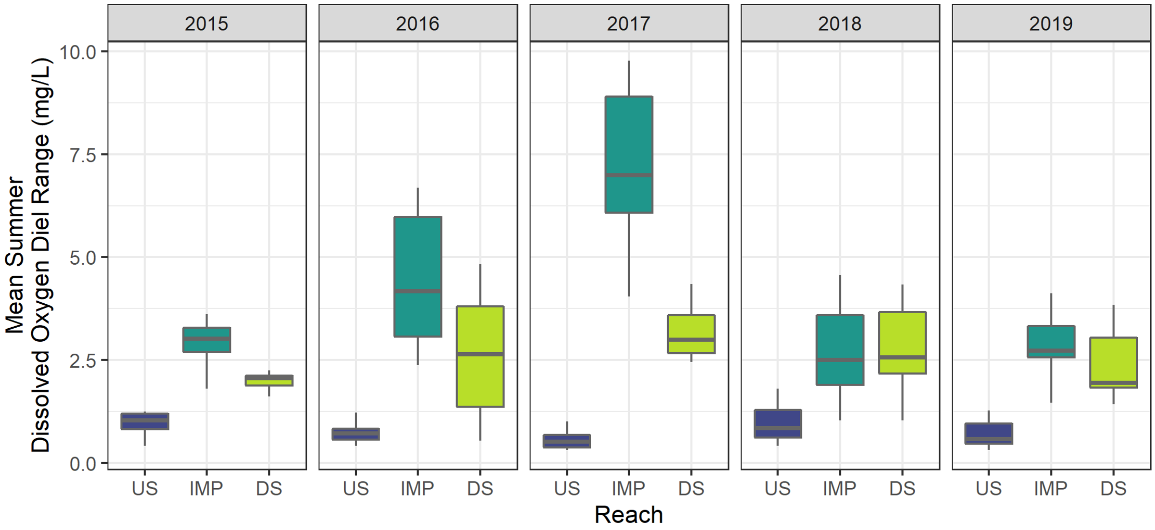


Figure A4.7) Mean summer (July-September) daily range of dissolved oxygen levels in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2019. Dam removal occurred in early 2018, prior to the summer deployment.

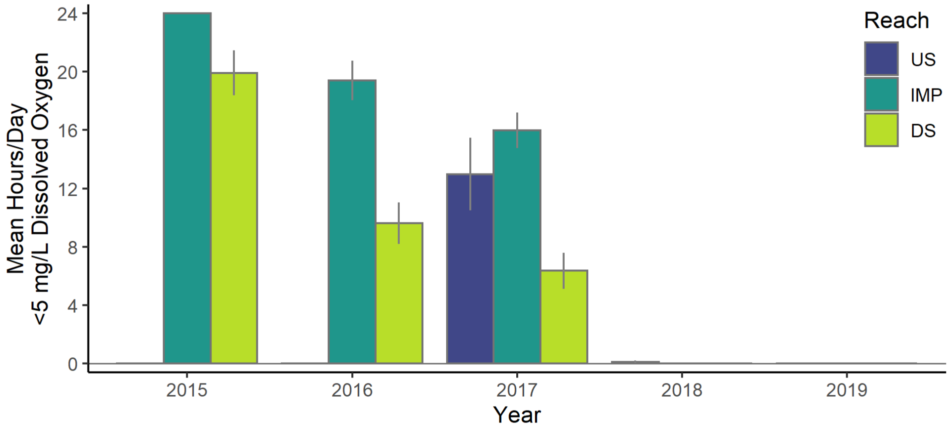


Figure A4.8) Mean and standard error (SE) hours per day that upstream (US), impoundment (IMP) and downstream (DS) stream sections spent below 5.0 mg/L, a threshold below which waters may be considered impaired for DO, prior to dam removal (MassDEP 2016).

Macroinvertebrates

Prior to dam removal, we found that macroinvertebrate taxa differed between upstream and downstream sections, as well as between flowing water and impounded sections. For example, the percent of taxa (unique organisms) classified as coldwater (thermal optimum <18 °C) was lower downstream (2.6%) as compared to upstream (5.7%), while the percent of warmwater (>20 °C) taxa was slightly higher downstream (2.5%) as compared to upstream (1.3%). In general, coolwater (18-20 °C) taxa dominated all sections at this site. We also observed a greater percentage of warmwater pollution-tolerant taxa within the impoundments than upstream sections, and fewer sensitive taxa (Fig. A4.9). The Hilsenhoff Biotic Index (HBI), which estimates the overall pollution tolerance weighted by the relative abundance of each taxa (Hilsenhoff 1988), also indicated more pollution tolerant taxa within the impoundment relative to flowing water sections. The total number of taxa (taxa richness) was slightly lower downstream compared to the upstream and impoundment, and diversity, which incorporates both richness and abundance of taxa, was slightly higher in the impoundment.

After dam removal, the former impoundment exhibited an increase in intolerant taxa, and a corresponding decrease in tolerant taxa (Fig. A4.9), which may reflect an improvement in water quality with the shift from stagnant to flowing water. The downstream section exhibited no significant changes in the percent sensitive taxa, percent tolerant taxa, or HBI score before to after dam removal (Fig. A4.9). HBI scores in the former impoundment decreased to become more similar to adjacent flowing water sections. There were slight increases in taxa richness and slight decreases in diversity in both the former impoundment and downstream sections (Fig. A4.10). Functional traits—feeding behavior and movement habits, for example—allow us to link environmental conditions to the abundance and diversity of the different functional groups sampled. In the former impoundment, we observed an increase in taxa that feed by scraping periphyton from rocks and detritus, like snails and some riffle beetles (Elmidae), which may indicate increased sunlight and algal growth. We also observed a reduction in taxa that burrow in the former impoundment after removal, reflecting the shift in habitat from stagnant to flowing water and from fine sediment and organic matter to coarser substrate (Fig. 2.11). Sensitive taxa within the impoundment and downstream recovered to be similar to upstream levels within 3 years after dam removal (Fig. 2.12).

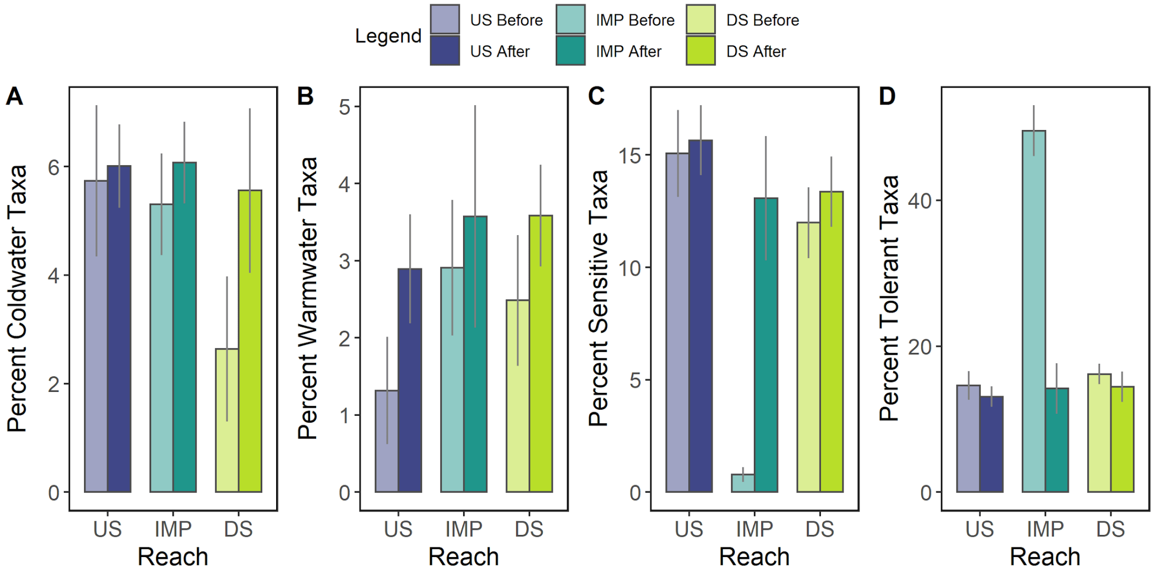


Figure A4.9) Mean percent of macroinvertebrate taxa by A) coldwater, B) warmwater, C) sensitive, and D) pollution-tolerant found within each sample in upstream (US), impoundment (IMP), and downstream (DS) stream sections before and after dam removal.

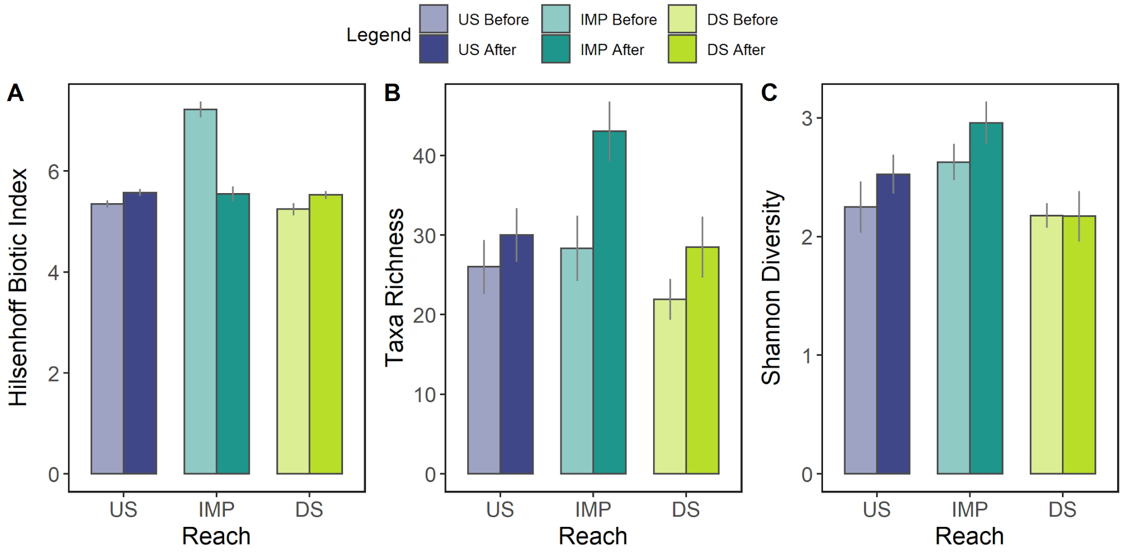


Figure A4.10) Mean macroinvertebrate biotic metric A) Hilsenhoff Biotic Index, B) total taxa richness, and C) Shannon diversity found in upstream (US), impoundment (IMP), and downstream (DS) sections before and after dam removal.

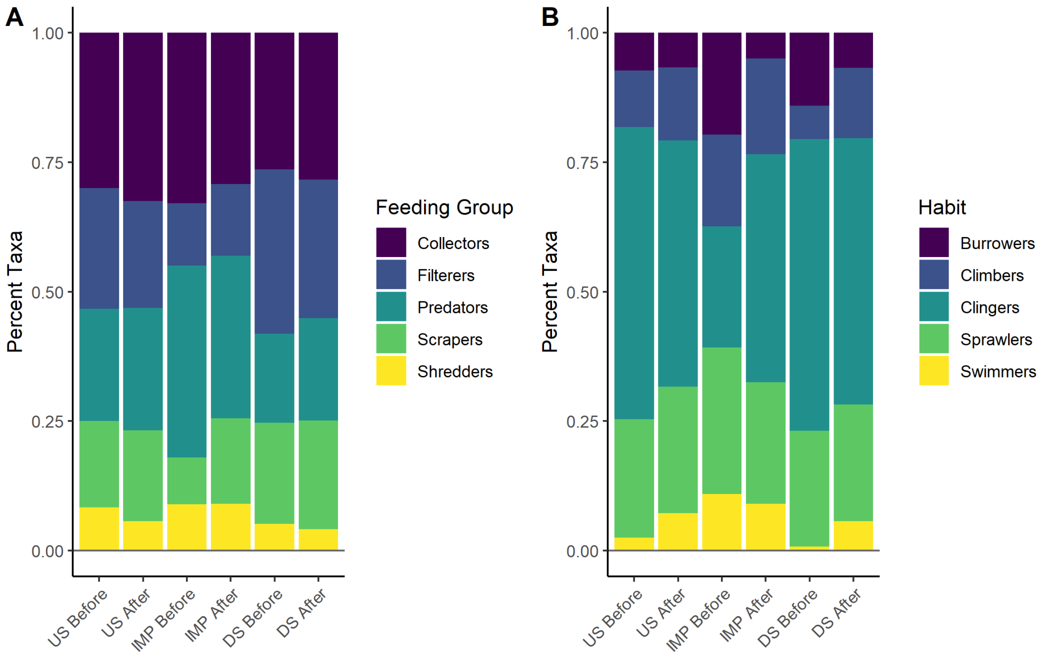


Figure A4.11) Percent of macroinvertebrate taxa by functional trait groups A) feeding group, and B) habit in upstream (US), impoundment (IMP), and downstream (DS) stream sections before and after dam removal. See Table A2.1 in Appendix 2 for information on feeding groups and habit categories.

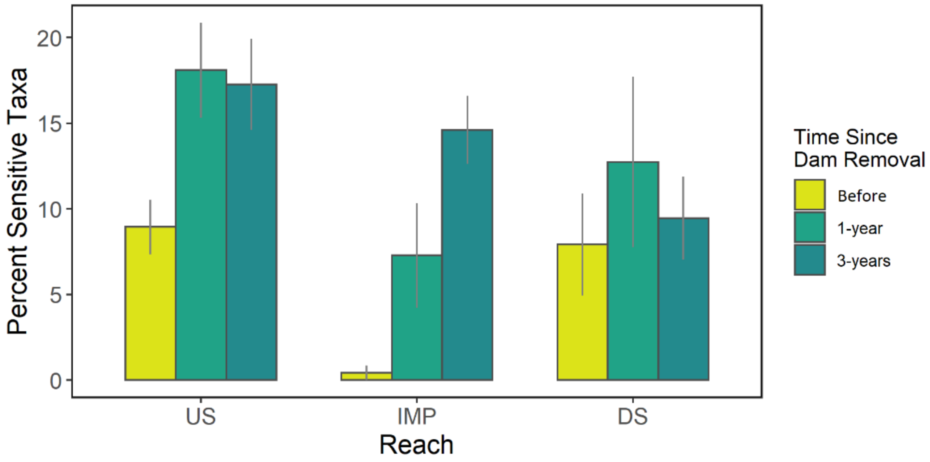


Figure A4.12) Percent of sensitive macroinvertebrate taxa in upstream (US), impoundment (IMP), and downstream (DS) stream sections before (pre) and in the years after dam removal (1- and 3-years after removal).

Table A4.1. Averages of key ecological parameters before and after dam removal in each stream section (± 1 standard deviation).

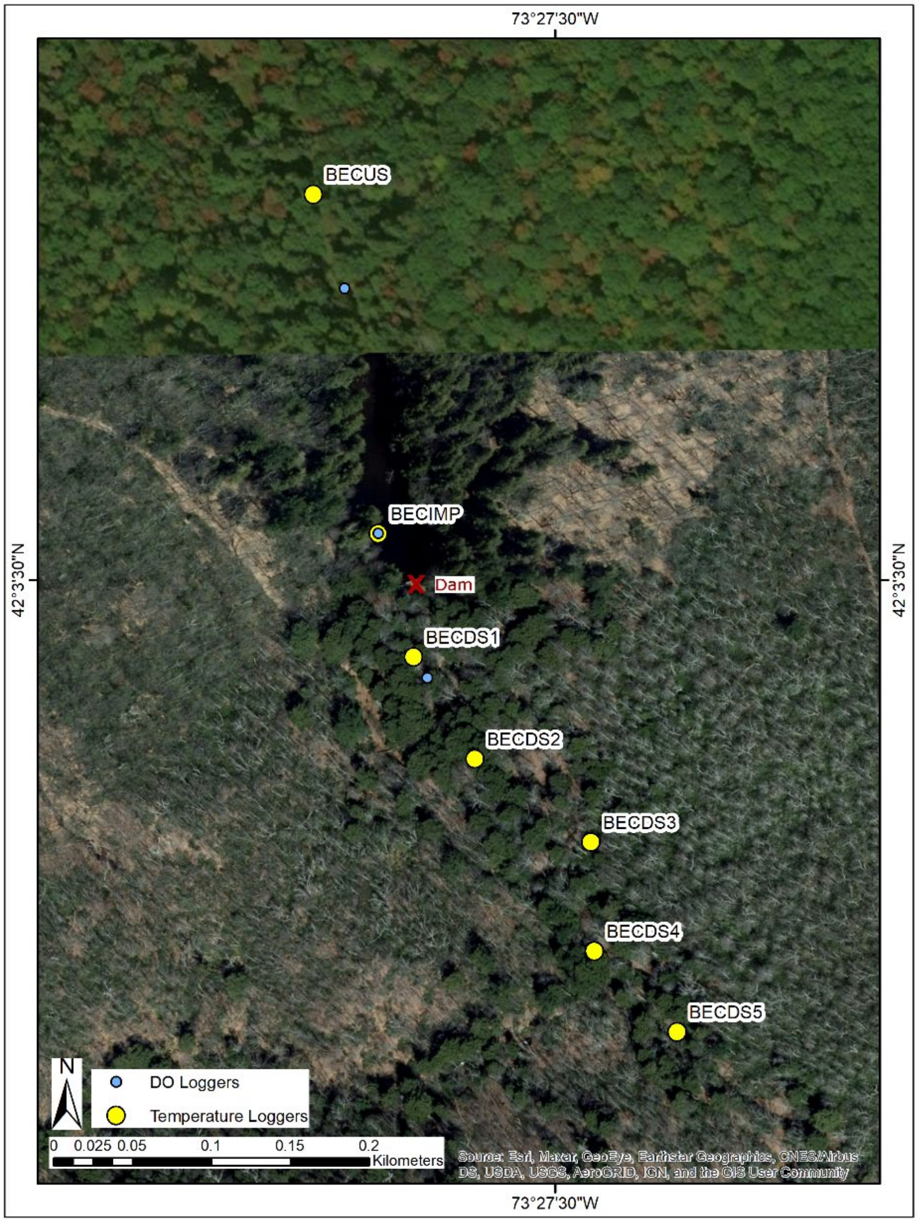
Ecological Parameter	Upstream Before	Upstream After	Impoundment Before	Impoundment After	Downstream† Before	Downstream After
Stream Temperature (C)	21.1 ± 2.2	20.4 ± 2.3	22.9 ± 2.8	21.5 ± 2.8	22.3 ± 2.6	21.3 ± 2.7
Dissolved Oxygen (mg/L)	5.8 ± 1.3	6.7 ± 0.6	3.1 ± 1.4	7.9 ± 0.5	5.5 ± 0.8	7.8 ± 0.5
Hilsenhoff Biotic Index†† (HBI)	5.3 ± 0.2	5.6 ± 0.2	7.2 ± 0.5	5.6 ± 0.3	5.2 ± 0.4	5.5 ± 0.2

†Temperature from first downstream logger (DS1) only. ††Higher HBI indicates a greater relative abundance of pollution-tolerant macroinvertebrate taxa and suggests poorer water quality.

APPENDIX 5: Becker Pond Dam (BEC)

Sampling Overview

Becker Pond Dam, located in Mount Washington, MA, is a 14.1 ft tall (4.3 m) surface-release dam forming an 0.74-acre (0.3 ha) impoundment. This structure is the only known barrier encountered on a small, unnamed tributary to Schenob Brook. This site is located in a 1.04 mi^2 (2.7 km^2) watershed that is 80.8% forest cover, 0.05% impervious cover, and 0% cultivated land, with a mean elevation of 1840 ft (560.8 m) above sea level. This site was monitored for temperature, dissolved oxygen, benthic macroinvertebrates, and fishes to determine the ecological impacts of the dam and to provide a baseline for future assessments of dam removal responses.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure A5.1. Map of temperature and dissolved oxygen logger locations in an unnamed tributary of Sages Ravine Brook, Mount Washington, MA. Macroinvertebrates were sampled in approximately 100m sections around BECUS, BECIMP, and BECDS1 loggers. See Figure 1 in Study Design section for location within Massachusetts. Esri World Imagery Basemap accessed 10/18/2022.

One temperature data logger was deployed upstream (BECUS), one within the impoundment (BECIMP), and five deployed downstream (BECDS1-BECDS5) of the dam, covering 0.16 mi (0.25 km) downstream to a confluence with another small stream (Fig. A5.1). Temperature loggers were deployed in June 2018 and have remained in the field through the present (Spring 2022), capturing 4 years of pre-removal stream temperature. Dissolved oxygen (DO) loggers were deployed upstream (BECUS), within the impoundment (BECIMP), and downstream (BECDS1) of Becker Pond Dam (Fig. A5.1) for approximately week-long deployments during summer months (July, August, and September) from 2018 to 2021, capturing 4 years of pre-removal DO concentrations.

Macroinvertebrates were sampled once per summer from 2018 to 2020, capturing 3 years of pre-removal assemblages. Within impounded areas, 3 replicate Ponar sediment grab samples were collected from randomly selected locations, and along impoundment margins, 3 replicate sweeps of submerged and emergent vegetation were conducted using a rectangular net. In flowing stream sections (e.g., upstream, downstream), 3 replicate Surber samples were taken in separate riffle habitats and a single representative multihabitat sample was collected throughout ~100 m of stream. All samples were preserved in 70% ethanol prior to sorting and identification by Cole Ecological, Inc. or a trained UMass researcher. Up to 300 individuals were identified to the lowest practical taxonomic unit (usually genus or species, referred to as “taxa”).

Temperature data are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Water quality data (temperature and dissolved oxygen) are also available through ScienceBase (https://doi.org/10.5066/P9L2ATHV). Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

Results

Temperature

The unnamed brook impacted by Becker Pond Dam exhibited some longitudinal variation in mean summer stream temperatures from the upstream (BECUS) to furthest downstream (BECDS5) loggers. The upstream, impoundment, and first downstream loggers were generally warmer than DS2-DS5. The upstream section of this stream is fed by a small wetland complex, which may explain the consistently warmer upstream temperatures. Impoundment temperatures were warmest in 2019 and 2020, suggesting interannual variability in thermal impacts related to higher ambient temperatures and relatively low precipitation. Conversely, periods of higher precipitation (e.g., 2021), may result in more consistent temperatures throughout the river due to higher flows and reduced residence times. Averaged across all years, summer impoundment temperatures were highest (mean: 18.6 °C), DS5 temperatures were lowest (mean: 17.4 °C), and the upstream reference temperatures averaged 18.4 °C. Downstream warming—the mean difference between upstream and downstream (DS1) daily temperatures—was highest during winter months and actually negative during summer months (Fig. A5.3), suggesting a slight cooling effect downstream. Summer downstream warming (July-Sept.) was on average -0.16 °C, with high variability (SD= 0.60; Fig. A5.4), suggesting that cool groundwater contributions may be helping to reduce the thermal impacts of the dam downstream. Summer stream temperatures cooled with increasing distance downstream from the dam with a slope of -3.2 °C/km (Fig. A5.5). Downstream temperatures may be reduced by groundwater contributions and cooled by increased canopy cover. Overall, results suggest that Becker Pond Dam has relatively small impacts on downstream temperatures, but impoundment temperature impacts are greater during periods of low precipitation and high air temperatures.

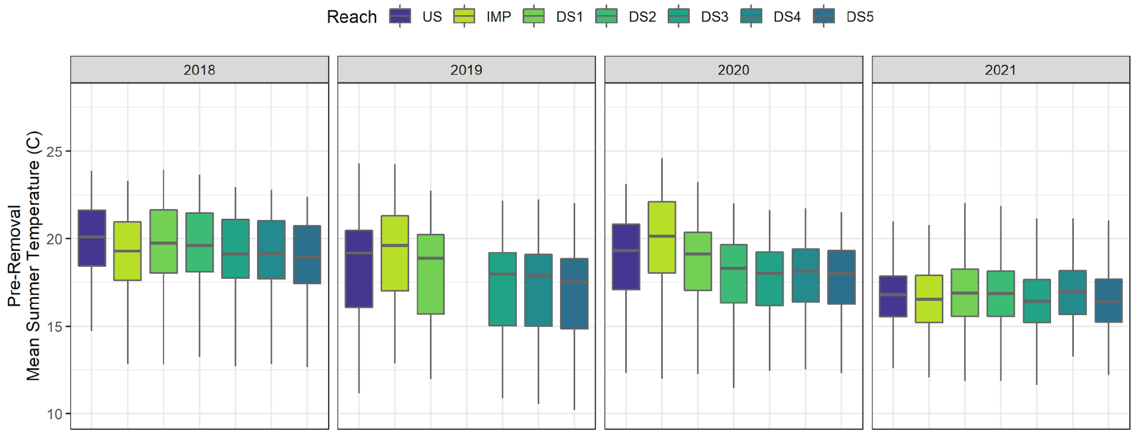


Figure A5.2) Mean summer (July-September) in-stream temperatures at each logger location during 2018-2021. Logger locations are indicated by the following abbreviations: US = upstream, IMP = Impoundment, DS1-DS5 = Downstream 1 through Downstream 5.

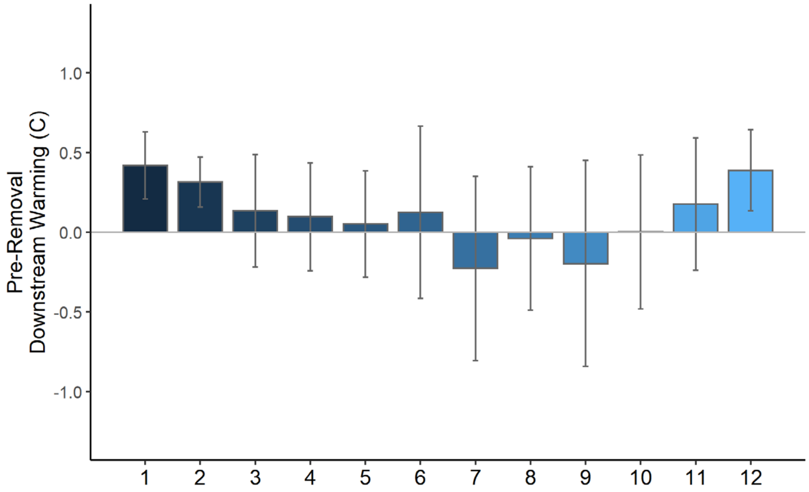


Figure A5.3) Mean downstream warming (i.e., downstream temperature minus upstream temperature) by month, across all years (2018-2021).

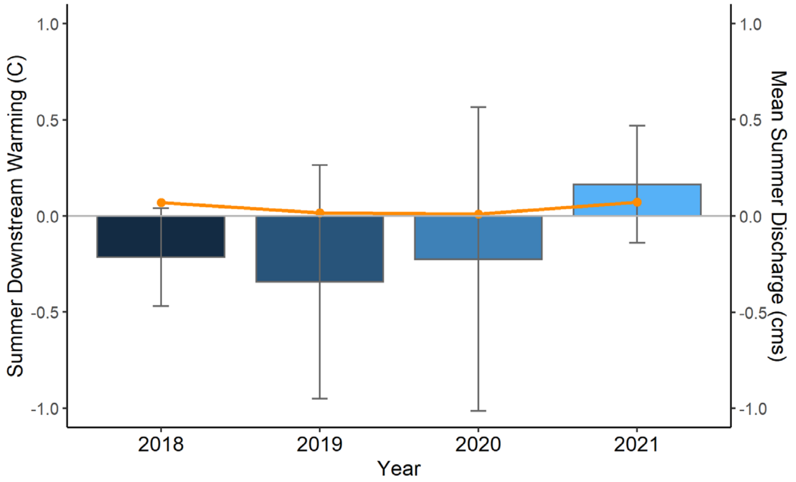


Figure A5.4) Summer (July-September) downstream warming (i.e., the difference between upstream and downstream temperatures ± SD; blue bars) and estimated mean summer discharge (orange line).

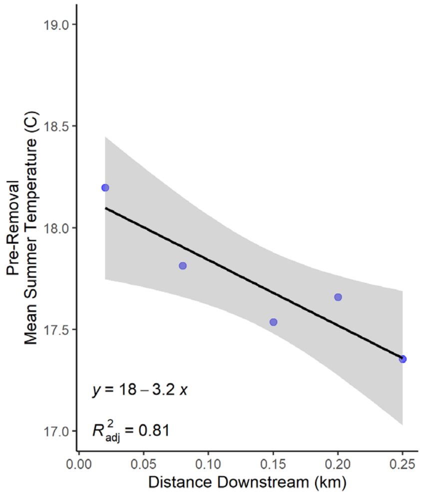


Figure A5.5) Mean summer temperature for each downstream logger (DS1-DS5) relative to the distance from the dam. The black line represents the mean slope of linear temperature decay downstream of the dam and the shaded grey area represents the 95% confidence interval.

Dissolved oxygen (DO)

Average surface DO within the impoundment of Becker Pond Dam (7.54 mg/L) was slightly lower than both the upstream (7.86 mg/L) and downstream (7.90 mg/L) section across all years. Differences among stream sections were variable across years monitored (Fig. A5.6). For example, in 2020, low precipitation and high temperatures may have resulted in lower DO within the impoundment. Higher-than-normal precipitation in 2021 may have led to relatively high DO across all stream sections, and more water spilling from the dam potentially contributing to high downstream DO. Daily ranges downstream were generally more consistent across stream sections, although downstream ranges averaged smaller (0.93 mg/L) than impoundment ranges (1.33 mg/L; Fig. A5.7). Larger daily ranges typically indicate more plant and algal growth, as high rates of oxygen production during daytime photosynthesis and oxygen consumption via nighttime respiration result in larger daily oxygen fluxes (Diamond et al. 2021). The impoundment and upstream sections experienced periods of very low DO only in 2020, with all stream sections experiencing some hours per day of DO less than 5 mg/L (Fig. A5.8), a threshold below which waters may be considered impaired for DO (MassDEP 2016). Similar to thermal impacts, the average dissolved oxygen impact of Becker Pond Dam is small, but may be exacerbated by warm, drought years.

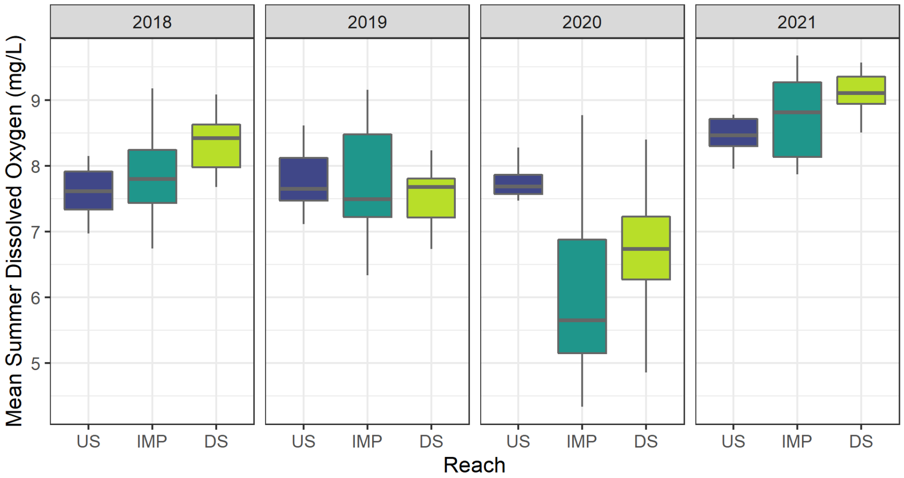


Figure A5.6) Mean summer (July-September) dissolved oxygen concentrations in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2018-2021.

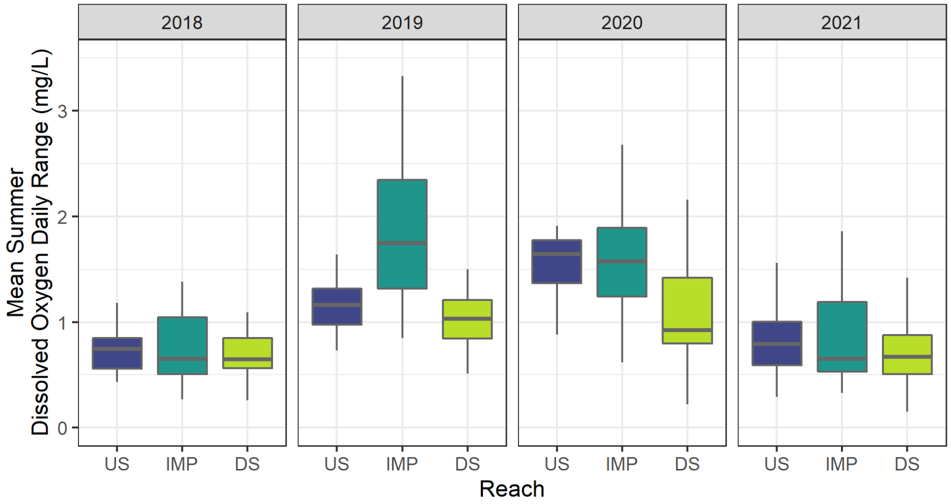


Figure A5.7) Mean summer (July-September) daily range of dissolved oxygen levels in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2018-2021.

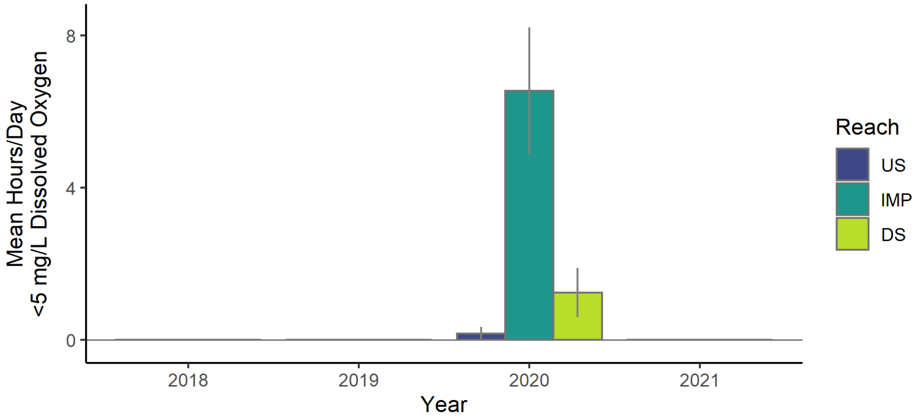


Figure A5.8) Mean and standard error (SE) hours per day that upstream (US), impoundment (IMP) and downstream (DS) stream sections spent below 5.0 mg/L, a threshold below which waters may be considered impaired for DO (MassDEP 2016). Stream sections in 2018, 2019, and 2021 did not experience DO < 5 mg/L at any time.

Macroinvertebrates

At this site, we found that macroinvertebrate taxa differed between upstream and downstream sections, as well as between flowing water and impounded sections. For example, the percent of taxa (unique organisms) classified as coldwater (thermal optimum <18 °C) was much lower within the impoundment (8.8%) as compared to upstream (28.4% %) and downstream (31.9 %) sections, while warmwater taxa (>20 °C) were only present upstream (0.5 %). In general, coolwater (18-20 °C) taxa dominated all sections at this site. We also observed a greater percentage of pollution-sensitive taxa within the downstream section than in the upstream and impoundment, and fewer tolerant taxa (Fig. A5.9). The most pollution-tolerant taxa were found within the impoundment (53.5%), which was dominated by amphipods (scuds) and chironomids (midges). The Hilsenhoff Biotic Index (HBI), which estimates the overall pollution tolerance weighted by the relative abundance of each taxa (Hilsenhoff 1988), also indicated more pollution-tolerant taxa within the impoundment relative to flowing water sections (Fig. A5.10), and downstream had a lower HBI than upstream. The total number of taxa (taxa richness) and the diversity, which incorporates both richness and abundance of taxa, were both lower within the impoundment (Fig. A5.10). Functional traits—feeding behavior and movement habits, for example—allow us to link environmental conditions to the abundance and diversity of the different functional groups sampled. In the impoundment, we observed a lower proportion of taxa that feed by "shredding" and "scraping", like stoneflies (Plecoptera) and some riffle beetles (Elmidae), which may indicate less coarse particulate matter is available to feed on (Fig. A5.11). We also observed a higher proportion of "filterers" downstream, which may be a result of particulate and nutrient-rich waters flowing from the impoundment. In the impoundment, we also found a higher percentage of taxa that burrow and a lower percentage of clingers than both flowing-water sections, reflecting the shift to stagnant waters and to finer sediment and organic matter (Fig. A5.11).

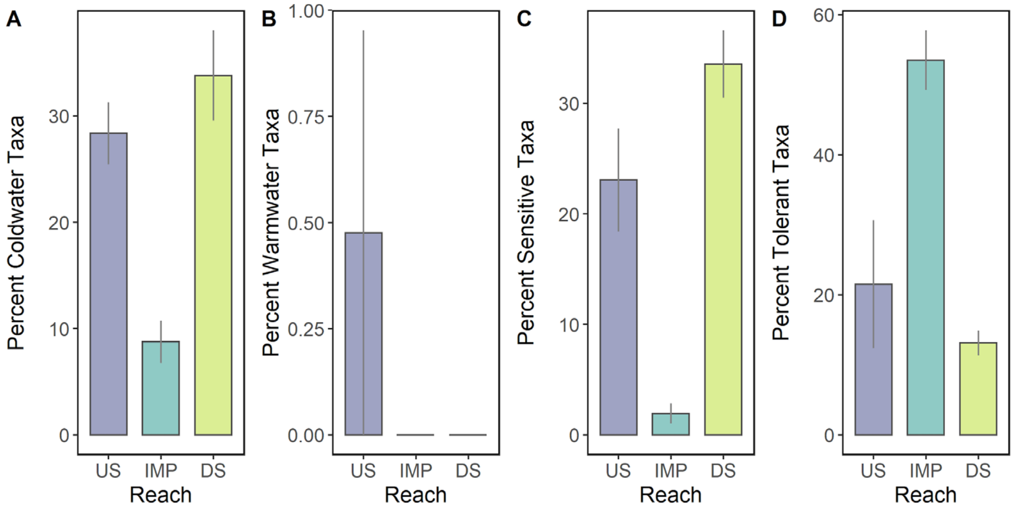


Figure A5.9) Mean percent of macroinvertebrate taxa by A) coldwater, B) warmwater, C) sensitive, and D) pollution-tolerant found within each sample in upstream (US), impoundment (IMP), and downstream (DS) stream sections.

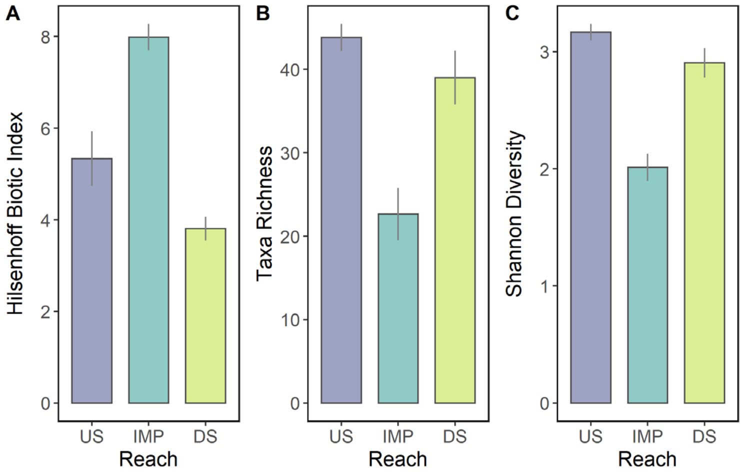


Figure A5.10) Mean macroinvertebrate biotic metric A) Hilsenhoff Biotic Index, B) total taxa richness, and C) Shannon diversity found in upstream (US), impoundment (IMP), and downstream (DS) sections.

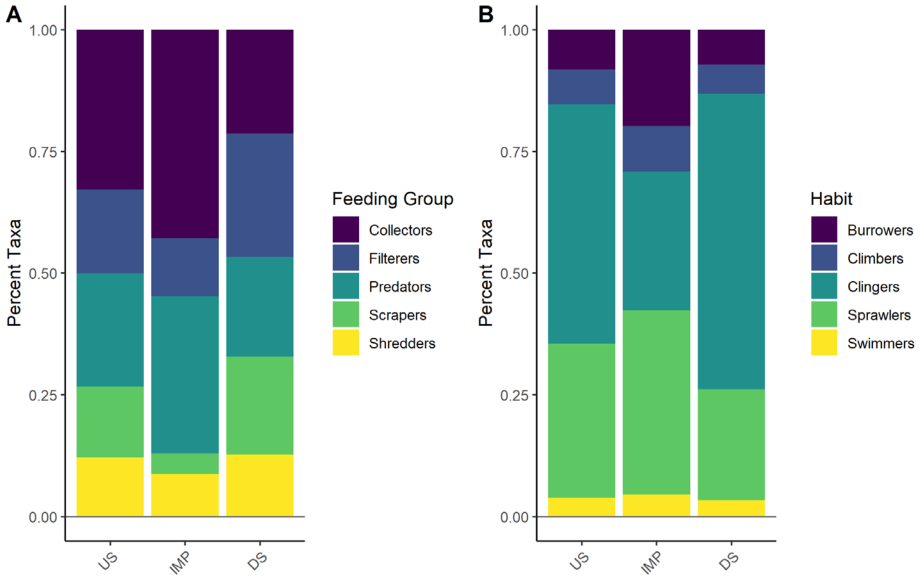


Figure A5.11) Percent of macroinvertebrate taxa by functional trait groups A) feeding group, and B) habit in upstream (US), impoundment (IMP), and downstream (DS) stream sections. See Table A2.1 in Appendix 2 for information on feeding groups and habit categories.

Table A5.1. Averages of key ecological parameters before dam removal in each stream section (± 1 standard deviation).

Ecological Parameter	**Upstream Before**	**Upstream After**	**Impoundment Before**	**Impoundment After**	**Downstream[†] Before**	**Downstream After**
Stream Temperature (C)	18.4 ± 2.9	-	18.6 ± 2.9	-	18.2 ± 2.8	-
Dissolved Oxygen (mg/L)	7.9 ± 0.5	-	7.5 ± 1.3	-	7.9 ± 1.1	-
Hilsenhoff Biotic Index[††] (HBI)	4.7 ± 0.3	-	8.0 ± 1.0	-	4.0 ± 0.6	-

[†] Temperature from first downstream logger (DS1) only. [††] Higher HBI indicates a greater relative abundance of pollution-tolerant macroinvertebrate taxa and suggests poorer water quality.

APPENDIX 6: Bostik/South Middleton Dam (BOS)

Sampling Overview

Bostik Dam (Ipswich River Dam), located in South Middleton, MA, is a 10.2 ft tall (3.1 m) surface-release dam forming an 18.5-acre (7.5 ha) impoundment. This structure is the third and last barrier encountered on the Ipswich River, upstream of the Willowdale Dam and Ipswich Mills Dam. This site is located in a 43.6 mi^2 (113 km^2) watershed that is 32% forest cover, 21% impervious cover, and 0.01% cultivated land, with a mean elevation of 108 ft (33 m) above sea level. This site was monitored for temperature, dissolved oxygen, benthic macroinvertebrates, and fishes to determine the ecological impacts of the dam and to provide a baseline for future assessments of dam removal responses.

One temperature data logger was deployed upstream (BOSUS), one within the impoundment (BOSIMP), and five deployed downstream (BOSDS1-BOSDS5) of the dam, covering 0.71 mi (1.15 km) downstream (Fig. A6.1). Temperature loggers were deployed in July 2015 and remained in the field until October 2021, capturing 7 years of pre-removal stream temperature. Temperature loggers are currently being maintained by the Ipswich River Watershed Association. Dissolved oxygen (DO) loggers were deployed upstream (BOSUS), within the impoundment (BOSIMP), and downstream (BOSDS1) of Bostik Dam (Fig. A6.1) for approximately week-long deployments during summer months (July, August, and September) from 2015 to 2020, capturing 6 years of pre-removal DO concentrations.

Figure A6.1. Map of temperature and dissolved oxygen logger locations in the Ipswich River, South Middleton, MA. Macroinvertebrates were sampled in approximately 100m sections around BOSUS, BOSIMP, and BOSDS1 loggers. See Figure 1 in Study Design section for location within Massachusetts. Esri World Imagery Basemap accessed 10/18/2022.

Macroinvertebrates were sampled once per summer from 2015 to 2020, capturing 6 years of pre-removal assemblages. Within impounded areas, 3 replicate Ponar sediment grab samples were collected from randomly selected locations, and along impoundment margins, 3 replicate sweeps of submerged and emergent vegetation were conducted using a rectangular net. In flowing stream sections (e.g., upstream, downstream), 3 replicate Surber samples were taken in separate riffle habitats and a single representative multihabitat sample was collected throughout ~100 m of stream. At the upstream location (BOSUS), minimal riffle habitat was present, and three replicate multihabitat samples were collected. All samples were preserved in 70% ethanol prior to sorting and identification by Cole Ecological, Inc. or a trained UMass researcher. Up to 300 individuals were identified to the lowest practical taxonomic unit (usually genus or species, referred to as "taxa").

Temperature data are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Water quality data (temperature and dissolved oxygen) are also available through ScienceBase (https://doi.org/10.5066/P9L2ATHV). Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

Results

Temperature

The Ipswich River near the Bostik Dam exhibited considerable longitudinal variation in mean summer stream temperatures from the upstream (BOSUS) to furthest downstream (BOSDS5) loggers. The upstream, impoundment, and first downstream loggers were generally warmer than DS3-DS5, potentially due to colder groundwater contributions occurring downstream near DS3-DS5. Annual variability may be due to periods of drought (e.g., 2016), which could lead to groundwater comprising a larger proportion of surface water flow. Conversely, periods of higher precipitation (e.g., 2018), may result in more consistent temperatures throughout the river due to higher flows and reduced residence times. Across all years, summer impoundment temperatures were highest (mean: 22.7 °C), DS4 temperatures were lowest (mean: 20.0 °C), and the upstream reference temperatures averaged 21.9 °C. Downstream warming—the mean difference between upstream and downstream (DS1) daily temperatures—was highest during September and October and negligible during winter months (Fig. A6.3), though with high variability year-to-year. Summer downstream warming (July-Sept.) was on average 0.10 °C, with high variability (SD= 0.99; Fig. A6.4). Despite relatively small magnitudes of warming on average, transient periods (e.g., days, weeks) of high temperatures induced by the dam may negatively impact sensitive fish and macroinvertebrate taxa. August stream temperatures cooled with increasing distance downstream from the dam with a slope of -1.0 °C/km (Fig. A6.5). These results suggest that Bostik Dam has small impacts on Ipswich River stream temperature, particularly within the impoundment, but that dam impacts are stronger during periods of low flow and high air temperatures.

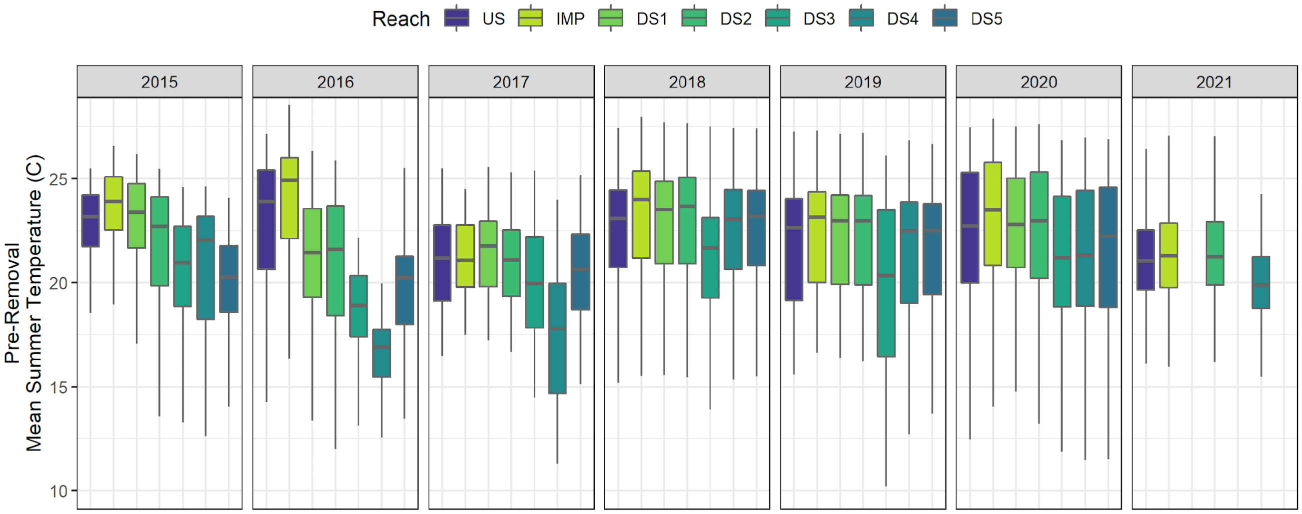


Figure A6.2) Mean summer (July-September) in-stream temperatures at each logger location during 2015-2021. Logger locations are indicated by the following abbreviations: US = upstream, IMP = Impoundment, DS1-DS5 = Downstream 1 through Downstream 5.

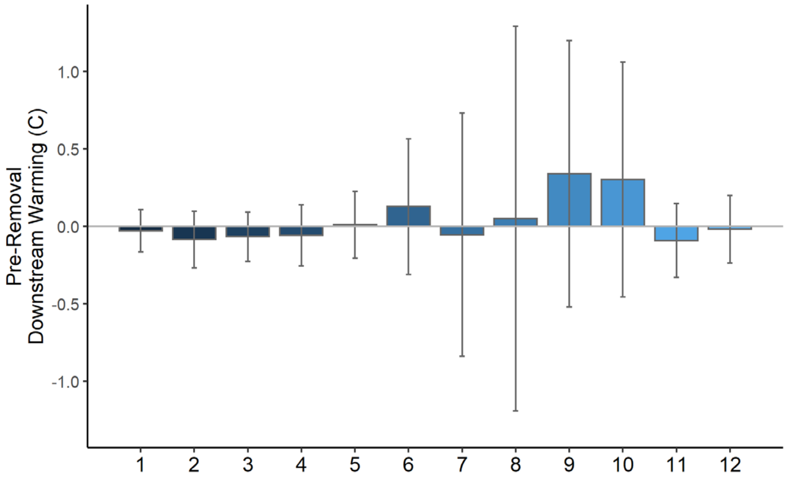


Figure A6.3) Mean downstream warming (i.e., downstream temperature minus upstream temperature) by month, across all years (2015-2021).

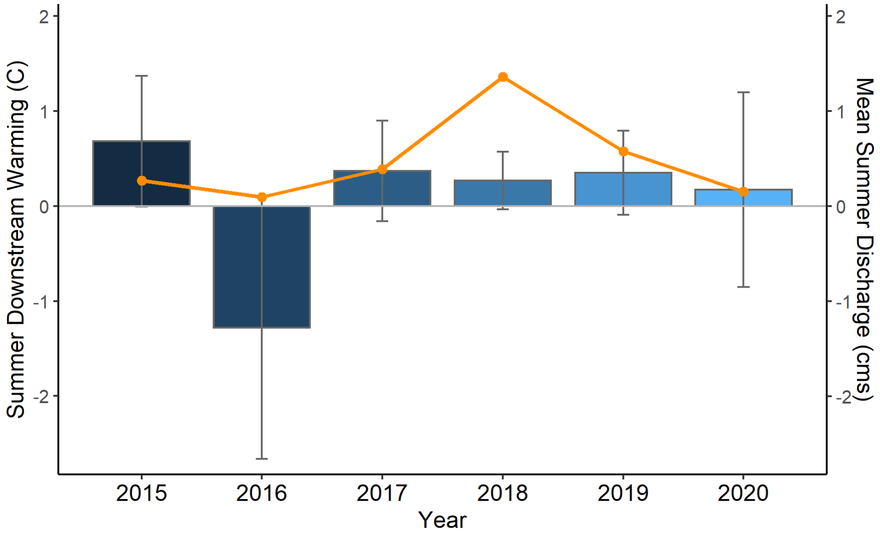


Figure A6.4) Summer (July-September) downstream warming (i.e., the difference between upstream and downstream temperatures ± SD; blue bars) and estimated mean summer discharge (orange line).

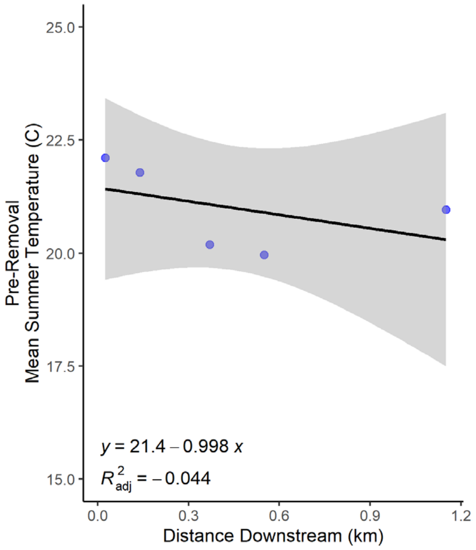


Figure A6.5) Mean summer temperature for each downstream logger (DS1-DS5) relative to the distance from the dam. The black line represents the mean slope of linear temperature decay downstream of the dam and the shaded grey area represents the 95% confidence interval.

Dissolved oxygen (DO)

Average surface DO within the impoundment of Bostik Dam (4.16 mg/L) was lower than the downstream section (6.57 mg/L) across all years, and the upstream section had, on average, the lowest DO (3.32 mg/L). The upstream section likely exhibited low DO due to wetland areas immediately upstream of this logger; wetlands have been shown to decrease DO concentrations through increasing residence time and oxygen demand from microbial processing, which may lead to low DO at the outflow of wetland complexes (Palmer 1997, Thouin et al. 2009). The section downstream of Bostik has abundant riffles, unlike much of the river, and thus may have naturally higher DO concentrations. Differences among stream sections were variable across years monitored (Fig. A6.6). For example, in 2016, reduced flows and high temperatures may have resulted in more stagnant water and decreased DO downstream, making it more similar to upstream concentrations. Daily ranges downstream were generally lower than upstream and impoundment ranges, except in 2016 (Fig. A6.7). Larger daily ranges may indicate more eutrophic conditions, as high rates of oxygen production during daytime photosynthesis and oxygen consumption via nighttime respiration result in larger daily oxygen fluxes (Diamond et al. 2021). The impoundment and upstream sections experienced periods of hypoxia and anoxia on several occasions, with both sections consistently experiencing over 8 hours/day of DO less than 5 mg/L (Fig. A6.8), a threshold below which waters may be considered impaired for DO (MassDEP 2016).

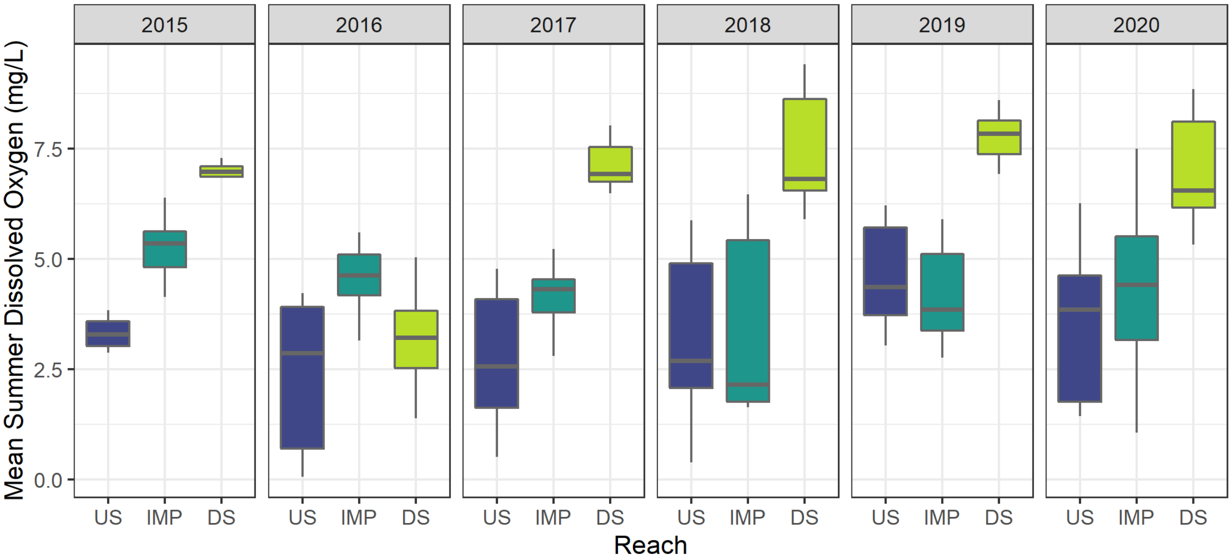


Figure A6.6) Mean summer (July-September) dissolved oxygen concentrations in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2020.

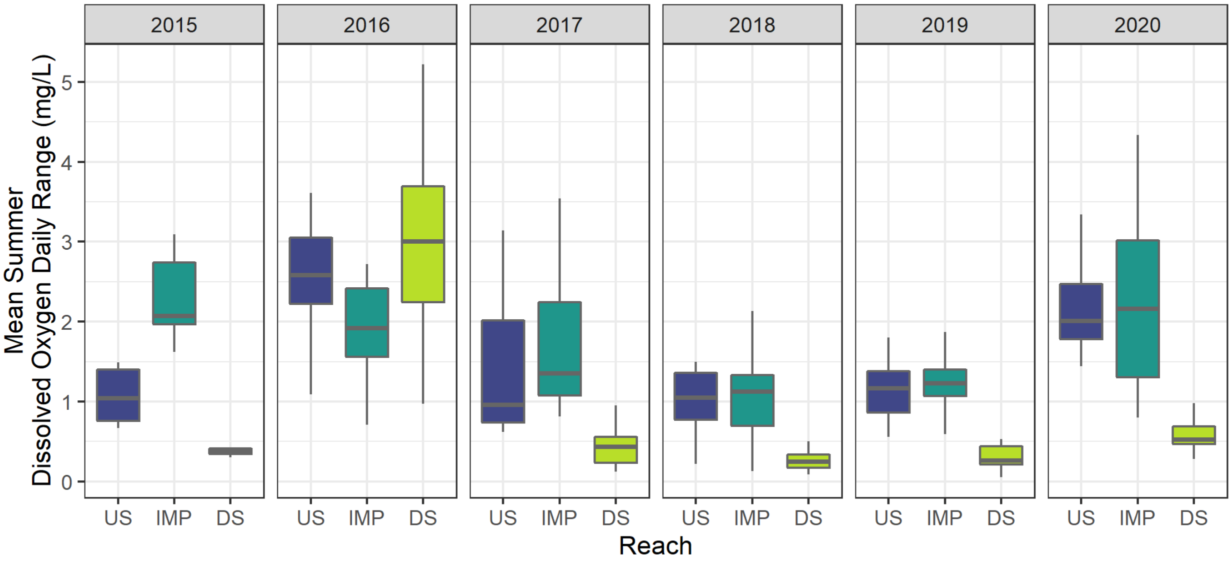


Figure A6.7) Mean summer (July-September) daily range of dissolved oxygen levels in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2020.

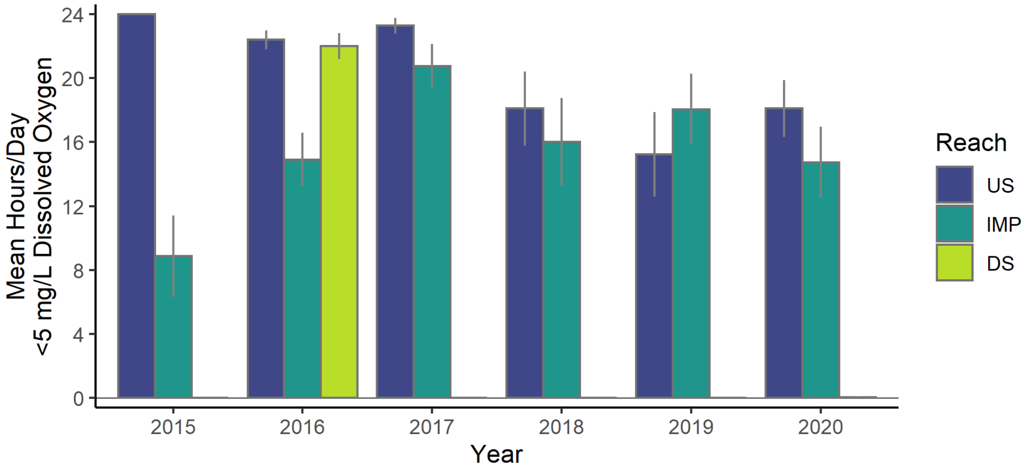


Figure A6.8) Mean and standard error (SE) hours per day that upstream (US), impoundment (IMP) and downstream (DS) stream sections spent below 5.0 mg/L, a threshold below which waters may be considered impaired for DO (MassDEP 2016).

Macroinvertebrates

At this site, we found that macroinvertebrate taxa differed between upstream and downstream sections, as well as between flowing water and impounded sections. For example, the percent of taxa (unique organisms) classified as coldwater (thermal optimum <18 °C) was lower within the impoundment (2.4%) as compared to upstream (4.7%) and downstream (3.5%) sections, while the percent of warmwater (>20 °C) taxa was slightly higher downstream (8.8%) as compared to upstream (5.1%). In general, coolwater (18-20 °C) taxa dominated all sections at this site. We also observed a greater percentage of pollution-sensitive taxa within the downstream section than in the upstream and impoundment, and fewer tolerant taxa (Fig. A6.9). This is consistent with the most abundant riffle habitat being found downstream of the dam, which is preferred habitat for many sensitive taxa. The most pollution-tolerant taxa were found within the impoundment (53.9%), which was dominated by amphipods (scuds) and oligochaetes (worms). The Hilsenhoff Biotic Index (HBI), which estimates the overall pollution tolerance weighted by the relative abundance of each taxa (Hilsenhoff 1988), also indicated more pollution-tolerant taxa within the impoundment relative to flowing water sections

(Fig. A6.10). The total number of taxa (taxa richness) and the diversity, which incorporates both richness and abundance of taxa, were similar across stream sections (Fig. A6.10). Functional traits—feeding behavior and movement habits, for example—allow us to link environmental conditions to the abundance and diversity of the different functional groups sampled. In the impoundment, we observed a lower proportion of taxa that feed by "shredding" and "scraping", like stoneflies (Plecoptera) and some riffle beetles (Elmidae), which may indicate less coarse particulate matter is available to feed on (Fig. A6.11). We also observed a higher proportion of "filterers" downstream, which may be a result of particulate and nutrient-rich waters flowing from the impoundment. In the impoundment, we also found a higher percentage of taxa that burrow and a lower percentage of clingers than both flowing-water sections, reflecting the shift to stagnant waters and to finer sediment and organic matter (Fig. A6.11).

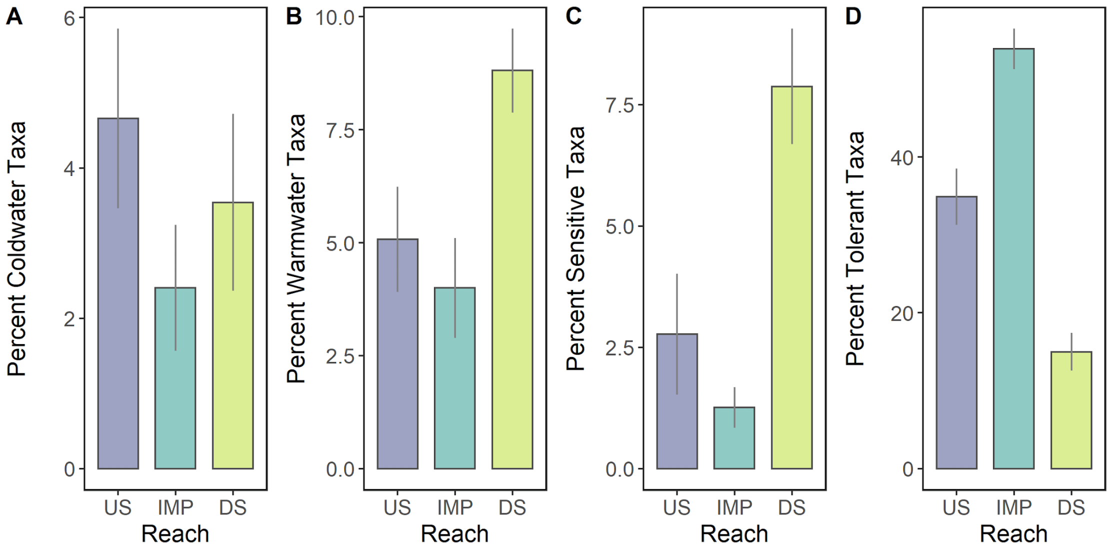


Figure A6.9) Mean percent of macroinvertebrate taxa by A) coldwater, B) warmwater, C) sensitive, and D) pollution-tolerant found within each sample in upstream (US), impoundment (IMP), and downstream (DS) stream sections.

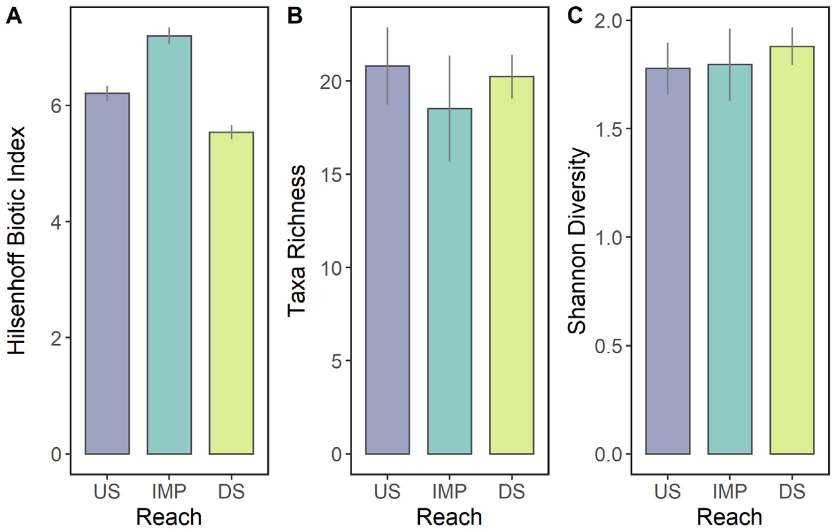


Figure A6.10) Mean macroinvertebrate biotic metric A) Hilsenhoff Biotic Index, B) total taxa richness, and C) Shannon diversity found in upstream (US), impoundment (IMP), and downstream (DS) sections.

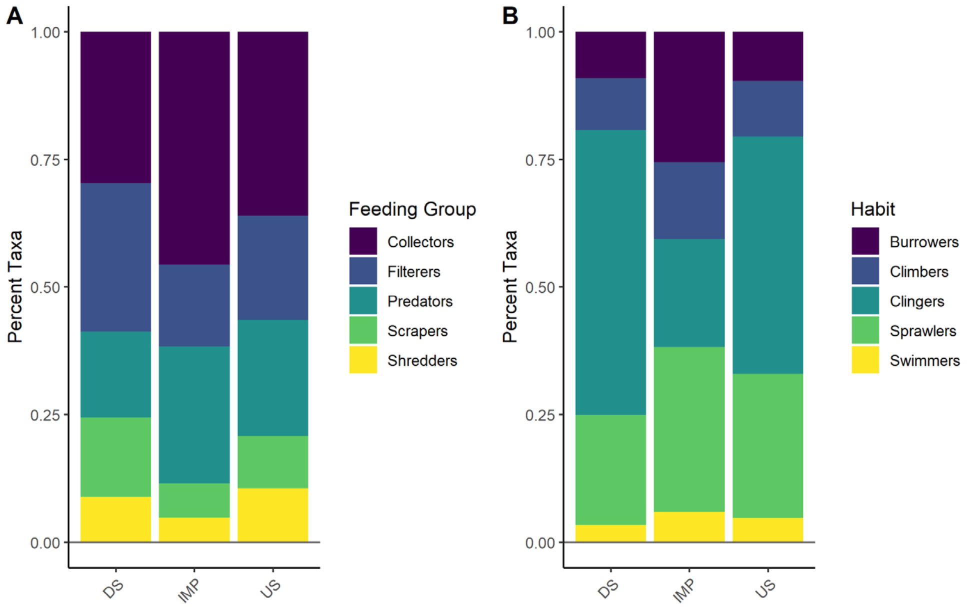


Figure A6.11) Percent of macroinvertebrate taxa by functional trait groups A) feeding group, and B) habit in upstream (US), impoundment (IMP), and downstream (DS) stream sections. See Table A2.1 in Appendix 2 for information on feeding groups and habit categories.

Table A6.1. Averages of key ecological parameters before dam removal in each stream section (± 1 standard deviation).

Ecological Parameter	**Upstream Before**	**Upstream After**	**Impoundment Before**	**Impoundment After**	**Downstream[†] Before**	**Downstream After**
Stream Temperature (C)	21.9 ± 2.9	-	22.7 ± 2.9	-	22.1 ± 2.9	-
Dissolved Oxygen (mg/L)	3.3 ± 1.6	-	4.2 ± 1.4	-	6.6 ± 1.8	-
Hilsenhoff Biotic Index[††] (HBI)	6.2 ± 0.4	-	7.2 ± 0.7	-	5.5 ± 0.5	-

[†] Temperature from first downstream logger (DS1) only. [††] Higher HBI indicates a greater relative abundance of pollution-tolerant macroinvertebrate taxa and suggests poorer water quality.

APPENDIX 7: Ballardvale Dam (BVL)

Sampling Overview

Ballardvale Dam, located in Andover MA, is a 14 ft tall (4.3 m) surface-release dam forming a 34-acre (13.8 ha) impoundment. This structure is the upstream-most barrier encountered on the Shawsheen River, which is a tributary of the Merrimack River. This dam is located upstream of two recent dam removals included in this study, the Marland Place and Balmoral Dams. This site is located in a 65.7 mi^2 (170.16 km^2) watershed that is 25.5% forest cover and 27.7% impervious cover. with a mean elevation of 145 ft (44.2 m) above sea level. This site was monitored for temperature, dissolved oxygen, benthic macroinvertebrates, and fishes to determine the ecological impacts of the dam and to provide a baseline for future assessments of dam removal responses.

Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure A7.1. Map of temperature and dissolved oxygen logger locations in the Shawsheen River in Andover, MA. Macroinvertebrates were sampled in approximately 100m sections around BVLUS, BVLIMP, and BVLDS1 loggers. See Figure 1 in Study Design section for location within Massachusetts. Esri World Imagery Basemap accessed 10/181/2022.

One temperature data logger was deployed upstream (BVLUS), one within the impoundment (BVLIMP), and three deployed downstream (BVLDS1-BVLDS3) of the dam, covering 0.29 mi (0.46 km) downstream (Fig. A7.1). Temperature loggers were deployed in June 2016 and remained in the field until October 2020, capturing 5 years of pre-removal stream temperature. Dissolved oxygen (DO) loggers were deployed upstream (BVLUS), within the impoundment (BVLIMP), and downstream (BVLDS1) of Ballardvale Dam (Fig. A7.1) for approximately week-long deployments during only July and August in 2018.

Macroinvertebrates were sampled once in 2019, capturing 1 year of pre-removal assemblages. Within impounded areas, 3 replicate Ponar sediment grab samples were collected from randomly selected locations, and along impoundment margins, 3 replicate sweeps of submerged and emergent vegetation were conducted using a rectangular net. In flowing stream sections (e.g., upstream, downstream), 3 replicate Surber samples were taken in separate riffle habitats and a single representative multihabitat sample was collected throughout ~100 m of stream. All samples were preserved in 70% ethanol prior to sorting and identification by Cole Ecological, Inc. or a trained UMass researcher. Up to 300 individuals were identified to the lowest practical taxonomic unit (usually genus or species, referred to as “taxa”).

Temperature data are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Water quality data (temperature and dissolved oxygen) are also available through ScienceBase (https://doi.org/10.5066/P9L2ATHV). Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

Results

Temperature

Results of longitudinal stream temperature monitoring around Ballardvale Dam on the Shawsheen River indicate that this dam is negatively impacting stream temperatures. Averaged across all years, summer impoundment temperatures were highest (mean: 23.2 °C), the furthest downstream temperatures were lower (mean: 22.7 °C), and the upstream reference temperatures averaged 22.4 °C. Downstream warming—the mean difference between upstream and downstream (DS1) daily temperatures—was highest during summer months, and particularly in September (Fig. A7.3). Summer downstream warming (July-Sept.) was on average 0.92 °C, with high variability (SD= 1.12; Fig. A7.4), suggesting high variability in dam impacts between years, potentially related to air temperature and precipitation. Summer stream temperatures cooled with increasing distance downstream from the dam with a slope of -0.57 °C/km (Fig. A7.5). These results suggest a relatively small, but persistent, warming effect due to this dam.

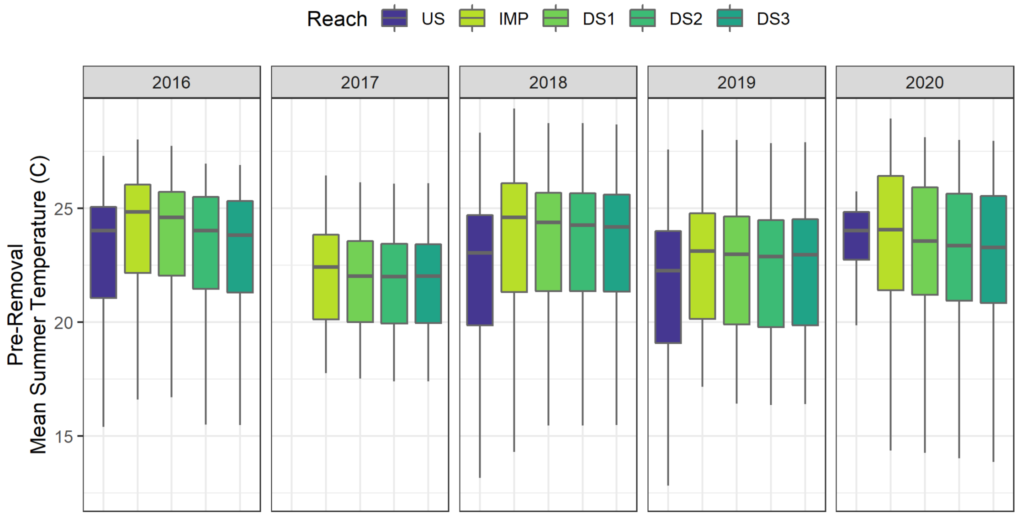


Figure A7.2) Mean summer (July-September) in-stream temperatures at each logger location during 2016-2020. Logger locations are indicated by the following abbreviations: US = upstream, IMP = Impoundment, DS1-DS3 = Downstream 1 through Downstream 3.

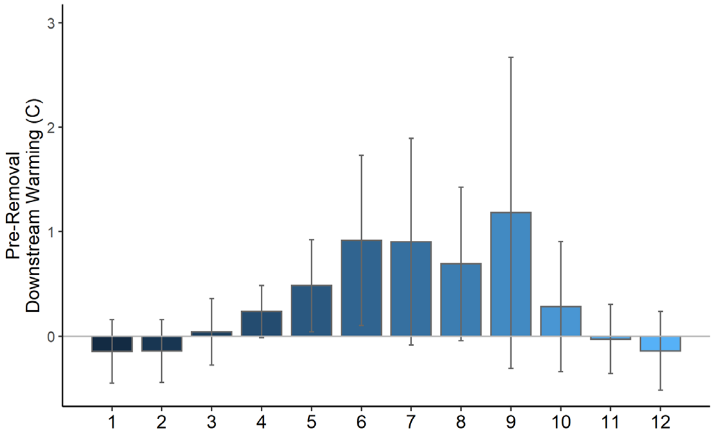


Figure A7.3) Mean downstream warming (i.e., downstream temperature minus upstream temperature) by month, across all years (2016-2020).

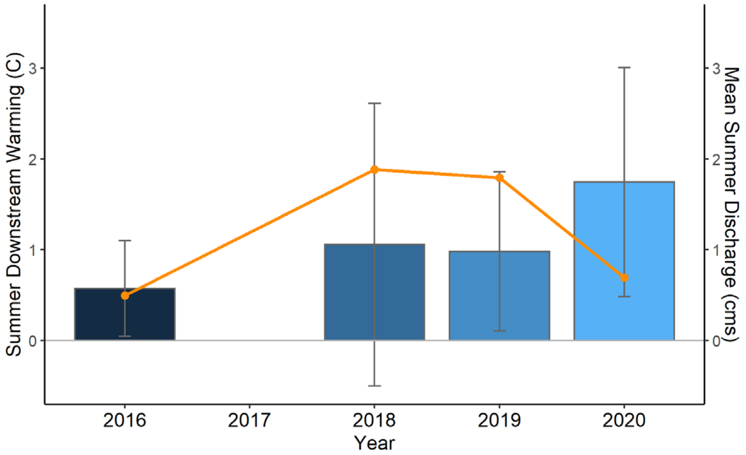


Figure A7.4) Summer (July-September) downstream warming (i.e., the difference between upstream and downstream temperatures ± SD; blue bars) and estimated mean summer discharge (orange line).

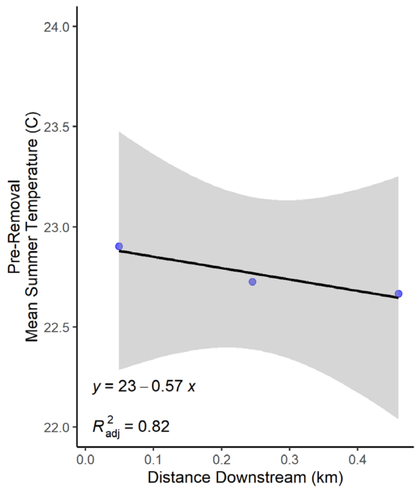


Figure A7.5) Mean summer temperature for each downstream logger (DS1-DS3) relative to the distance from the dam. The black line represents the mean slope of linear temperature decay downstream of the dam and the shaded grey area represents the 95% confidence interval.

Dissolved oxygen (DO)

Average surface DO within the impoundment of Ballardvale Dam (4.80 mg/L) was much lower than both the upstream (6.40 mg/L) and downstream (7.38 mg/L) section in 2018 (Fig. A7.6). Downstream DO was likely higher than the upstream reference due to constant spilling and re-aeration of water over the dam. Daily ranges downstream (0.75 mg/L) were much smaller than upstream (4.01 mg/L) and impoundment (5.37 mg/L; Fig. A7.7). Larger daily ranges typically indicate more plant and algal growth, as high rates of oxygen production during daytime photosynthesis and oxygen consumption via nighttime respiration result in larger daily oxygen fluxes (Diamond et al. 2021). Downstream ranges were likely smaller due to the relatively constant spilling of water, which may vary more due to precipitation events rather than on a daily basis. The impoundment and upstream sections experienced periods of very low DO in 2018, with the impoundment experiencing over 12 hours per day of DO less than 5 mg/L (Fig. A7.8), a threshold below which waters may be considered impaired for DO (MassDEP 2016). These results suggest Ballardvale Dam is negatively impacting stream DO regimes in the Shawsheen River, potentially to such an extent as to impact sensitive fish and macroinvertebrate taxa.

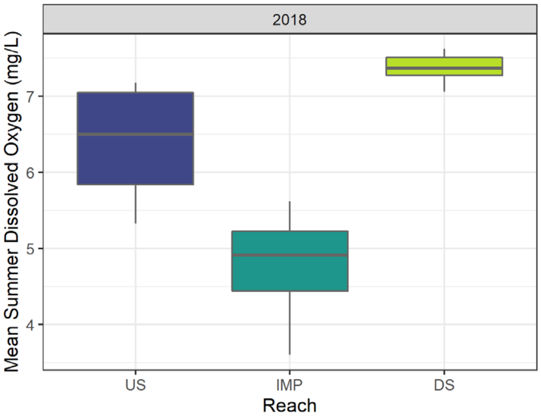


Figure A7.6) Mean summer (July & August) dissolved oxygen concentrations in upstream (US), impoundment (IMP) and downstream (DS) stream sections in 2018.

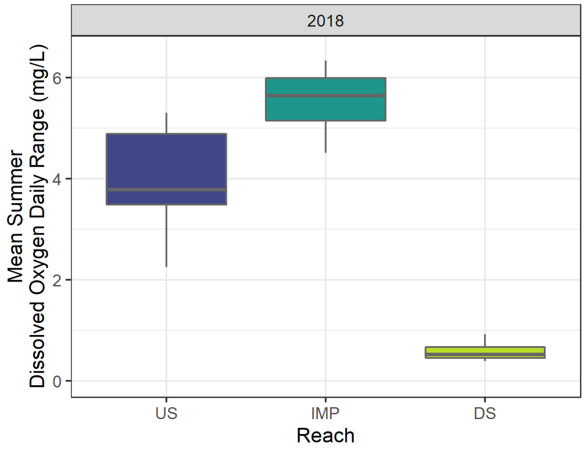


Figure A7.7) Mean summer (July & August) daily range of dissolved oxygen levels in upstream (US), impoundment (IMP) and downstream (DS) stream sections in 2018.

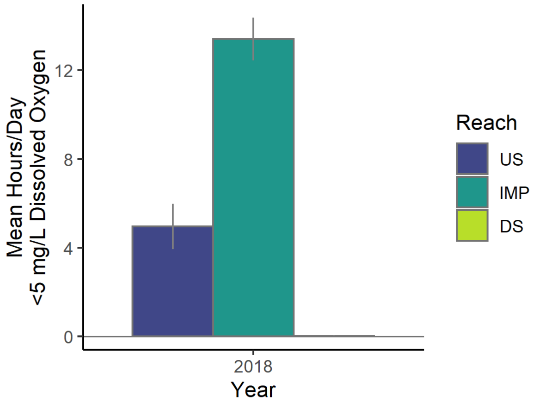


Figure A7.8) Mean and standard error (SE) hours per day that upstream (US), impoundment (IMP) and downstream (DS) stream sections spent below 5.0 mg/L, a threshold below which waters may be considered impaired for DO (MassDEP 2016).

Macroinvertebrates

At this site, we found that some macroinvertebrate metrics differed between flowing water and impounded sections, while others were consistent across sections. For example, the percent of taxa (unique organisms) classified as coldwater (thermal optimum <18 °C) were similar across stream sections, while warmwater taxa (>20 °C) were higher in upstream (13.3 %) and downstream (12.9 %) section than the impoundment (3.7 %). In general, coolwater (18-20 °C) taxa dominated all sections at this site. We observed a greater percentage of pollution-sensitive taxa within the upstream section than in the downstream and impoundment, and fewer tolerant taxa (Fig. A7.9). The most pollution-tolerant taxa were found within the impoundment (50.7 %), which was dominated by amphipods (scuds) and chironomids (midges). The Hilsenhoff Biotic Index (HBI), which estimates the overall pollution tolerance weighted by the relative abundance of each taxa (Hilsenhoff 1988), also indicated more pollution-tolerant taxa within the impoundment relative to flowing water sections (Fig. A7.10), and upstream had a slightly lower HBI than downstream. The total number of taxa (taxa richness) was slightly higher downstream, while diversity, which incorporates both richness and abundance of taxa, was lowest within the impoundment (Fig. A7.10). Functional traits—feeding behavior and movement habits, for example—allow us to link environmental conditions to the abundance and diversity of the different functional groups sampled. In the impoundment, we observed a greater proportion of taxa that feed by "collecting" fine particulate organic matter (Fig. A7.11). In the impoundment, we also found a higher percentage of taxa that burrow and a lower percentage of clingers than both flowing-water sections, reflecting the shift to stagnant waters and to finer sediment and organic matter (Fig. A7.11).

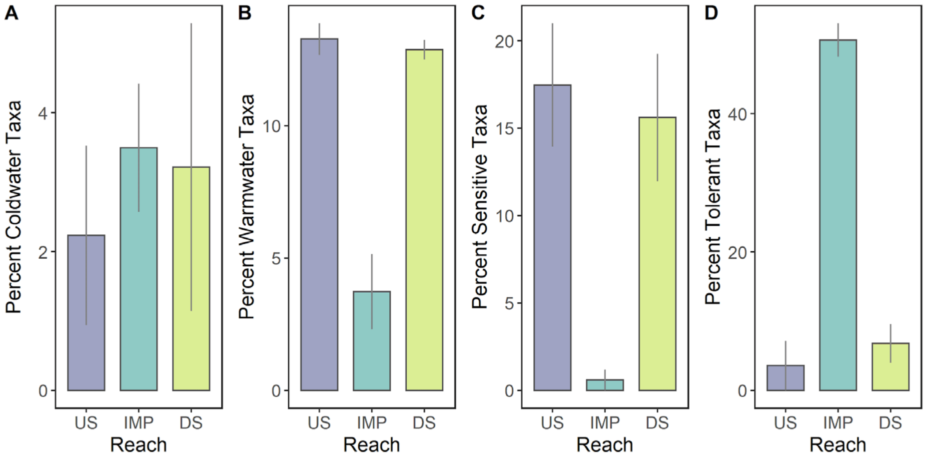


Figure A7.9) Mean percent of macroinvertebrate taxa by A) coldwater, B) warmwater, C) sensitive, and D) pollution-tolerant found within each sample in upstream (US), impoundment (IMP), and downstream (DS) stream sections.

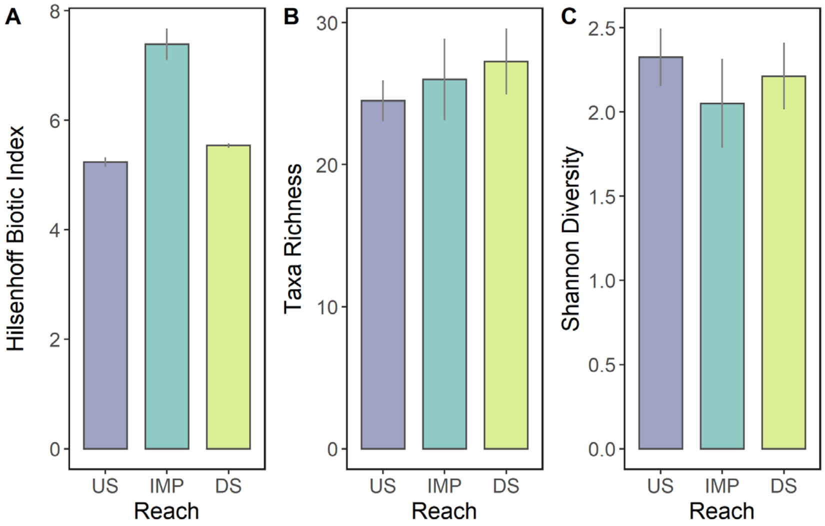


Figure A7.10) Mean macroinvertebrate biotic metric A) Hilsenhoff Biotic Index, B) total taxa richness, and C) Shannon diversity found in upstream (US), impoundment (IMP), and downstream (DS) sections.

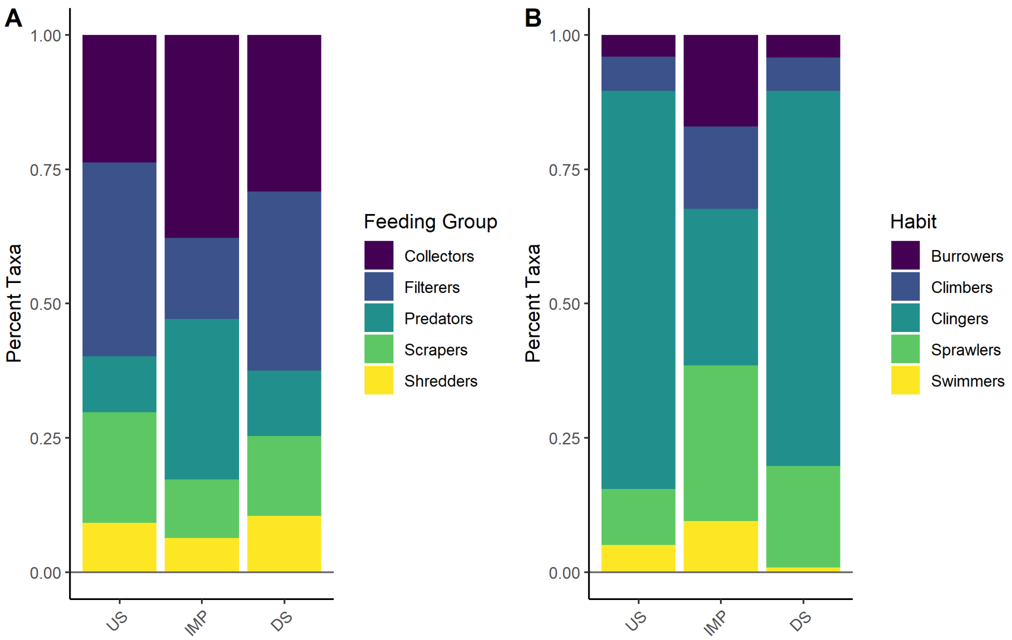


Figure A7.11) Percent of macroinvertebrate taxa by functional trait groups A) feeding group, and B) habit in upstream (US), impoundment (IMP), and downstream (DS) stream sections. See Table A2.1 in Appendix 2 for information on feeding groups and habit categories.

Table A7.1. Averages of key ecological parameters before dam removal in each stream section (± 1 standard deviation).

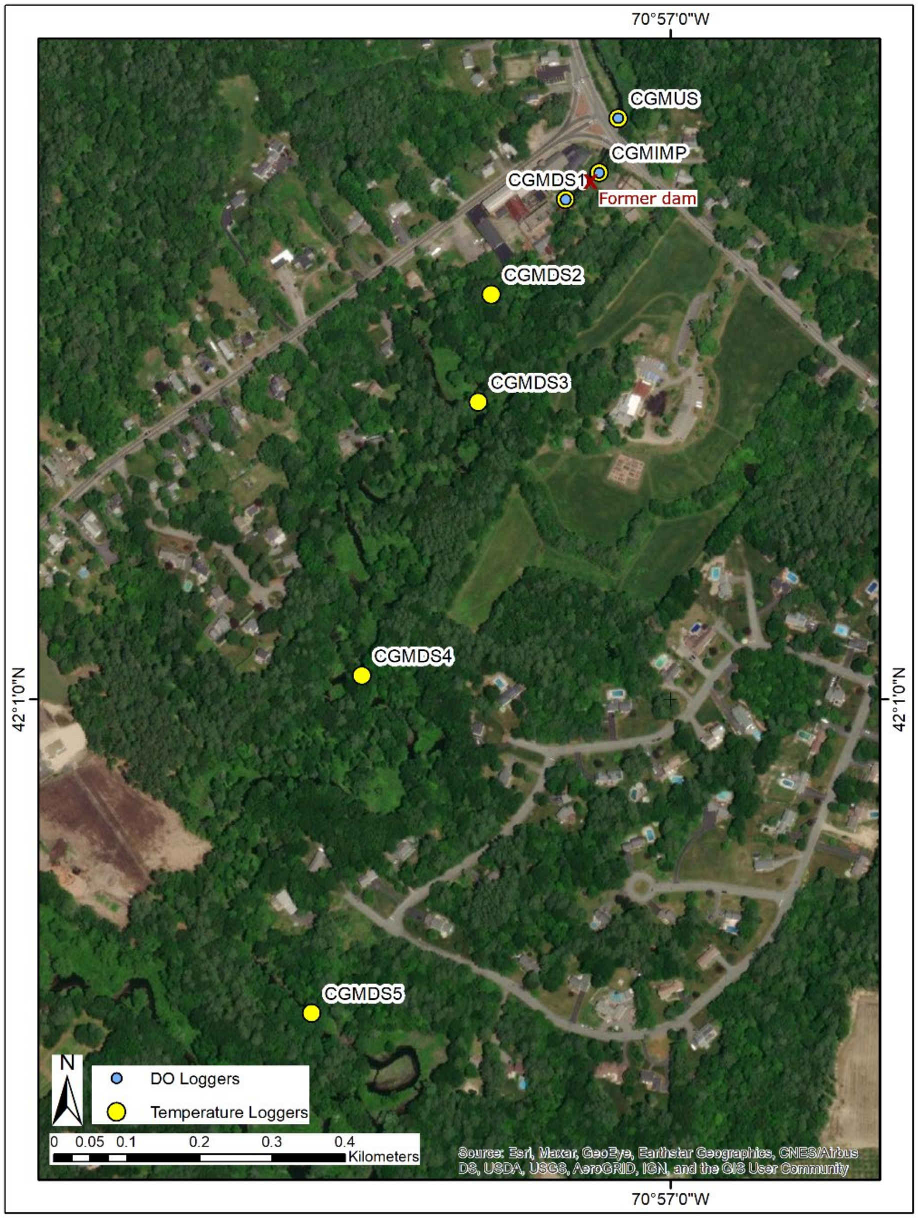
Ecological Parameter	Upstream Before	Upstream After	Impoundment Before	Impoundment After	Downstream[†] Before	Downstream After
Stream Temperature (C)	22.4 ± 3.3	-	23.2 ± 3.1	-	22.9 ± 3.1	-
Dissolved Oxygen (mg/L)	6.4 ± 0.7	-	4.8 ± 0.6	-	7.4 ± 0.2	-
Hilsenhoff Biotic Index[††] (HBI)	5.2 ± 0.2	-	7.4 ± 0.7	-	5.5 ± 0.1	-

[†] Temperature from first downstream logger (DS1) only. [††] Higher HBI indicates a greater relative abundance of pollution-tolerant macroinvertebrate taxa and suggests poorer water quality.

APPENDIX 8: Cotton Gin Mill Dam (CGM)

Sampling Overview

Cotton Gin Mill Dam, a 4.9 ft tall (1.5 m) surface-release dam forming a 0.25-acre (0.1 ha) impoundment, was removed in Fall 2017. This structure was the first barrier to upstream fish passage on the Satucket River in East Bridgewater, MA. The low-level outlet gate was permanently removed in 2001 by order of the Office of Dam Safety, resulting in little to no effective impoundment behind the dam. This site is located in a 21.4 mi^2 (55.4 km^2) watershed that is 41% forest cover, 15% impervious cover, and 0.8% cultivated land, with a mean elevation of 93.5 ft (28.5 m) above sea level. This site was monitored for temperature, dissolved oxygen, benthic macroinvertebrates, and fishes both before and after dam removal.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure A8.1 Map of temperature and dissolved oxygen logger locations in the Satucket River, East Bridgewater, MA. Macroinvertebrates were sampled in approximately 100m sections around CGMUS, CGMIMP, and CGMDS1 loggers. See Figure 1 in Study Design section for location within Massachusetts. Esri World Imagery Basemap accessed 10/181/2022.

One temperature data logger was deployed upstream (CGMUS), one within the impoundment or former impoundment (CGMIMP), and five deployed downstream (CGMDS1-CGMDS5) of the dam, covering 1.02 mi (1.63 km) of the river downstream (Figure A8.1). Temperature loggers were deployed in July 2015 and remained in the field until October 2020, capturing 3 years of pre-removal stream temperature and 3 years of post-removal stream temperature. Dissolved oxygen (DO) loggers were deployed upstream (CGMUS), within the impoundment (CGMIMP), and downstream (CGMDS1) of Cotton Gin Mill Dam or former dam location (Fig. A8.1) for approximately week-long deployments during summer months (July, August, and September) in 2015, 2016, and 2018. Summer DO was monitored for 2 years before removal and 1 year after dam removal.

Macroinvertebrates were sampled once per summer from 2015 to 2020, capturing 3 years of pre-removal and 1 and 3 years of post-removal assemblages. In flowing stream sections (e.g., upstream, downstream, and impoundment/former impoundment), 3 replicate Surber samples were taken in separate riffle habitats and a single representative multihabitat sample was collected throughout ~100 m of stream. All samples were preserved in 70% ethanol prior to sorting and identification by Cole Ecological, Inc. or a trained UMass researcher. Up to 300 individuals were identified to the lowest practical taxonomic unit (usually genus or species, referred to as "taxa").

Fish sampling was also conducted in upstream and downstream sections by MassWildlife intermittently before and after dam removal; data summaries are provided in the General Results section of this final report. Temperature data are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Water quality data (temperature and dissolved oxygen) are also available through ScienceBase (https://doi.org/10.5066/P9L2ATHV). Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

Results

Temperature

Prior to dam removal, mean summer temperatures within the impoundment (23.4 °C) were slightly warmer than the upstream reference temperatures (23.2 °C; Fig. A8.2) and downstream temperatures decreased longitudinally from 23.1 °C (DS1) to 20.8 °C (DS5). Downstream warming—the mean difference between upstream and downstream (DS1) daily temperatures—was highest during September (Fig. A8.3). Summer downstream warming was on average 0.02 °C, with high variability (SD= 0.37; Fig. A8.4), suggesting minimal effect of the dam on downstream summer temperatures. Summer stream temperatures cooled with increasing distance downstream from the dam with a slope of -1.32 °C/km (Fig. A8.5). These results suggest that Cotton Gin Mill Dam had a small effect on Satucket River stream temperatures within the dam's impoundment and immediately downstream.

In the former impoundment, temperatures were reduced from 23.4 °C to 22.7 °C (0.7 °C difference); during the same years, upstream reference temperatures averaged 23.2 °C before removal to 22.8 °C after removal (0.4 °C difference). Mean downstream warming did not significantly change after dam removal (-0.05 °C; Fig. A8.3), but variability in downstream temperatures was substantially reduced (before: SD= 0.37, after: SD=0.06), indicating downstream temperatures became more consistently similar to upstream reference temperatures. After removal, August stream temperatures continued to decrease with increasing distance downstream, but at a reduced rate of change (-0.83 °C/km; Fig. A8.5). Overall, while dam removal at this site did not have a large effect on average stream temperatures, it appears to have led to a more consistent thermal regime throughout the study area, with fewer fluctuations in stream temperature.

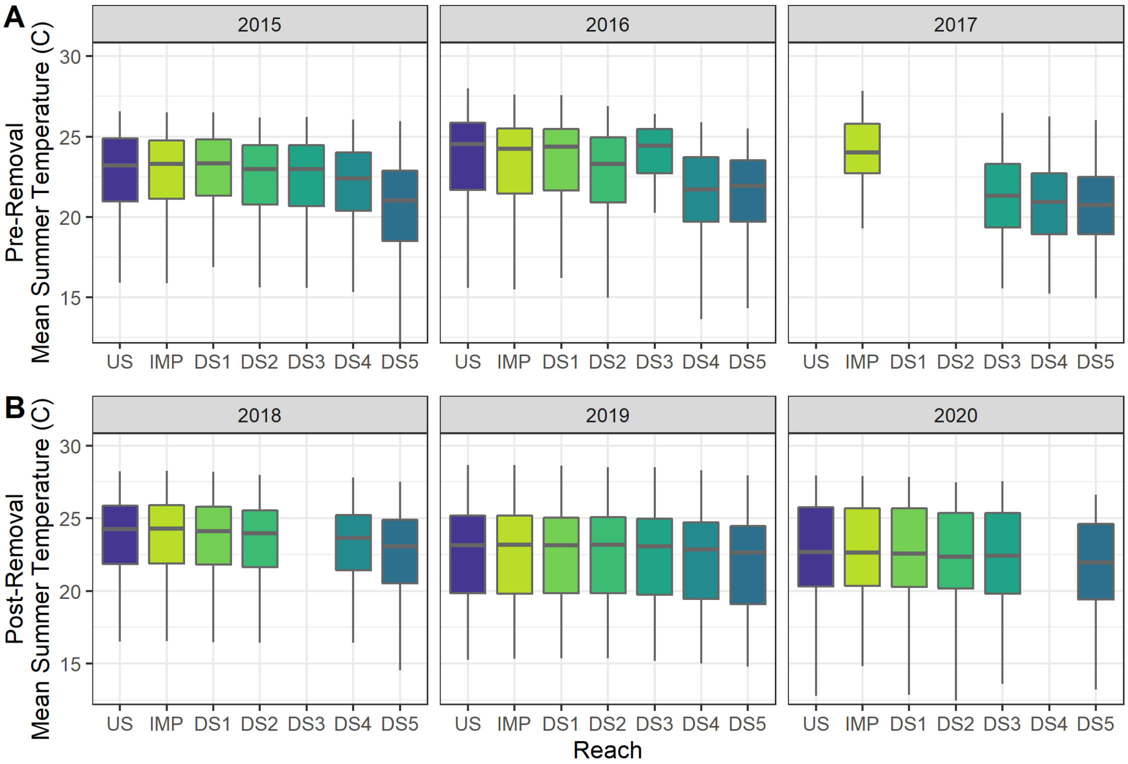


Figure A8.2) Mean summer (July-September) in-stream temperatures at each logger location A) before dam removal (2015-2017) and B) after dam removal (2018-2020). Logger locations are indicated by the following abbreviations: US = upstream, IMP = Impoundment, DS1-DS5 = Downstream 1 through Downstream 5.

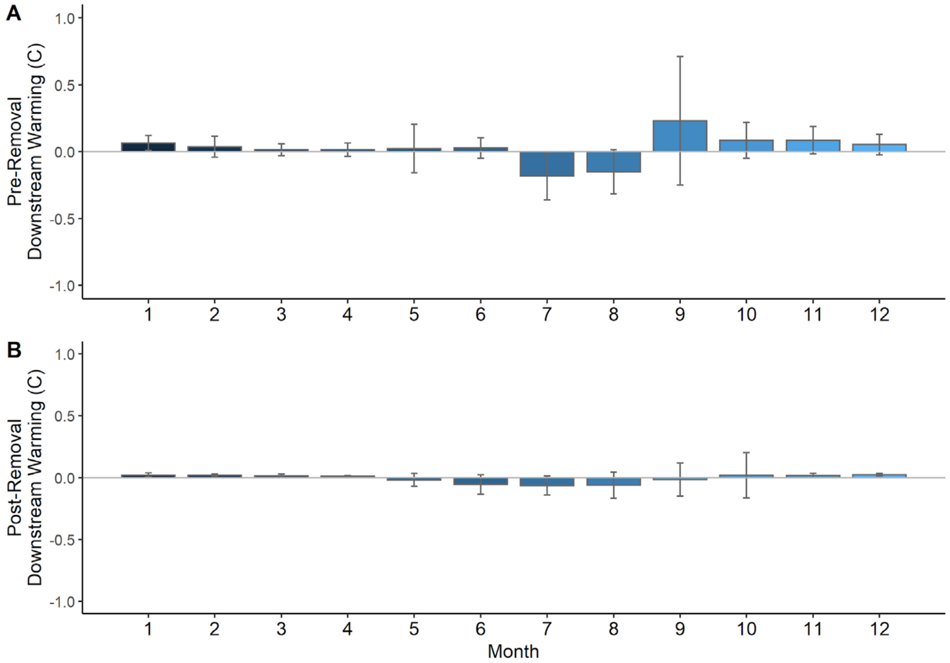


Figure A8.3) Downstream warming by month A) before (2015-2017) and B) after dam removal (2018-2020).

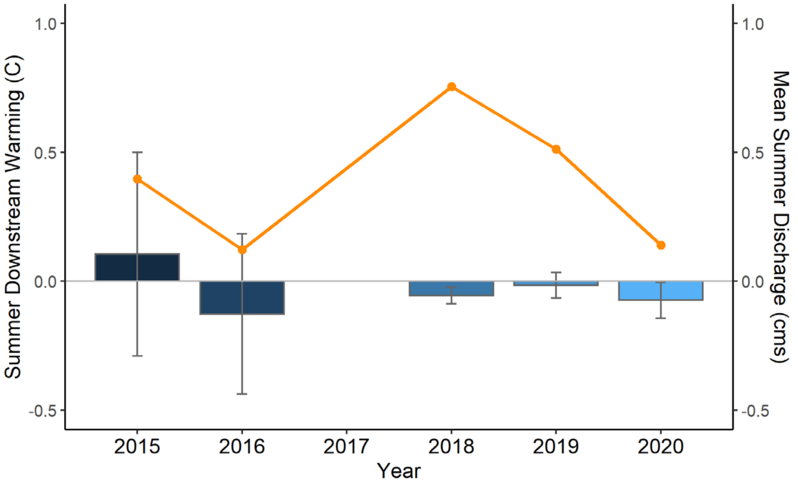


Figure A8.4) Summer (July-September) downstream warming (i.e., the difference between upstream and downstream temperatures ± SD; blue bars) and estimated mean summer discharge (orange line).

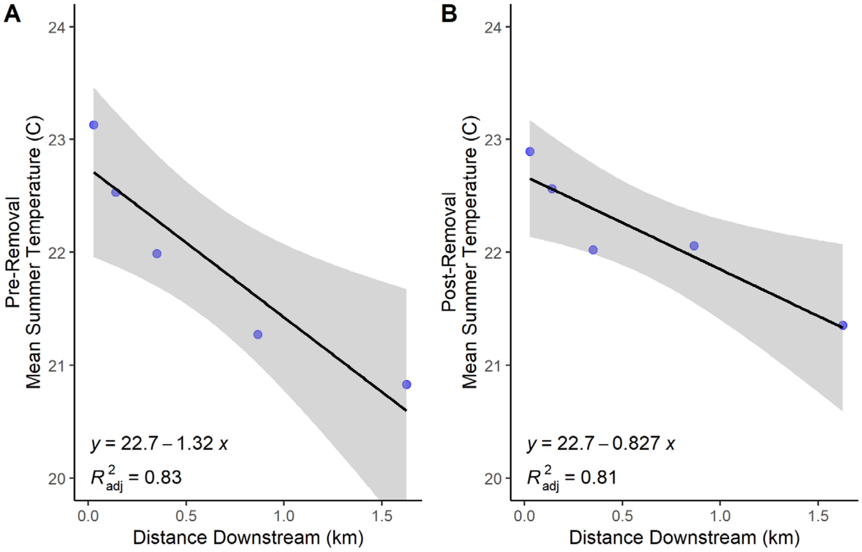


Figure A8.5) Mean summer temperature for each downstream logger (DS1-DS5) relative to the distance from the dam A) before and B) after dam removal. The black line represents the mean slope of linear temperature decay downstream of the dam and the shaded grey area represents the 95% confidence interval.

Dissolved oxygen (DO)

Prior to removal in 2017, Cotton Gin Mill Dam had small impacts on DO concentrations within the impoundment and downstream. Mean DO was similar between the impoundment (7.05 mg/L) and upstream section (7.07 mg/L), and downstream DO averaged slightly higher at 7.38 mg/L (Fig. A8.6). Daily ranges were also similar between the impoundment (3.31 mg/L) and upstream section (3.29 mg/L), but downstream ranges were slightly smaller (2.58 mg/L). There was some interannual variability in DO (Fig. A8.6), where in 2016—a year with drought conditions and high air temperature—impoundment and downstream DO concentrations were lower. Although the impoundment was technically dewatered, it still caused some pooling behind the remaining dam structure during periods of lower flow, which may have led to reduced DO. In 2016, both impoundment and upstream sections experienced over 4 hours/day of DO less than 5 mg/L (Fig. A8.8), a threshold below which waters may be considered impaired for DO (MassDEP 2016).

DO concentrations were measured the summer after dam removal in 2018. DO concentrations were consistently lower throughout all stream sections in 2018, but remained similar across sections, with only 0.24 mg/L difference between upstream and downstream sections (Fig. A8.6). Across all sections, daily ranges following removal were reduced (Fig A8.7). DO impairment (i.e., concentrations less than 5 mg/L) occurred infrequently in upstream and downstream sections (Fig. A8.8) after removal. While the removal of Cotton Gin Mill Dam did not substantially improve dissolved oxygen levels in the Satucket River on average, it may have reduced the likelihood of the river experiencing transient, but consequential, low DO during periods of low flow (e.g, 2016).

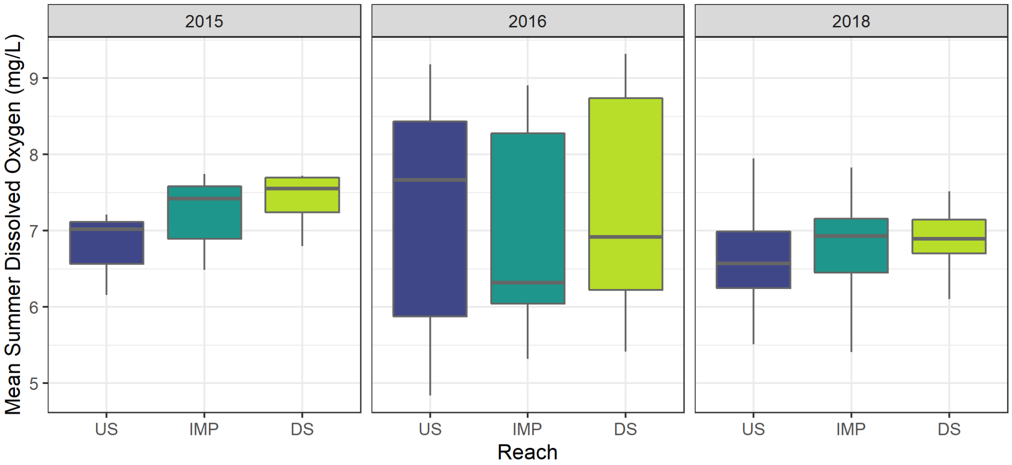


Figure A8.6) Mean summer (July-September) dissolved oxygen concentrations in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2018. Dam removal occurred in the fall of 2017.

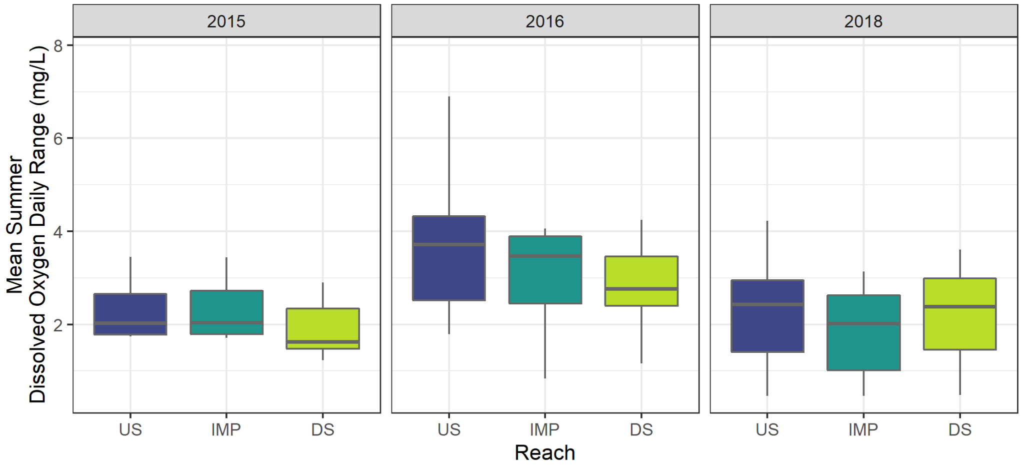


Figure A8.7) Mean summer (July-September) daily range of dissolved oxygen levels in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2018. Dam removal occurred in the fall of 2017.

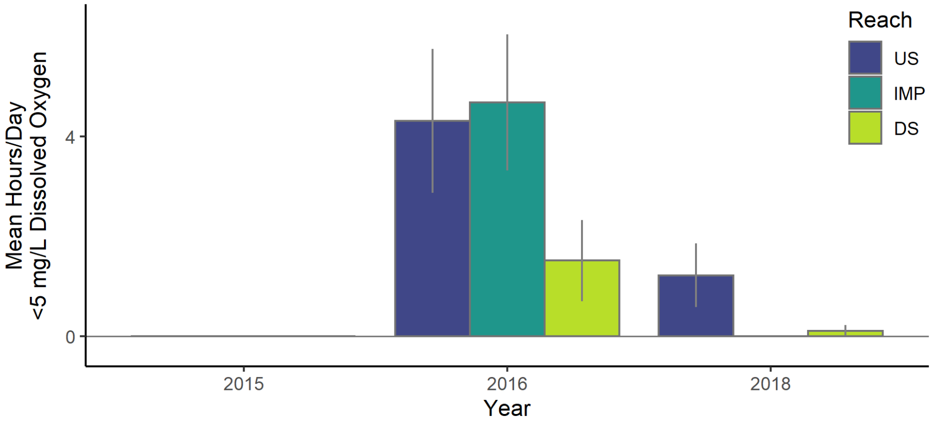


Figure A8.8) Mean and standard error (SE) hours per day that upstream (US), impoundment (IMP) and downstream (DS) stream sections spent below 5.0 mg/L, a threshold below which waters may be considered impaired for DO (MassDEP 2016).

Macroinvertebrates

Prior to dam removal, we found that some macroinvertebrate taxa traits differed among stream sections, while others did not appear to be impacted by the remaining dam structure. For example, the percent of taxa (unique organisms) classified as coldwater (thermal optimum <18 °C) were similar across all stream sections. The percent of warmwater (>20 °C) taxa was slightly higher in the downstream section (9.0 %) than the impoundment (6.7 %). In general, coolwater (18-20 °C) taxa comprised most taxa at this site. We observed a smaller percentage of sensitive taxa within the impoundments (6.6%) than both the upstream (14.9 %) and downstream (13.1 %) sections, and a greater percentage of pollution-tolerant taxa (31.2%; Fig. A8.9). The Hilsenhoff Biotic Index (HBI), which estimates the overall pollution tolerance weighted by the relative abundance of each taxa (Hilsenhoff 1988), also indicated more pollution tolerant taxa within the impoundment relative to upstream and downstream sections. The total number of taxa (taxa richness), and diversity, which incorporates both richness and abundance of taxa, were consistent across stream sections (Fig. A8.10).

Within one year after dam removal, the former impoundment exhibited a large increase in sensitive taxa, and a corresponding decrease in tolerant taxa (Fig. A8.9), which may reflect an improvement in water quality and habitat availability. The downstream section exhibited a slight decrease in the percent sensitive taxa after dam removal (Fig. A8.9). HBI scores in the former impoundment decreased to become more similar to upstream and downstream sections. Taxa richness downstream decreased slightly, and diversity in the former impoundment increased to become more similar to the upstream section (Fig. A8.10), suggesting that increasing connectivity can lead to more consistent biotic assemblages throughout a stream section. Functional traits—feeding behavior and movement habits, for example—allow us to link environmental conditions to the abundance and diversity of the different functional groups sampled. In the former impoundment, we observed an increase in taxa that feed by filtering water, like Hydropsychidae caddisflies, which may reflect increased water flow. We also observed a reduction in taxa that burrow and an increase in taxa that cling to rocks in the former impoundment after removal, reflecting the shift in habitat from stagnant to flowing water and from fine sediment and organic matter to coarser substrate (Fig. A8.11). Although this dam was not creating a true impoundment due to the removal of the low-level outlet gate, it still had the potential to alter flows and sediment transport, impacting habitat availability for macroinvertebrates. These data suggest dam removal may have reduced fragmentation and increased similarity in macroinvertebrate assemblages across this section of stream, although it may take longer (e.g., 3 years after removal) for full recovery to occur.

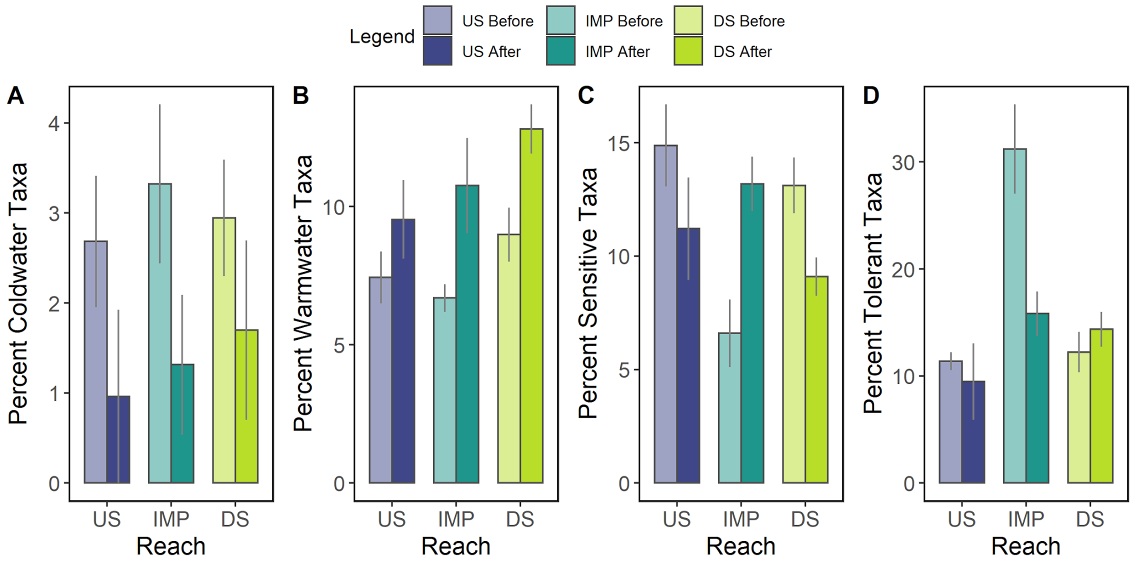


Figure A8.9) Mean percent of macroinvertebrate taxa by A) coldwater, B) warmwater, C) sensitive, and D) pollution-tolerant found within each sample in upstream (US), impoundment (IMP), and downstream (DS) stream sections before (2015-2017) and after dam removal (2018).

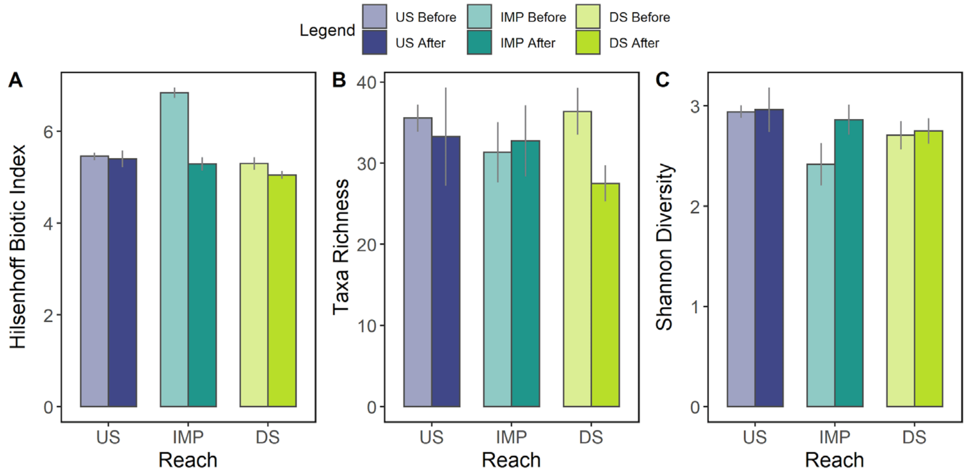


Figure A8.10) Mean macroinvertebrate biotic metric A) Hilsenhoff Biotic Index, B) total taxa richness, and C) Shannon diversity found in upstream (US), impoundment (IMP), and downstream (DS) sections before (2015-2017) and after dam removal (2018).

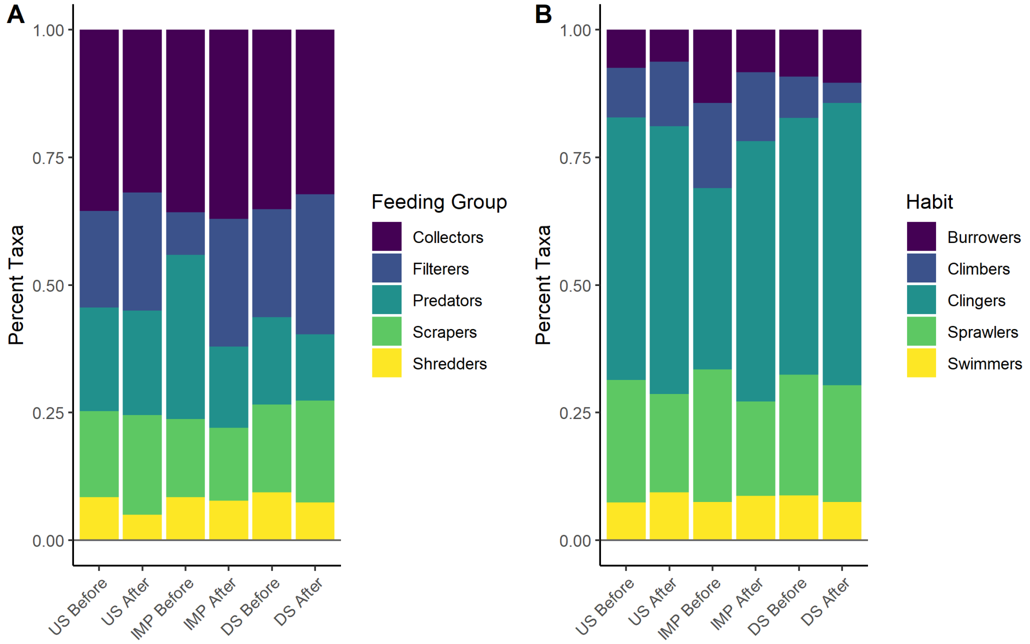


Figure A8.11) Percent of macroinvertebrate taxa by functional trait groups A) feeding group, and B) habit in upstream (US), impoundment (IMP), and downstream (DS) stream sections before (2015-2017) and after dam removal (2018). See Table A2.1 in Appendix 2 for information on feeding groups and habit categories.

Table A8.1. Averages of key ecological parameters before and after dam removal in each stream section (± 1 standard deviation).

Ecological Parameter	Upstream Before	Upstream After	Impoundment Before	Impoundment After	Downstream† Before	Downstream After
Stream Temperature (C)	23.2 ± 3.1	22.8 ± 3.4	23.4 ± 2.8	22.7 ± 3.5	23.1 ± 2.9	22.8 ± 3.3
Dissolved Oxygen (mg/L)	7.1 ± 1.3	6.6 ± 0.6	7.1 ± 1.1	6.8 ± 0.7	7.4 ± 1.2	6.8 ± 0.6
Hilsenhoff Biotic Index†† (HBI)	5.5 ± 0.3	5.4 ± 0.4	6.8 ± 0.3	5.3 ± 0.3	5.3 ± 0.5	5.0 ± 0.2

†Temperature from first downstream logger (DS1) only. ††Higher HBI indicates a greater relative abundance of pollution-tolerant macroinvertebrate taxa and suggests poorer water quality.

APPENDIX 9: Hunter's Pond Dam (HUN)

Sampling Overview

Hunter's Pond Dam, an 11.2-ft tall (3.4 m) surface-release dam forming a 1.24-acre (0.5 ha) impoundment, was removed in the summer of 2017. This structure was a head-of-tide dam that impeded fish passage up Bound Brook, which flows into The Gulf estuary in Scituate, MA. This site is located in an 11.4 mi^2 (29.5 km^2) watershed that is 73% forest cover, 3% impervious cover, and 0.6% cultivated land, with a mean elevation of 97.8 ft (29.8 m) above sea level. This site was monitored for temperature, dissolved oxygen, benthic macroinvertebrates, and fishes both before and after dam removal.

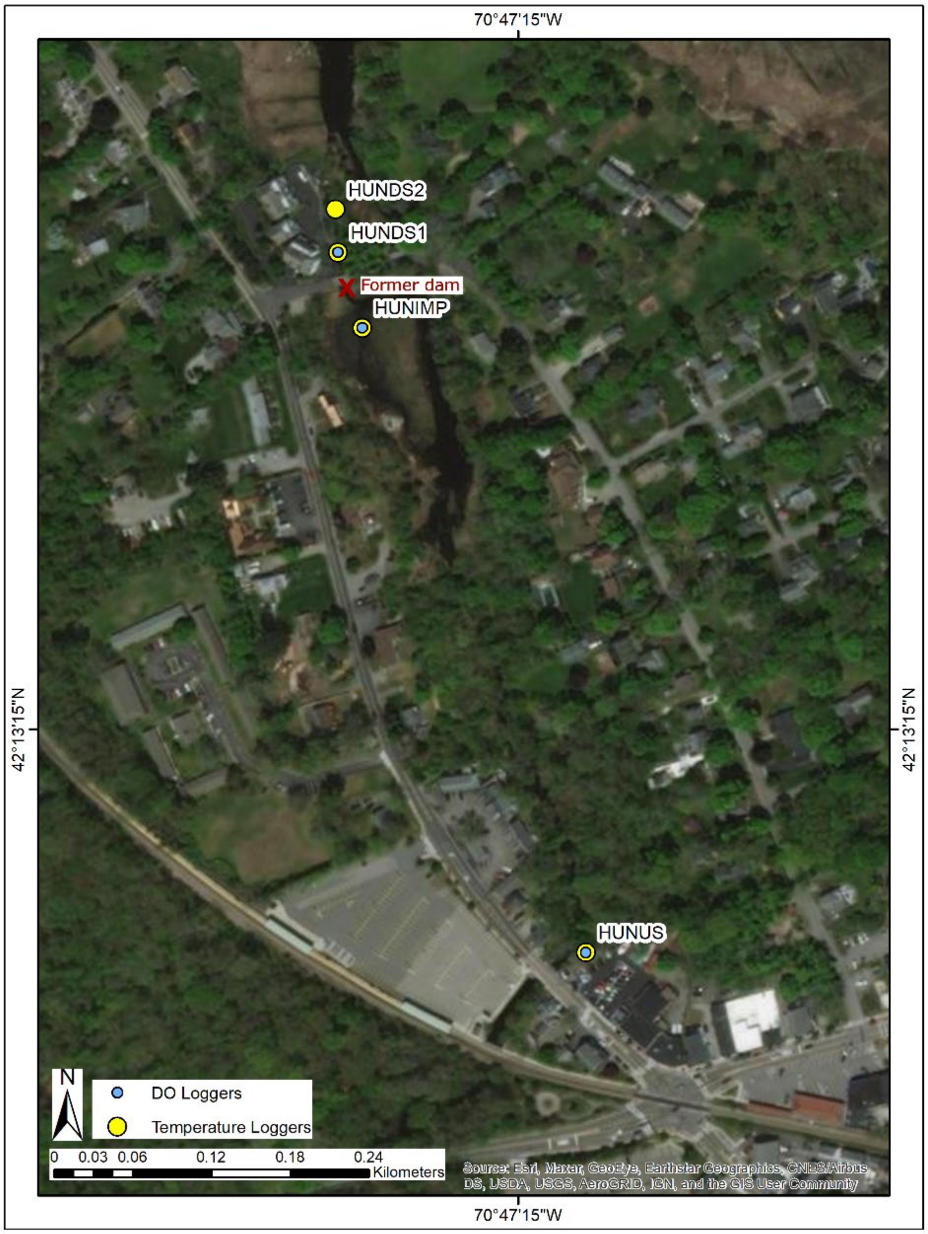


Figure A9.1. Map of temperature and dissolved oxygen logger locations in Bound Brook, Scituate, MA. Macroinvertebrates were sampled in approximately 100m sections around HUNUS, HUNIMP, and HUNDS1 loggers. See Figure 1 in Study Design section for location within Massachusetts. Esri World Imagery Basemap accessed 10/18/2022.

One temperature data logger was deployed upstream (HUNUS), one within the impoundment (HUNIMP), and 2 deployed downstream (HUNDS1-DS2) of the dam, covering 165 ft (50 m) of the river downstream to The Gulf estuary (Fig. A9.1). Temperature loggers were deployed in June 2015 and remained in the field until October 2020, capturing 2 years of pre-removal stream temperature and 4 years of post-removal stream temperature. DS2 was deployed only after removal in 2017. Dissolved oxygen (DO) loggers were deployed upstream (HUNUS), within the impoundment (HUNIMP), and downstream (HUNDS1) of Hunter's Pond Dam or former dam location (Fig. A9.1) for approximately week-long deployments during summer months (July, August, and September) from 2015-2016 and in 2018. Summer DO was monitored for 2 years before removal and 1 year after dam removal.

Macroinvertebrates were sampled once per summer from 2016 to 2019, capturing 1 year of pre-removal and up to 3 years of post-removal assemblages. Within impounded areas, 3 replicate Ponar sediment grab samples were collected from randomly selected locations, and along impoundment margins, 3 replicate sweeps of submerged and emergent vegetation were conducted using a rectangular net. In flowing stream sections (e.g., upstream, downstream, and former impoundment), 3 replicate Surber samples were taken in separate riffle habitats and a single representative multihabitat sample was collected throughout ~100 m of stream. All samples were preserved in 70% ethanol prior to sorting and identification by Cole Ecological, Inc. or a trained UMass researcher. Up to 300 individuals were identified to the lowest practical taxonomic unit (usually genus or species, referred to as "taxa").

Fish sampling was also conducted in upstream sections by MassWildlife intermittently prior to removal (1998-2017) and after removal; data summaries are provided in the General Results section of this final report. Temperature data are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Water quality data (temperature and dissolved oxygen) are also available through ScienceBase (https://doi.org/10.5066/P9L2ATHV). Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

Results

Temperature

Prior to dam removal, mean summer temperatures within the impoundment (22.4 °C) were higher than the upstream reference temperatures (20.1 °C; Fig. A9.2) and downstream temperatures were similar to the impoundment (22.3 °C). Downstream warming—the mean difference between upstream and downstream (DS1) daily temperatures—was highest during summer months (July-September), and the downstream section experienced cooling during winter months (Fig. A9.3). Summer downstream warming was on average 2.19 °C (SD =1.70), with high variability from year to year (Fig. A9.4). In 2016, a relatively dry and warm year, summer downstream warming averaged 3.6 °C, while in 2015, downstream warming averaged 0.79 °C. This suggests that Hunter's Pond Dam had a moderate to large thermal effect within the impoundment and downstream, and the impact seemed to be exacerbated by low precipitation and high air temperatures.

We observed improvements in stream temperature following the removal of Hunter's Pond Dam in 2017. In the former impoundment, temperatures were reduced from 22.4 °C to 21.5 °C (0.9 °C difference); during the same years, upstream reference temperatures averaged 20.1 °C before removal to 20.2 °C after removal (0.1 °C difference). Downstream temperatures were likewise reduced following dam removal from 22.3 °C to 21.3 °C (1.0 °C difference). Downstream warming remained highest during summer months (Fig. A9.3), but mean summer downstream warming was significantly reduced (before: 2.19 °C, after: 1.35 °C; $p < 0.001$, $t = -6.13$), indicating downstream temperatures became consistently more similar to upstream reference temperatures. Impoundment and downstream temperatures did not fully recover to meet upstream reference conditions, which may be due to the relatively open canopy of the former impoundment which can allow for greater solar radiation and warming than in the forested and shaded upstream site.

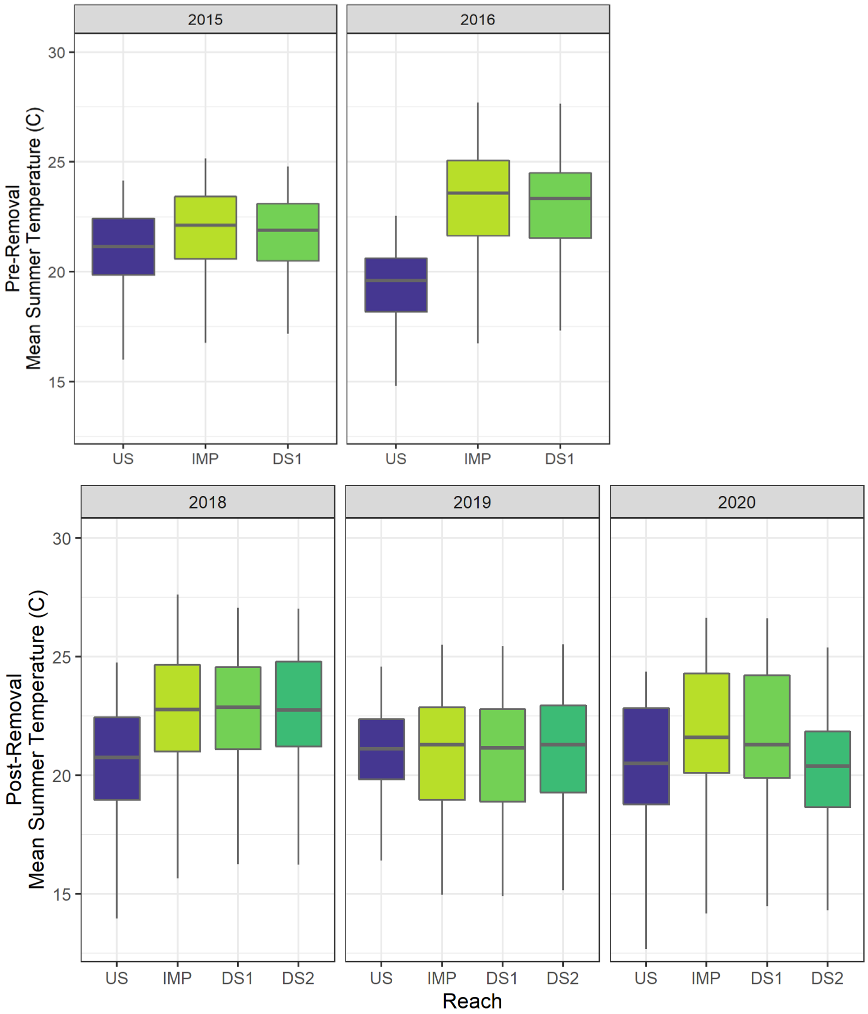


Figure A9.2) Mean summer (July-September) in-stream temperatures at each logger location A) before dam removal (2015-2016) and B) after dam removal (2018-2020). Logger locations are indicated by the following abbreviations: US = upstream, IMP = Impoundment, DS1-DS2 = Downstream 1 through Downstream 2.

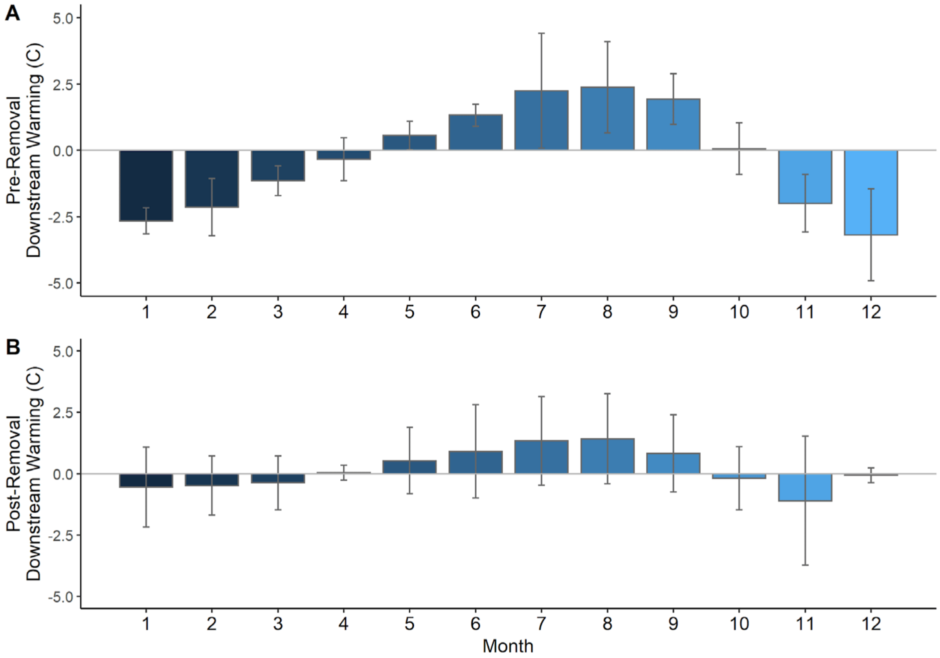


Figure A9.3) Downstream warming by month A) before (2015-2016) and B) after dam removal (2018-2021).

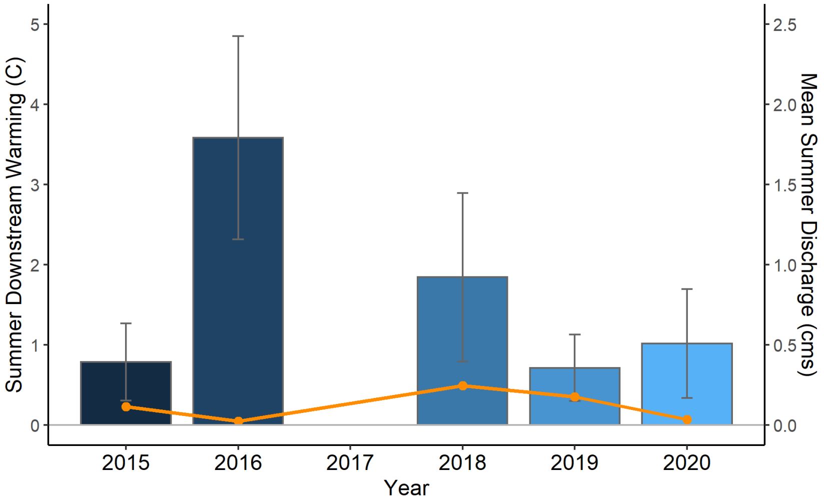


Figure A9.4) Summer (July-September) downstream warming (i.e., the difference between upstream and downstream temperatures ± SD; blue bars) and estimated mean summer discharge (orange line).

Dissolved oxygen (DO)

Prior to removal in 2017, Hunter's Pond Dam had large negative impacts on DO concentrations within the impoundment. Surface DO within the impoundment was consistently lower than either of the upstream or downstream sections (mean daily DO concentration of 1.51 mg/L; Fig. A9.5). The mean daily range within the downstream section (1.27 mg/L) was smaller than the ranges within the impoundment and upstream sections (Fig. A9.6). Prior to dam removal, the impoundment experienced long periods of time (on average 24 hours/day) of DO less than 5 mg/L (Fig. A9.7), a threshold below which waters may be considered impaired for DO (MassDEP 2016).

Following dam removal in summer 2017, DO concentrations within the former impoundment substantially increased by 5.7 mg/L, from 1.5 to 7.2 mg/L. Mean downstream DO also increased by 2.3 mg/L, while upstream DO only increased by 0.01 mg/L. Daily ranges within the former impoundment and downstream increased, likely reflecting a shift from freshwater dominant to tidally influenced. After removal, the extent of DO impairment (i.e., concentrations less than 5 mg/L) within the impoundment decreased from an average of 24 hours/day to <8 hours/day (Fig. A9.7). Overall, these results suggest dam removal improved dissolved oxygen concentrations within the impoundment and downstream and induced a more natural DO regime expected in this tidal system.

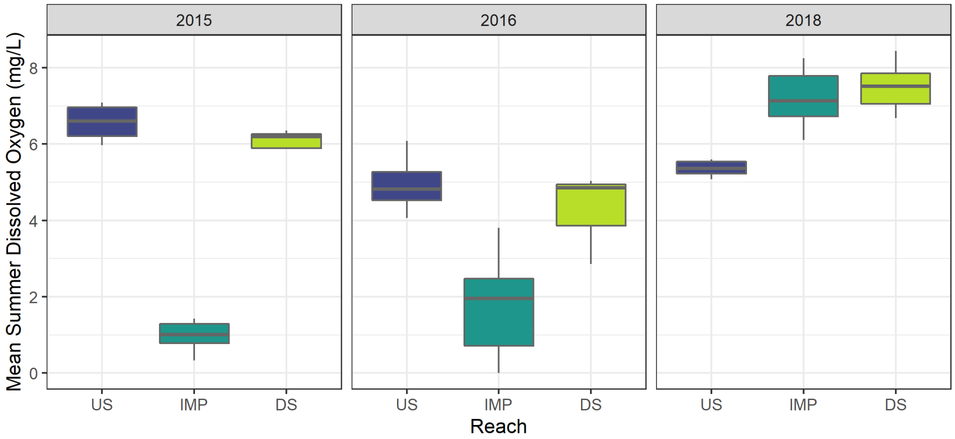


Figure A9.5) Mean summer (July-September) dissolved oxygen concentrations in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2018. Dam removal occurred in summer 2017.

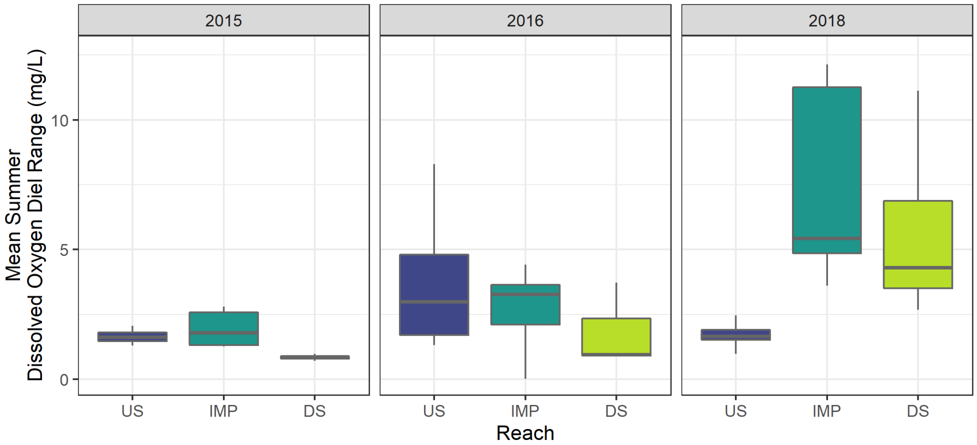


Figure A9.6) Mean summer (July-September) daily range of dissolved oxygen levels in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2018. Dam removal occurred in summer 2017.

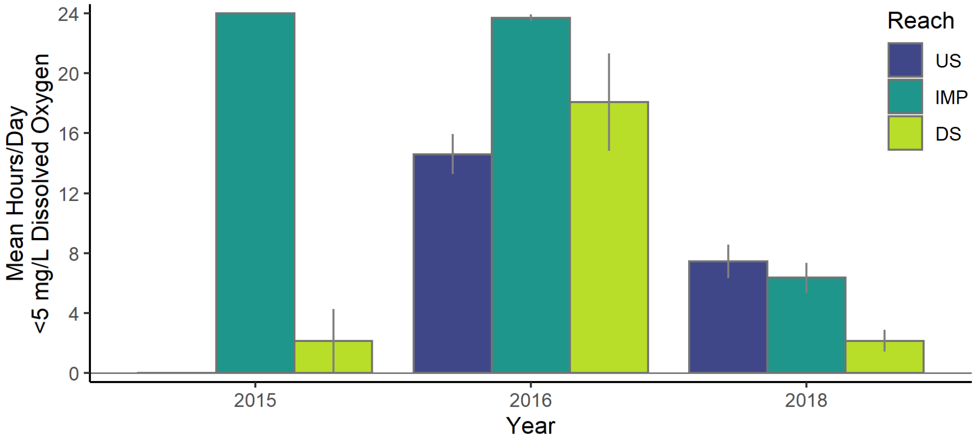


Figure A9.7) Mean and standard error (SE) hours per day that upstream (US), impoundment (IMP) and downstream (DS) stream sections spent below 5.0 mg/L, a threshold below which waters may be considered impaired for DO, prior to dam removal (MassDEP 2016).

Macroinvertebrates

Prior to dam removal, we found that macroinvertebrate taxa differed between upstream and downstream sections, as well as between flowing water and impounded sections. At this site, the downstream section was tidally influenced, and thus, macroinvertebrate assemblages may be impacted by tidal conditions in addition to dam impacts. For example, we found a much lower density of macroinvertebrates downstream of the dam (51 organisms per 0.09 m^2) as compared to the upstream section (497 organisms per 0.09 m^2). The percent of coldwater taxa (thermal optima <18 °C) was slightly higher downstream than upstream, which may be due to the small total number of taxa and coldwater-classified organisms accounting for a larger proportion of taxa. In general, coolwater (18-20 °C) taxa comprised most taxa at this site. We observed a much smaller percentage of sensitive taxa within the impoundments (0.43%) than the upstream section (8.9%) and a greater percentage of pollution-tolerant taxa (49.9%) than upstream (35.3%; Fig. A9.8). The Hilsenhoff Biotic Index (HBI), which estimates the overall pollution tolerance weighted by the relative abundance of each taxa (Hilsenhoff 1988), also indicated more pollution tolerant taxa within the impoundment relative to flowing water sections. The total number of taxa (taxa richness) was slightly lower in the downstream section compared to the upstream section and impoundment, and diversity, which incorporates both richness and abundance of taxa, followed a similar pattern. The reduced richness downstream may be reflective of estuarine waters, which can limit the presence of taxa that lack physiological adaptations to saline water and water level fluctuations.

After dam removal, the former impoundment exhibited an increase in sensitive taxa, and a corresponding decrease in tolerant taxa (Fig. A9.8), which may reflect an improvement in water quality and habitat with the shift from stagnant to flowing water. However, thermal groups (e.g., cold and warmwater taxa) remained similar after removal, with high variation. The downstream section exhibited a slight increase in the percent sensitive taxa after dam removal (Fig. A9.8). HBI scores in the former impoundment decreased to become more similar to adjacent flowing water sections. Taxa richness and diversity in both the former impoundment and downstream sections were not substantially altered after dam removal (Fig. A9.9). Functional traits—feeding behavior and movement habits, for example—allow us to link environmental conditions to the abundance and diversity of the different functional groups sampled. In the former impoundment, we observed an increase in taxa that feed by filtering water, like Hydropsychidae caddisflies, which may reflect increased water flow. We also observed a reduction in taxa that burrow and an increase in taxa that cling to rocks in the former impoundment after removal, reflecting the shift in habitat from stagnant to flowing water and from fine sediment and organic matter to coarser substrate (Fig. A9.10).

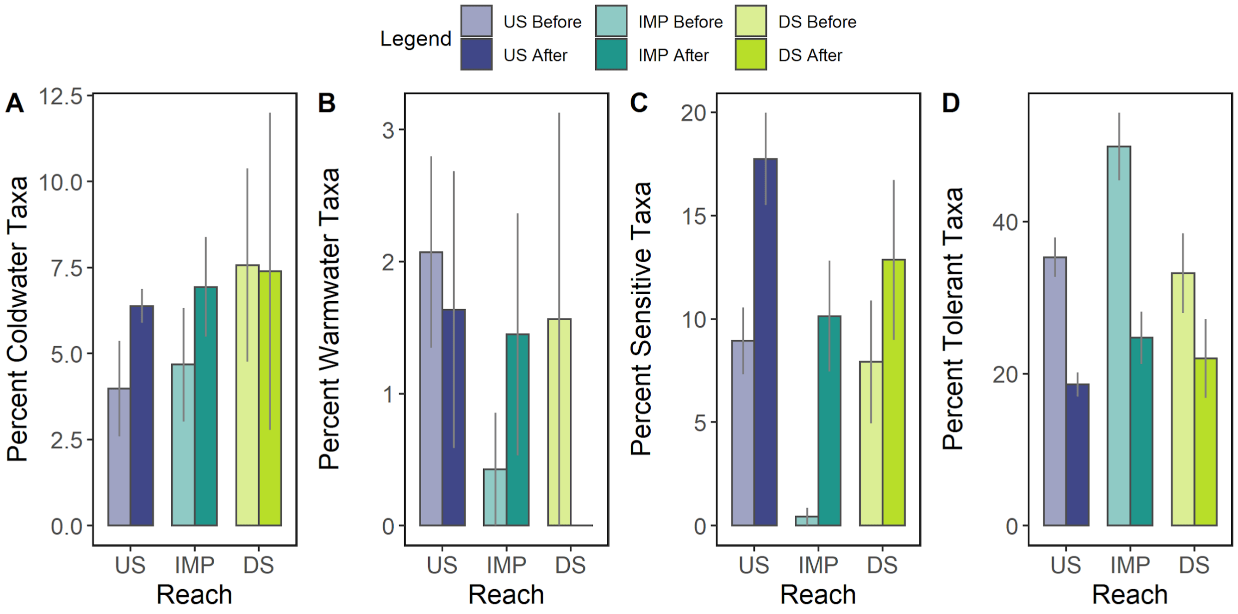


Figure A9.8) Mean percent of macroinvertebrate taxa by A) coldwater, B) warmwater, C) sensitive, and D) pollution-tolerant found within each sample in upstream (US), impoundment (IMP), and downstream (DS) stream sections before and after dam removal.

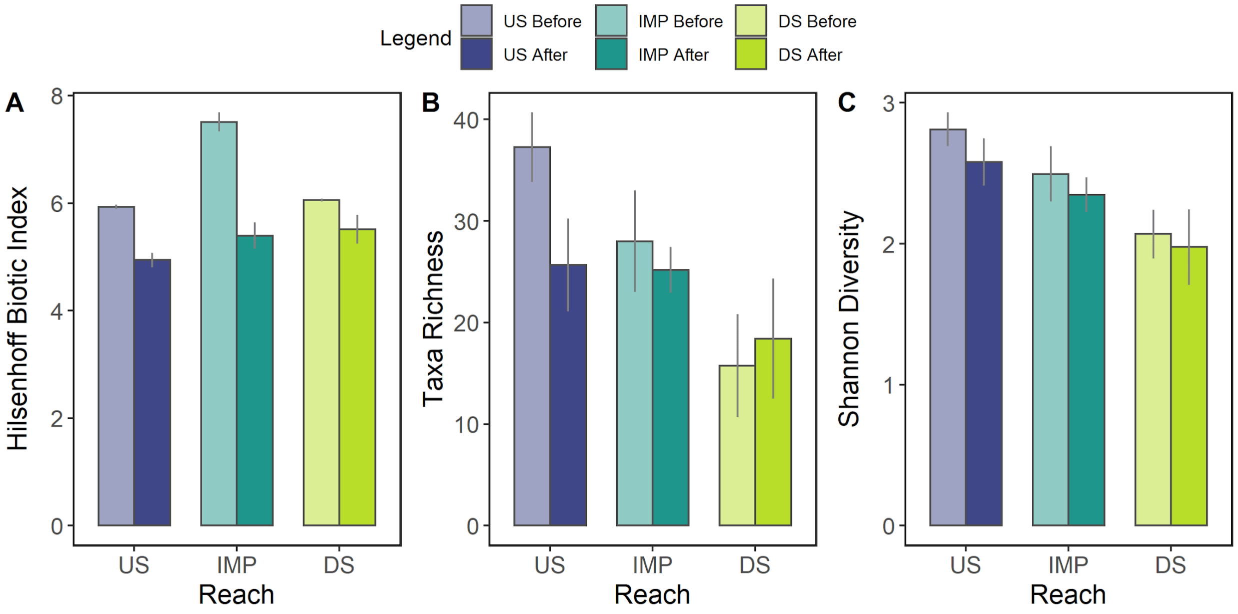


Figure A9.9) Mean macroinvertebrate biotic metric A) Hilsenhoff Biotic Index, B) total taxa richness, and C) Shannon diversity found in upstream (US), impoundment (IMP), and downstream (DS) sections before and after dam removal.

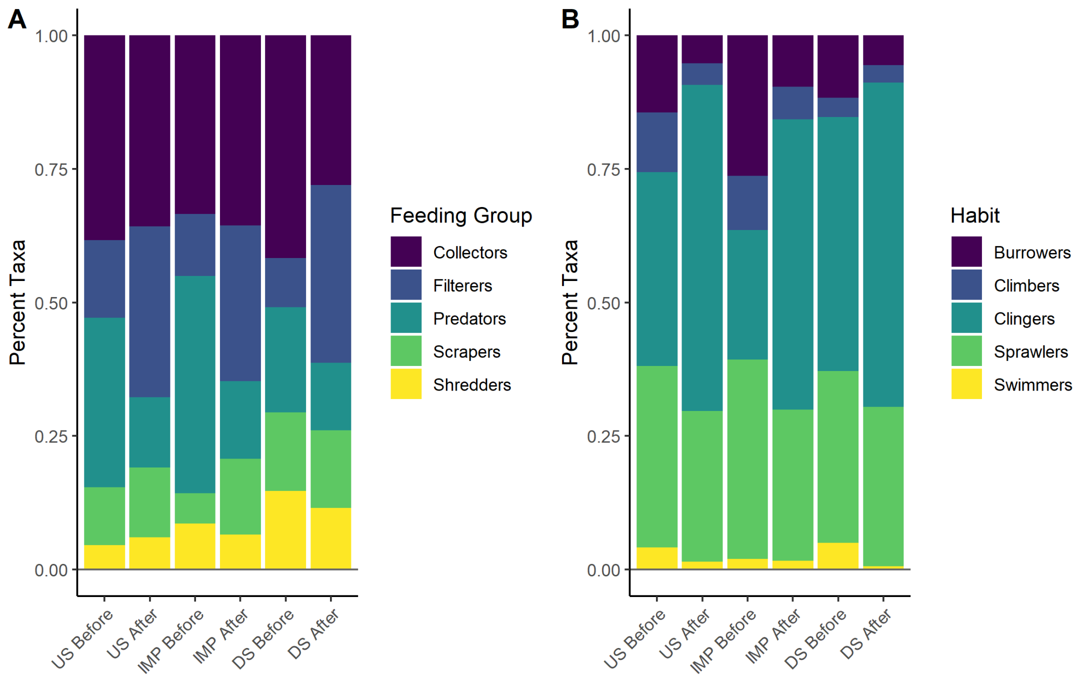


Figure A9.10) Percent of macroinvertebrate taxa by functional trait groups A) feeding group, and B) habit in upstream (US), impoundment (IMP), and downstream (DS) stream sections before and after dam removal. See Table A2.1 in Appendix 2 for information on feeding groups and habit categories.

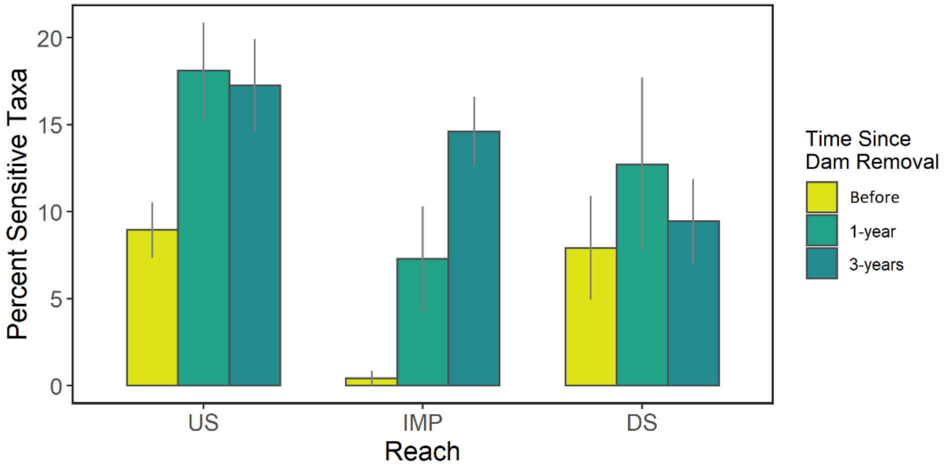


Figure A9.11) Percent of sensitive macroinvertebrate taxa in upstream (US), impoundment (IMP), and downstream (DS) stream sections before (pre) and in the years after dam removal (1 and 3 years).

Table A9.1. Averages of key ecological parameters before and after dam removal in each stream section (± 1 standard deviation).

Ecological Parameter	Upstream Before	Upstream After	Impoundment Before	Impoundment After	Downstream[†] Before	Downstream After
Stream Temperature (C)	20.1 ± 2.2	20.2 ± 2.5	22.4 ± 2.6	21.5 ± 2.8	22.3 ± 2.3	21.3 ± 2.9
Dissolved Oxygen (mg/L)	5.5 ± 1.1	5.5 ± 0.4	1.5 ± 1.1	7.2 ± 0.7	5.2 ± 1.2	7.5 ± 0.5
Hilsenhoff Biotic Index[††] (HBI)	5.9 ± 0.1	4.9 ± 0.3	7.5 ± 0.4	5.4 ± 0.5	6.1 ± 0.0	5.6 ± 0.5

[†] Temperature from first downstream logger (DS1) only. [††] Higher HBI indicates a greater relative abundance of pollution-tolerant macroinvertebrate taxa and suggests poorer water quality.

APPENDIX 10: Ipswich Mills Dam (IPS)

Sampling Overview

The Ipswich Mills Dam, located in Ipswich, MA, is a 10.5 ft tall (3.2 m) surface-release dam forming a 32.4-acre (13.1 ha) impoundment. This structure is a head-of-tide barrier encountered on the mainstem Ipswich River, downstream of the Willowdale and South Middleton (Bostik) Dams. This site is located in a 150.2 mi^2 (389 km^2) watershed that is 50% forest cover, 13% impervious cover, and 1.1% cultivated land, with a mean elevation of 99 ft (30.2 m) above sea level. This site was monitored for temperature, dissolved oxygen, benthic macroinvertebrates, and fishes to determine the ecological impacts of the dam and to provide a baseline for future assessments of dam removal responses.

One temperature data logger was deployed upstream (IPSUS), one within the impoundment (IPSIMP), and two deployed downstream (IPSDS1-IPSDS2) of the dam, covering 0.12 mi (0.2 km) downstream (Fig. A10.1). Temperature loggers were deployed in July 2015 and remained in the field until October 2020, capturing 6 years of pre-removal stream temperature. Due to the tidal influence at this site, we had issues with downstream loggers remaining submerged, and thus, data from periods where loggers were out-of-water were removed during the quality control process. Temperature loggers are currently being maintained by the Ipswich River Watershed Association. Dissolved oxygen (DO) loggers were deployed upstream (IPSUS), within the impoundment (IPSIMP), and downstream (IPSDS1) of the dam (Fig. A10.1) for approximately week-long deployments during summer months (July, August, and September) from 2015 to 2016, capturing 2 years of pre-removal DO concentrations.

Figure A10.1. Map of temperature and dissolved oxygen logger locations in the Ipswich River, Ipswich, MA. Macroinvertebrates were sampled in approximately 100m sections around IPSUS, IPSIMP, and IPSDS1 loggers. See Figure 1 in Study Design section for location within Massachusetts. Esri World Imagery Basemap accessed 10/18/2022.

Macroinvertebrates were sampled once per summer in 2015 and 2016, capturing 2 years of pre-removal assemblages. Within impounded areas in 2016, 3 replicate Ponar sediment grab samples were collected from randomly selected locations, and along impoundment margins, 3 replicate sweeps of submerged and emergent vegetation were conducted using a rectangular net. In flowing stream sections (e.g., upstream, downstream), 3 replicate Surber samples were taken in separate riffle habitats and a single representative multihabitat sample was collected throughout ~100 m of stream. All samples were preserved in 70% ethanol prior to sorting and identification by Cole Ecological, Inc. or a trained UMass researcher. Up to 300 individuals were identified to the lowest practical taxonomic unit (usually genus or species, referred to as "taxa").

Temperature data are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Water quality data (temperature and dissolved oxygen) are also available through ScienceBase (https://doi.org/10.5066/P9L2ATHV). Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

Results

Temperature

The Ipswich River near the Ipswich Mills Dam exhibited small, but consistent thermal impacts, particularly within the impoundment and in river sections closest to the dam. Across all years, summer impoundment temperatures were highest (mean: 23.5 °C), upstream temperatures were lowest (mean: 22.3 °C), and downstream sections (DS1 and DS2) averaged 23.4 °C, and 22.9 °C, respectively (Fig. A10.2). Downstream warming—the mean difference between upstream and downstream (DS1) daily temperatures—was highest during September and negligible during winter months (Fig. A10.3), though with high variability year-to-year. Summer downstream warming (July-Sept.) was on average 0.61 °C, with high variability (SD= 0.65; Fig. A10.4). High variability in downstream warming between years may be related to precipitation and ambient air temperatures. For example, during a year of lower-than-average precipitation and high summer temperatures (2016), downstream thermal impacts of the dam appear to be exacerbated. Summer stream temperatures decreased with increasing distance downstream from the dam with a slope of -2.7 °C/km (Fig. A10.5). These results suggest that the Ipswich Mills Dam has small impacts on Ipswich River stream temperature, and that dam impacts are stronger during periods of low flow and high air temperatures.

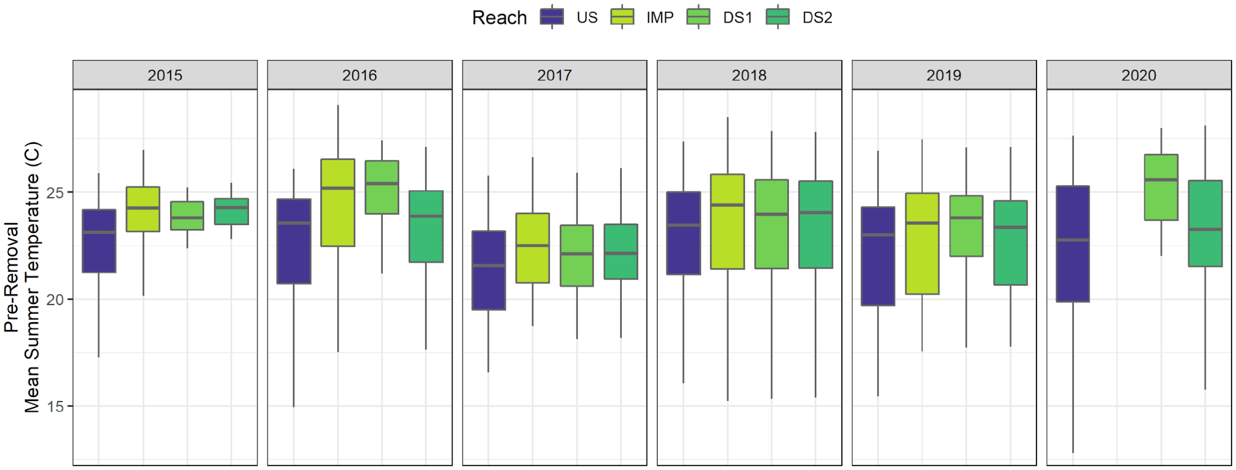


Figure A10.2) Mean summer (July-September) in-stream temperatures at each logger location during 2015-2020. Logger locations are indicated by the following abbreviations: US = upstream, IMP = Impoundment, DS1-DS2 = Downstream 1 through Downstream 2.

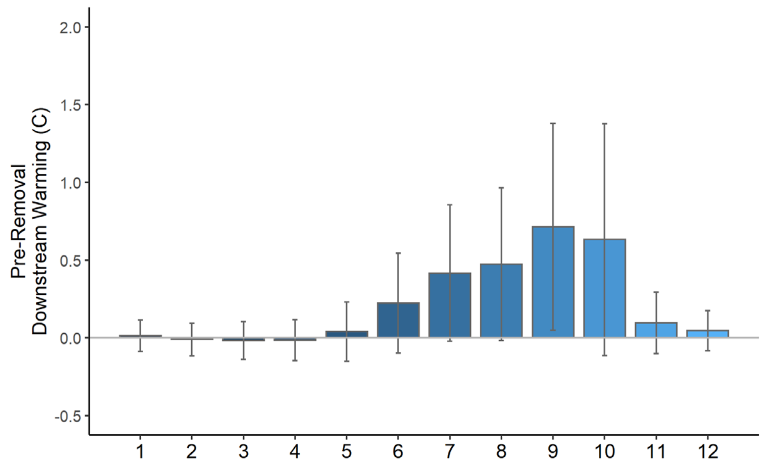


Figure A10.3) Mean downstream warming (i.e., downstream temperature minus upstream temperature) by month, across all years (2015-2020).

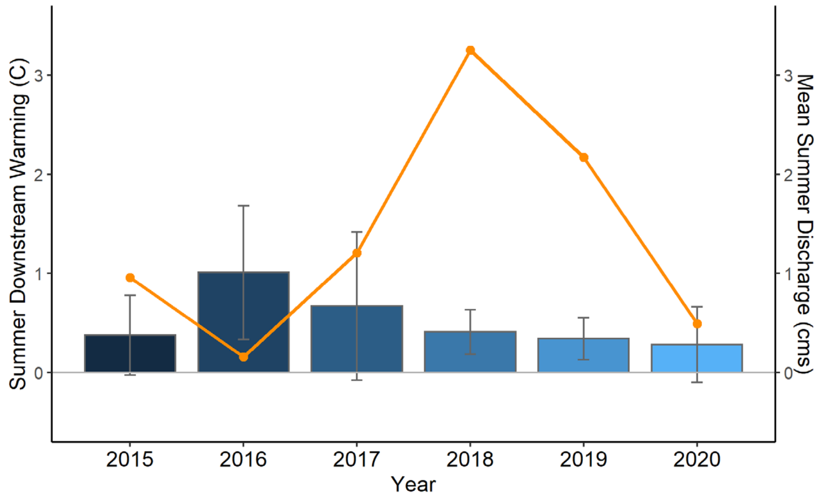


Figure A10.4) Summer (July-September) downstream warming (i.e., the difference between upstream and downstream temperatures ± SD; blue bars) and estimated mean summer discharge (orange line).

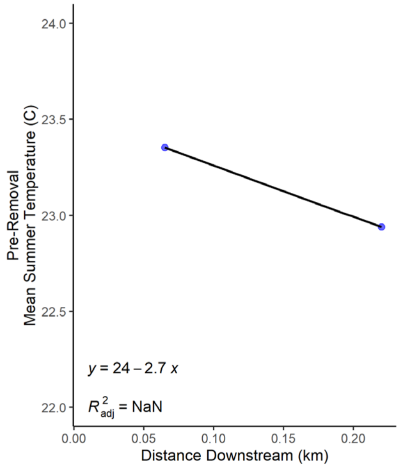


Figure A10.5) Mean summer temperature for each downstream logger (DS1-DS2) relative to the distance from the dam. The black line represents the mean slope of linear temperature decay downstream of the dam.

Dissolved oxygen (DO)

There was no difference between mean surface DO within the impoundment (6.45 mg/L) and the upstream section (6.46 mg/L), and the downstream section had, on average, slightly lower DO (5.92 mg/L; Fig. A10.6). Due to the strong tidal influence downstream of Ipswich Mills Dam, the most apparent difference in DO between stream sections was the extremely high daily range downstream (9.42 mg/L) as compared to upstream and the impoundment (2.69 and 1.82 mg/L, respectively; Fig. A10.7). Differences among stream sections were variable across years monitored (Fig. A10.6). The downstream section consistently experienced over 4 hours/day of DO less than 5 mg/L (Fig. A10.8), a threshold below which waters may be considered impaired for DO (MassDEP 2016). These results suggest that Ipswich Mills Dam has a relatively small impact on river dissolved oxygen levels within the impoundment; however, the dam is likely altering natural DO regimes by eliminating tidal variability upstream of the dam.

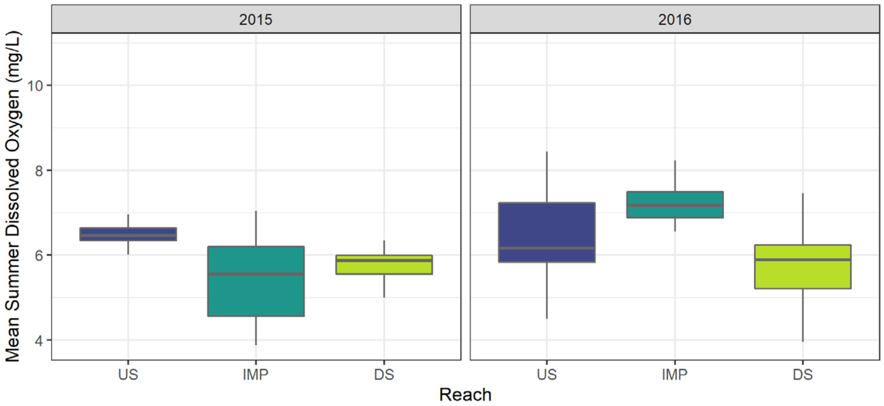


Figure A10.6) Mean summer (July-September) dissolved oxygen concentrations in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2016

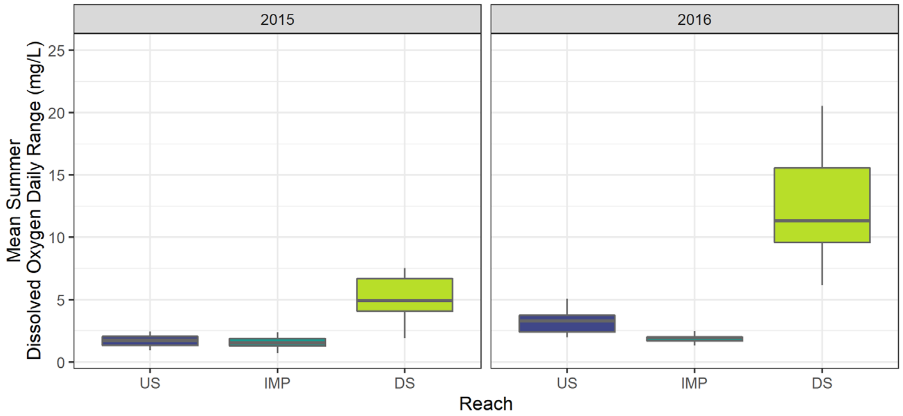


Figure A10.7) Mean summer (July-September) daily range of dissolved oxygen levels in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2016.

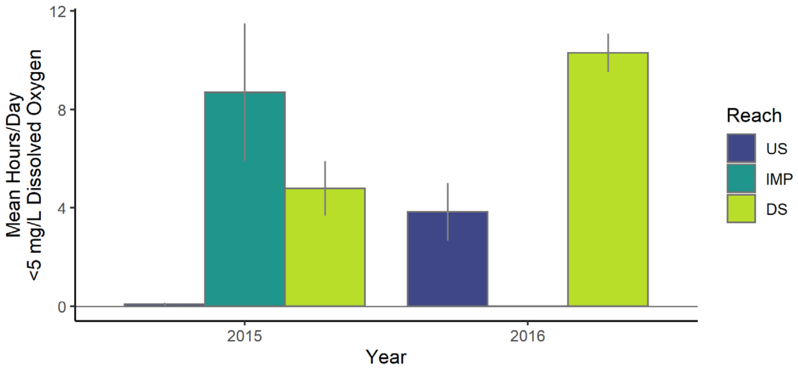


Figure A10.8) Mean and standard error (SE) hours per day that upstream (US), impoundment (IMP) and downstream (DS) stream sections spent below 5.0 mg/L, a threshold below which waters may be considered impaired for DO (MassDEP 2016).

Macroinvertebrates

At this site, we found that macroinvertebrate taxa differed between upstream and downstream sections, as well as between flowing water and impounded sections. At this site, the downstream section was tidally influenced, and thus, macroinvertebrate assemblages may be impacted by tidal conditions in addition to dam impacts. While the percent of taxa (unique organisms) classified as coldwater (thermal optimum <18 °C) were similar across stream sections, the percent of warmwater (>20 °C) taxa was lower within the impoundment and downstream as compared to upstream. In general, coolwater (18-20 °C) taxa dominated all stream sections at this site. We also observed a greater percentage of pollution-sensitive taxa within the upstream section than in the downstream and impoundment, and fewer tolerant taxa (Fig. A10.9). The most pollution-tolerant taxa were found within the impoundment (51.2 %). The Hilsenhoff Biotic Index (HBI), which estimates the overall pollution tolerance weighted by the relative abundance of each taxa (Hilsenhoff 1988), also indicated more tolerant taxa within the impoundment and downstream relative to upstream (Fig. A10.10). The total number of taxa (taxa richness) and the diversity, which incorporates both richness and abundance of taxa, were highest upstream and within the impoundment (Fig. A10.10). The reduced richness and diversity downstream may be reflective of brackish waters, which can limit the presence of taxa that lack physiological adaptations to saline water. Functional traits—feeding behavior and movement habits, for example—allow us to link environmental conditions to the abundance and diversity of the different functional groups sampled. Downstream, we observed a lower proportion of taxa that feed on other macroinvertebrates (i.e., predators), which may indicate fewer resources are available and there is a shorter trophic chain (Fig. A10.11). In the impoundment, we also found a higher percentage of taxa that burrow and a lower percentage of clingers than both flowing-water sections, reflecting the shift to stagnant waters and to finer sediment and organic matter (Fig. A711).

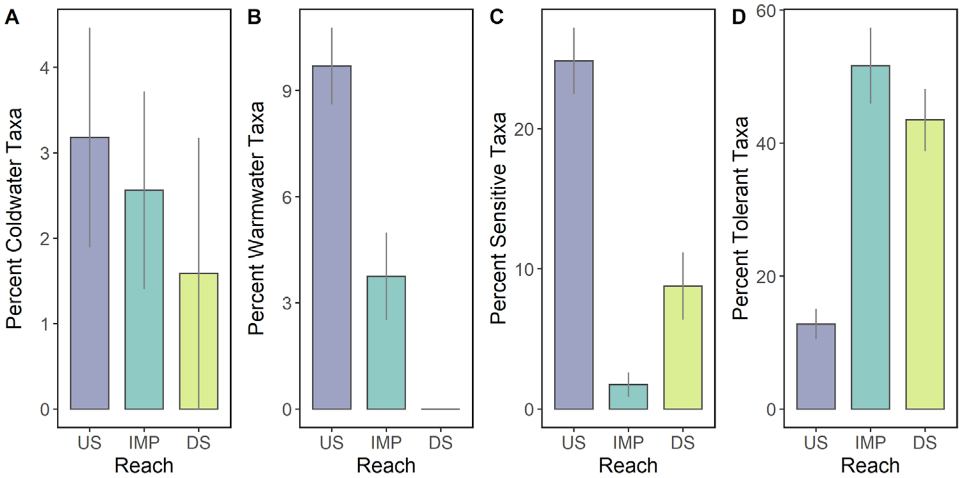


Figure A10.9) Mean percent of macroinvertebrate taxa by A) coldwater, B) warmwater, C) sensitive, and D) pollution-tolerant found within each sample in upstream (US), impoundment (IMP), and downstream (DS) stream sections.

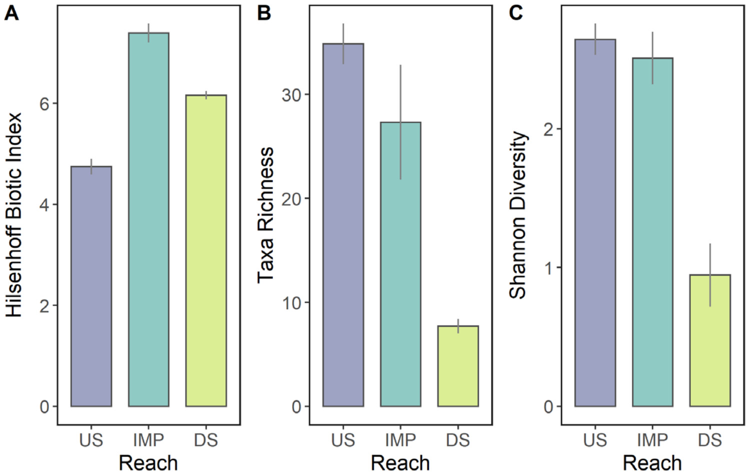


Figure A10.10) Mean macroinvertebrate biotic metric A) Hilsenhoff Biotic Index, B) total taxa richness, and C) Shannon diversity found in upstream (US), impoundment (IMP), and downstream (DS) sections.

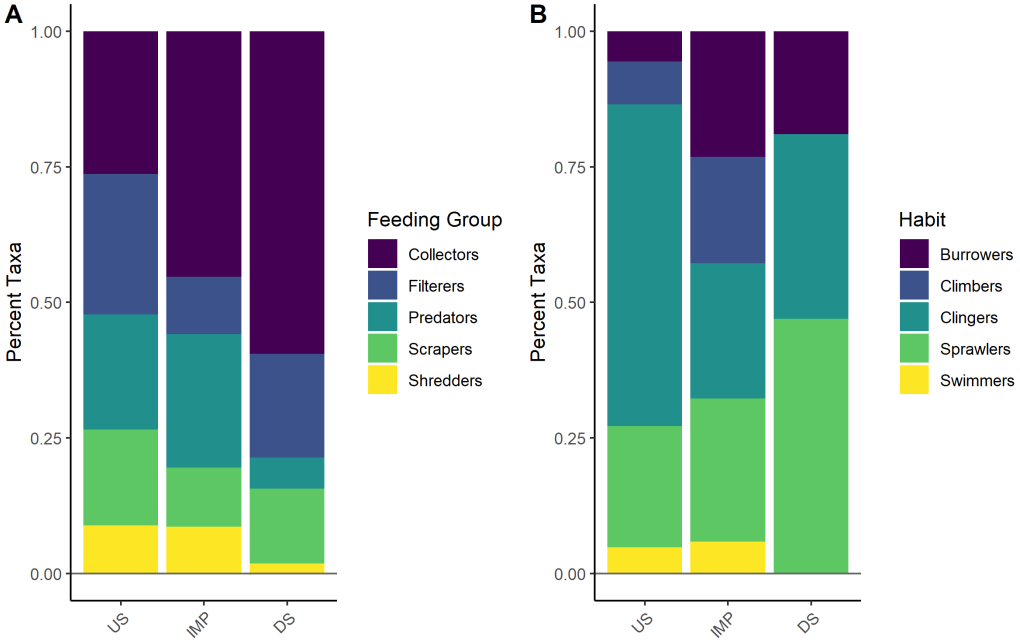


Figure A10.11) Percent of macroinvertebrate taxa by functional trait groups A) feeding group, and B) habit in upstream (US), impoundment (IMP), and downstream (DS) stream sections. See Table A2.1 in Appendix 2 for information on feeding groups and habit categories.

Table A10.1. Averages of key ecological parameters before dam removal in each stream section (± 1 standard deviation).

Ecological Parameter	**Upstream Before**	**Upstream After**	**Impoundment Before**	**Impoundment After**	**Downstream[†] Before**	**Downstream After**
Stream Temperature (C)	22.3 ± 2.9	-	23.5 ± 2.7	-	23.4 ± 2.5	-
Dissolved Oxygen (mg/L)	6.5 ± 0.8	-	6.4 ± 1.1	-	5.9 ± 1.1	-
Hilsenhoff Biotic Index[††] (HBI)	4.7 ± 0.4	-	7.4 ± 0.4	-	6.2 ± 0.2	-

[†] Temperature from first downstream logger (DS1) only. [††] Higher HBI indicates a greater relative abundance of pollution-tolerant macroinvertebrate taxa and suggests poorer water quality.

APPENDIX 11: Marland Place Dam (MAR)

Sampling Overview

Marland Place Dam, a 12.5 ft tall (3.8 m) surface-release dam forming a 5.2-acre (2.1 ha) impoundment, was removed in early 2017. This structure was the second of three remaining barriers on the Shawsheen River, which is a tributary of the Merrimack River in Andover, MA. This dam was concurrently removed with the adjacent downstream dam, the Balmoral Dam (See Appendix 3). This site is located in a 71.0 mi^2 (183.9 km^2) watershed that is 26% forest cover, 27% impervious cover, and 0.3% cultivated land, with a mean elevation of 146 ft (44.5 m) above sea level. This site was monitored for temperature, dissolved oxygen, benthic macroinvertebrates, and fishes both before and after dam removal.

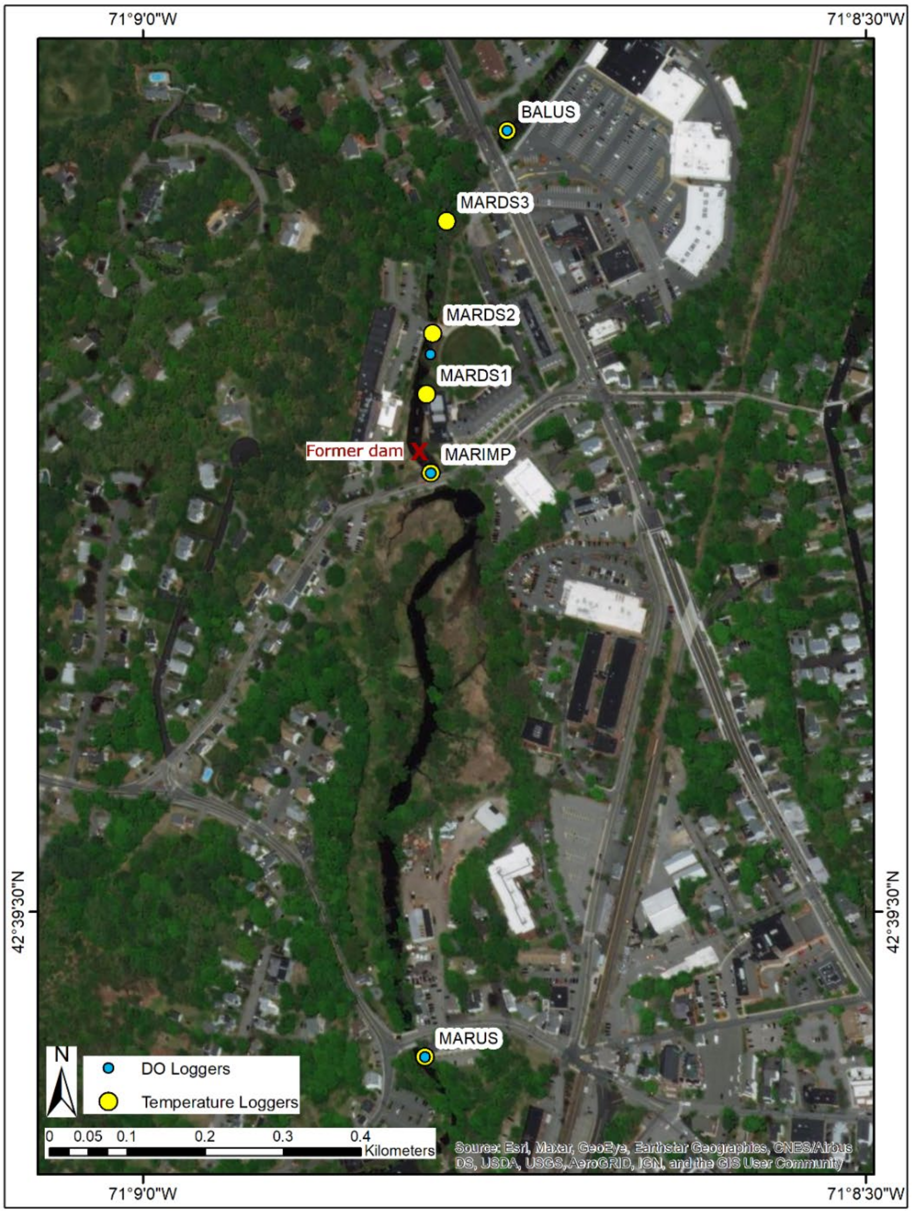


Figure A11.1. Map of temperature and dissolved oxygen logger locations in the Shawsheen River, Andover, MA. Macroinvertebrates were sampled in approximately 100m sections around MARUS, MARIMP, and MARDS1 loggers. See Figure 1 in Study Design section for location within Massachusetts. Esri World Imagery Basemap accessed 10/18/2022.

One temperature data logger was deployed upstream (MARUS), one within the impoundment (MARIMP), and four deployed downstream (MARDS1-BALUS) of the dam, covering 0.19 mi (0.31 km) of the river downstream to the upstream section of the Balmoral Dam site, where BALUS logger is also the MARDS4 logger (Fig. A11.1). Temperature loggers were deployed in July 2015 and remained in the field until October 2021, capturing 2 years of pre-removal stream temperature and 5 years of post-removal stream temperature. Dissolved oxygen (DO) loggers were deployed upstream (MARUS), within the impoundment (MARIMP), and downstream (MARDS1) of Balmoral Dam or former dam location (Fig. A11.1) for approximately week-long deployments during summer months (July, August, and September) from 2015 to 2017. Summer DO was monitored for 2 years before removal and 1 year after dam removal.

Macroinvertebrates were sampled once per summer from 2015 to 2019, and again in 2021, capturing 2 years of pre-removal and up to 5 years of post-removal assemblages. Within impounded areas, 3 replicate Ponar sediment grab samples were collected from randomly selected locations, and along impoundment margins, 3 replicate sweeps of submerged and emergent vegetation were conducted using a rectangular net. In flowing stream sections (e.g., upstream, downstream, and former impoundment), 3 replicate Surber samples were taken in separate riffle habitats and a single representative multihabitat sample was collected throughout ~100 m of stream. All samples were preserved in 70% ethanol prior to sorting and identification by Cole Ecological, Inc. or a trained UMass researcher. Up to 300 individuals were identified to the lowest practical taxonomic unit (usually genus or species, referred to as "taxa").

Fish sampling was also conducted in upstream and downstream sections by MassWildlife intermittently prior to removal (1998-2015) and after removal (2018, 2020); data summaries are provided in the General Results section of this final report. Temperature data are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Water quality data (temperature and dissolved oxygen) are also available through ScienceBase (https://doi.org/10.5066/P9L2ATHV). Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

Results

Temperature

Prior to dam removal, mean summer temperatures within the impoundment (22.9 °C) were slightly warmer than the upstream reference temperatures (22.3°C; Fig. A11.2) and downstream temperatures ranged from 22.3 °C (DS2) to 23.0 °C (DS4). Downstream warming—the mean difference between upstream and downstream (DS1) daily temperatures—was highest during September (Fig. A11.3). Summer downstream warming was on average 0.31 °C, with high variability (SD= 0.51; Fig. A11.4), suggesting a minimal effect of the dam on downstream summer temperatures. Summer stream temperatures warmed with increasing distance downstream from the dam with a slope of 2.1 °C/km (Fig. A11.5). These results suggest that Marland Place Dam had a small effect on Shawsheen River stream temperatures within the dam's impoundment and immediately downstream, and temperatures may be additionally impacted by other stressors, such as warm runoff from the abundant impervious cover (e.g., parking lots and roads) in the vicinity.

We observed a small improvement in stream temperatures following the removal of Marland Place Dam in 2017. Mean summer temperatures across all stream sections were slightly lower in the years following dam removal. In the former impoundment, temperatures were reduced from 22.9 °C to 21.9 °C (1.0 °C difference); during the same years, upstream reference temperatures averaged 22.3 °C before removal to 22.1 °C after removal (0.2 °C difference). Downstream warming was reduced in all spring and summer months, with winter months exhibiting a smaller magnitude of warming after removal (Fig. A11.3). Mean summer downstream warming reduced from 0.31 to 0.02 °C following dam removal, and variability was also reduced (before: SD= 0.51, after: SD=0.07), indicating downstream temperatures became more consistently similar to upstream reference temperatures. After removal, summer stream temperatures still warmed with increasing distance downstream, but with a reduced slope (0.43 °C/km), which suggests a more natural thermal regime (Fig. A11.5).

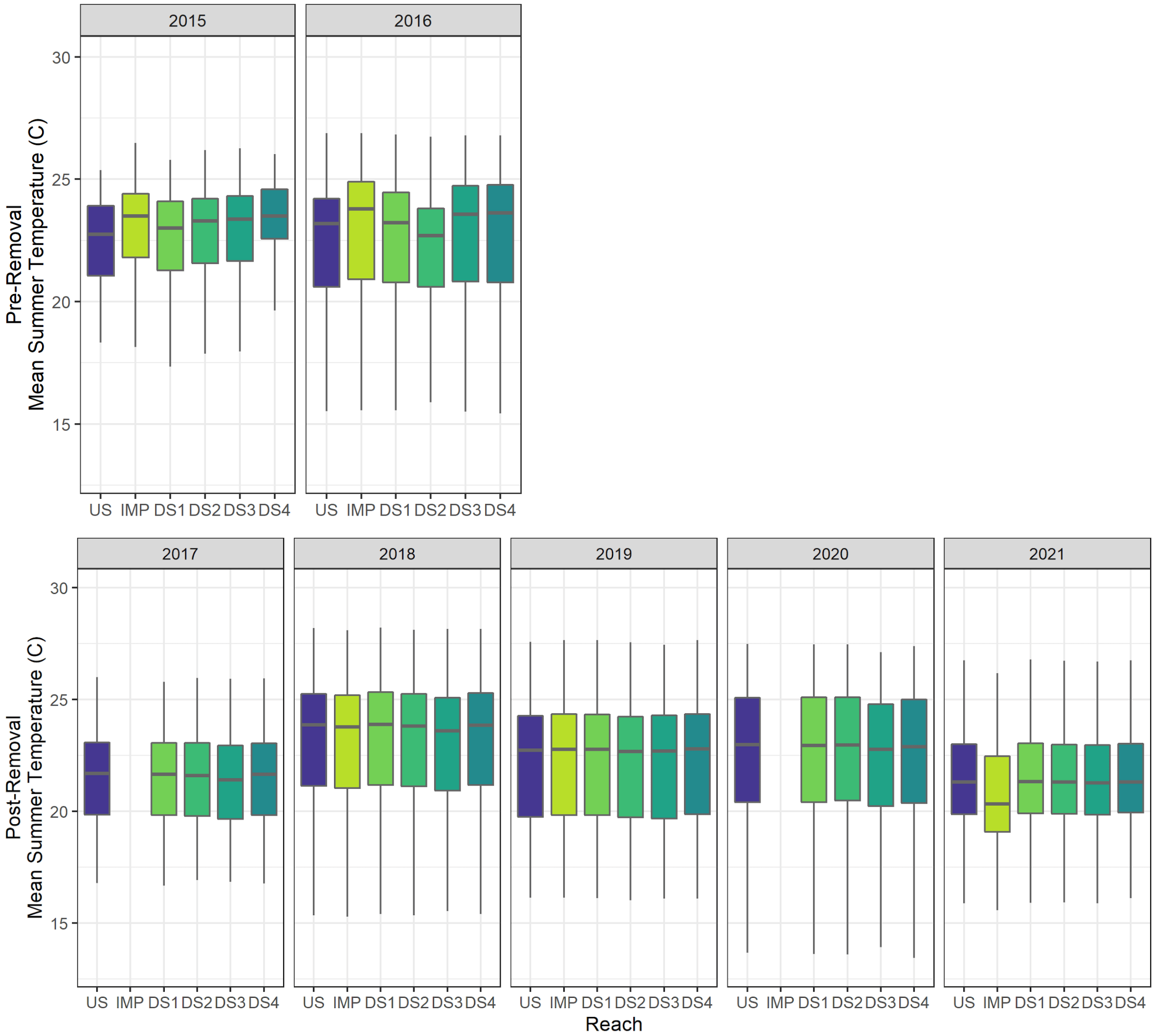


Figure A11.2) Mean summer (July-September) in-stream temperatures at each logger location A) before dam removal (2015-2016) and B) after dam removal (2017-2021). Logger locations are indicated by the following abbreviations: US = upstream, IMP = Impoundment, DS1-DS4 = Downstream 1 through Downstream 4.

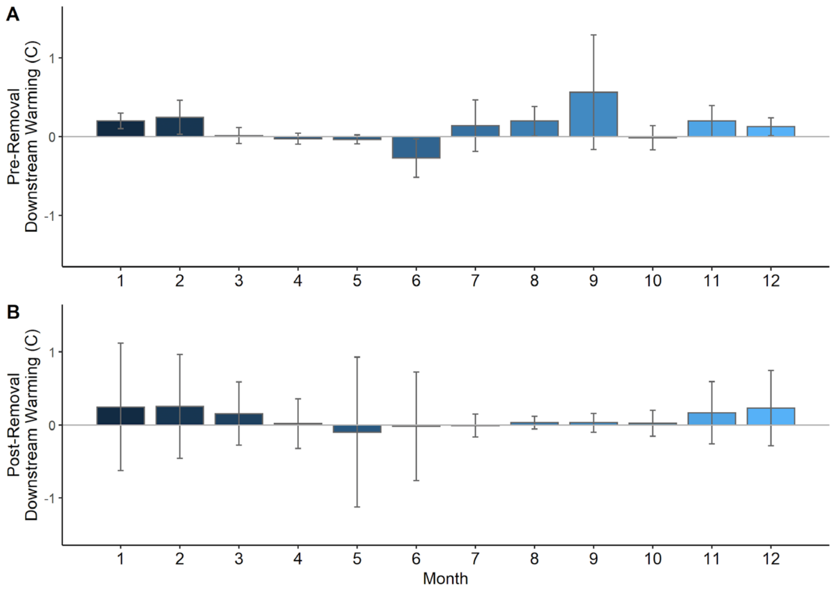


Figure A11.3) Downstream warming by month A) before (2015-2016) and B) after dam removal (2017-2021).

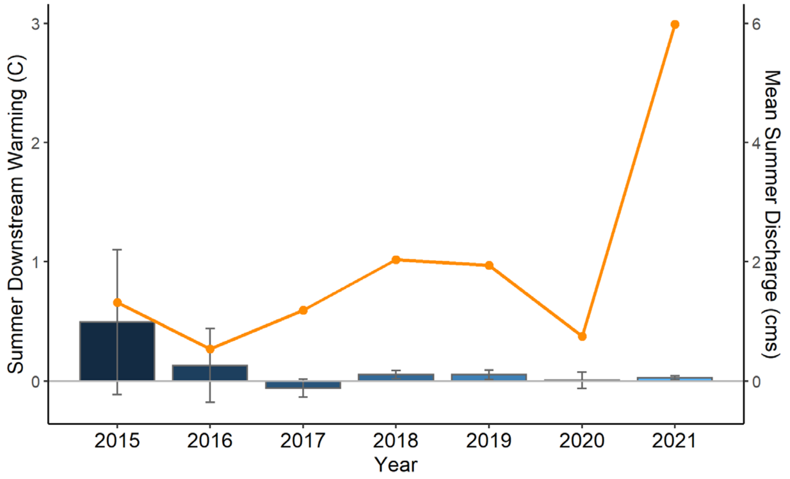


Figure A11.4) Summer (July-September) downstream warming (i.e., the difference between upstream and downstream temperatures ± SD; blue bars) and estimated mean summer discharge (orange line).

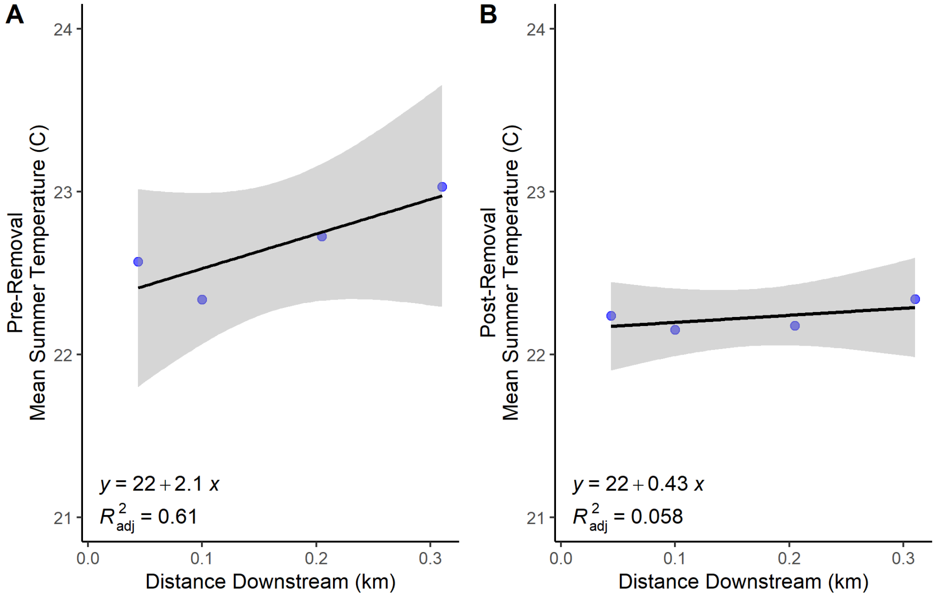


Figure A11.5) Mean summer temperature for each downstream logger (DS1-DS4) relative to the distance from the dam A) before and B) after dam removal. The black line represents the mean slope of linear temperature decay downstream of the dam and the shaded grey area represents the 95% confidence interval.

Dissolved oxygen (DO)

Prior to removal in 2017, Marland Place Dam had moderate negative impacts on DO concentrations within the impoundment and downstream. Surface DO within the impoundment was consistently lower than the upstream section (mean daily DO concentration of 7.33 mg/L; Figure A11.6), and the daily range downstream was much smaller than both the upstream and impoundment sections (mean daily range: 0.96 mg/L; Fig. A11.7), potentially influenced by consistent spilling of water over the dam. No stream sections at this site experienced periods of DO less than 5 mg/L, a threshold below which waters may be considered impaired for DO (MassDEP 2016), suggesting this section of river generally maintains good water quality with respect to DO.

Following dam removal in early 2017, DO concentrations within the former impoundment experienced a slight increase of 0.39 mg/L, from 7.33 to 7.72 mg/L, but this section did not recover to become equal to upstream concentrations. Downstream DO also increased by 0.20 mg/L, while upstream DO increased by 0.06 mg/L. Daily ranges within the former impoundment and upstream became smaller following removal, and downstream ranges increased to be more similar to the formerly impounded section, suggesting a more natural DO regime throughout this section of river. DO impairment (i.e., concentrations less than 5 mg/L) did not occur in any stream section after removal.

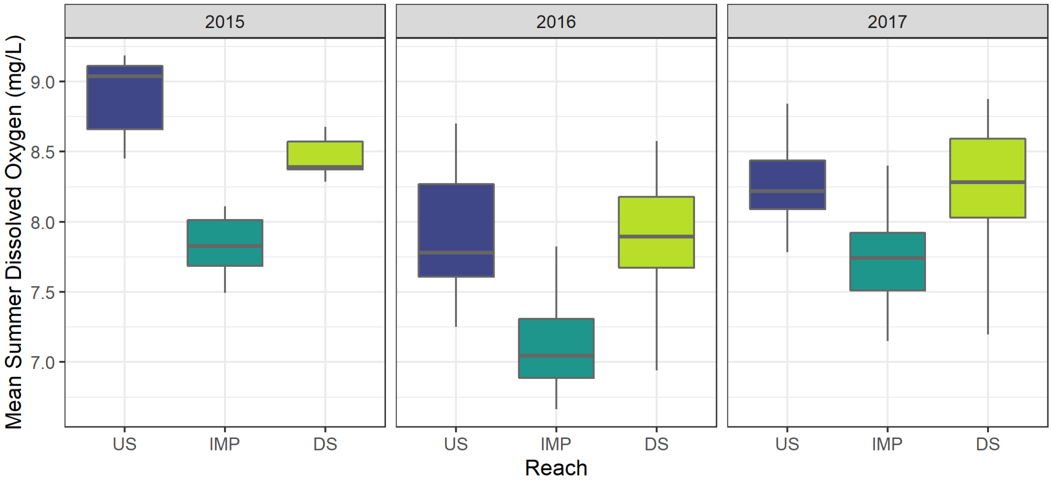


Figure A11.6) Mean summer (July-September) dissolved oxygen concentrations in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2017. Dam removal occurred in early 2017, prior to the summer deployment.

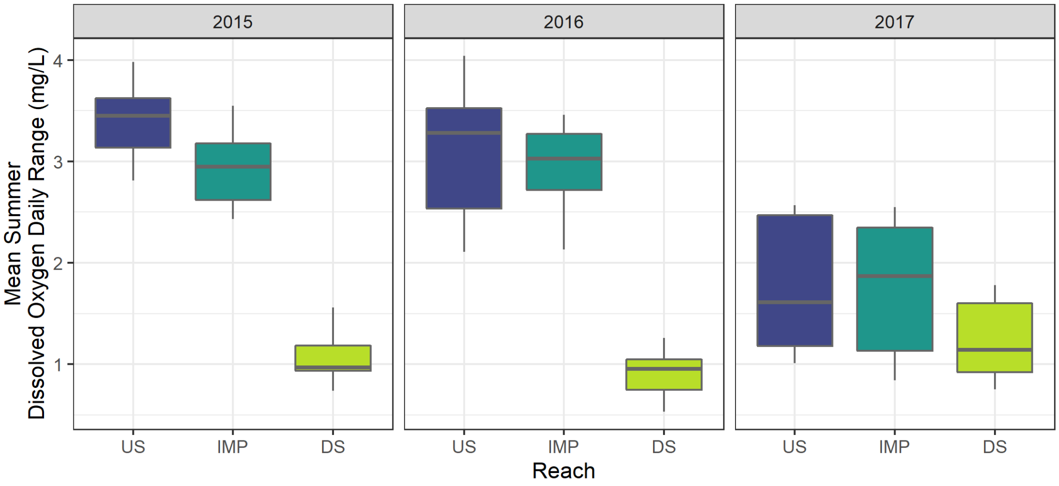


Figure A11.7) Mean summer (July-September) daily range of dissolved oxygen levels in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2017. Dam removal occurred in early 2017, prior to the summer deployment.

Macroinvertebrates

Prior to dam removal, we found that macroinvertebrate taxa differed between upstream and downstream sections, as well as between flowing water and impounded sections. For example, the percent of taxa (unique organisms) classified as coldwater (thermal optimum <18 °C) were similar in downstream and upstream reaches (3.3 %), and both had slightly more coldwater taxa than the impoundment (2.1%). The percent of warmwater (>20 °C) taxa was also higher in upstream (15.6 %) and downstream reaches (11.5%) as compared to the impoundment (2.9%). In general, coolwater (18-20 °C) and warmwater taxa equally comprised most taxa at this site. We observed a smaller percentage of sensitive taxa within the impoundments (2.3%) than the upstream section (18.0%) and a higher percentage of pollution-tolerant taxa (51.8%) than upstream (13.3%; Fig. A11.8). The Hilsenhoff Biotic Index (HBI), which estimates the overall pollution tolerance weighted by the relative abundance of each taxa (Hilsenhoff 1988), also indicated more pollution tolerant taxa within the impoundment relative to flowing water sections. The total number of taxa (taxa richness) was lower in impoundment sections compared to flowing water sections, and diversity, which incorporates both richness and abundance of taxa, was highest downstream (Fig. A11.9).

Following dam removal, the former impoundment exhibited a large increase in sensitive taxa, and a corresponding decrease in tolerant taxa (Fig. A11.8), which may reflect an improvement in water quality and habitat with the shift from stagnant to flowing water. Downstream taxa groups were not substantially altered after dam removal (Fig. A11.8). HBI scores in the former impoundment decreased to become more similar to adjacent flowing water sections. Taxa richness and diversity in both the former impoundment and downstream sections both shifted after dam removal to become more similar to the upstream section (Fig.A11.9), suggesting that reducing habitat fragmentation due to dams can lead to more consistent biotic assemblages throughout a stream section. Functional traits—feeding behavior and movement habits, for example—allow us to link environmental conditions to the abundance and diversity of the different functional groups sampled. In the former impoundment, we observed an increase in taxa that feed by filtering water, like Hydropsychidae caddisflies, which may reflect increased water flow. We also observed a reduction in taxa that burrow and an increase in taxa that cling to rocks in the former impoundment after removal, reflecting the shift in habitat from stagnant to flowing water and from fine sediment and organic matter to coarser substrate (Fig. A11.10). The percent of sensitive taxa within the impoundment and downstream recovered to be similar to upstream levels within 1 year after dam removal (Fig. 8.11), suggesting the potential for relatively quick re-colonization of pollution-sensitive organisms.

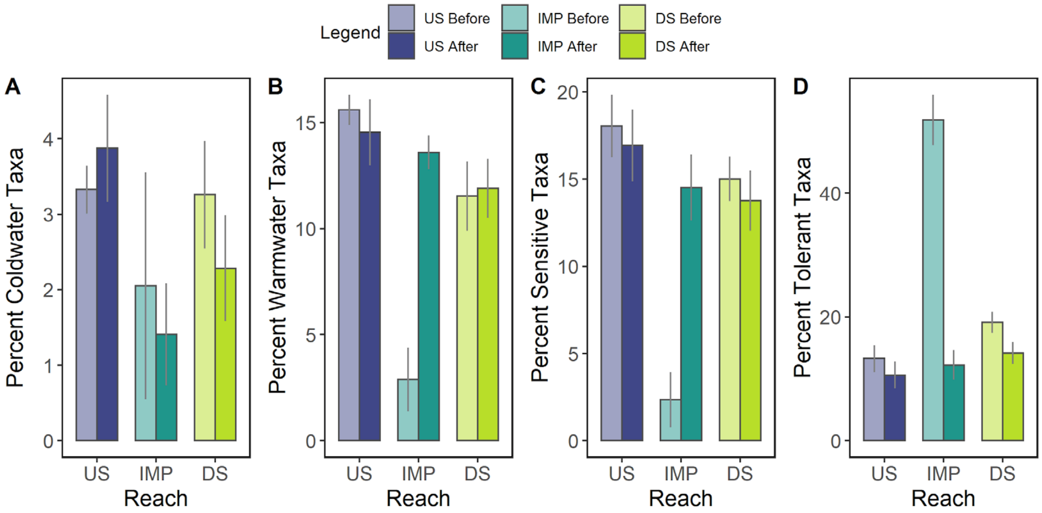


Figure A11.8) Mean percent of macroinvertebrate taxa by A) coldwater, B) warmwater, C) sensitive, and D) pollution-tolerant found within each sample in upstream (US), impoundment (IMP), and downstream (DS) stream sections before and after dam removal.

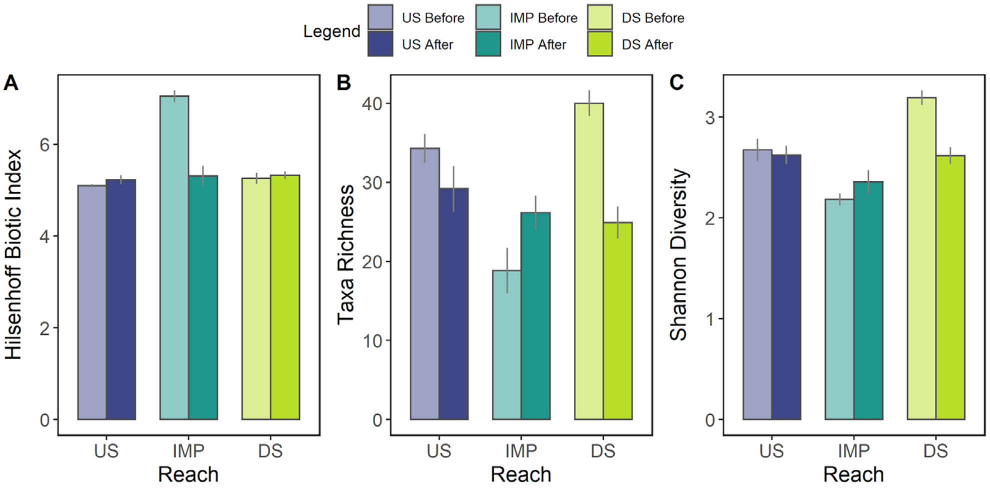


Figure A11.9) Mean macroinvertebrate biotic metric A) Hilsenhoff Biotic Index, B) total taxa richness, and C) Shannon diversity found in upstream (US), impoundment (IMP), and downstream (DS) sections before and after dam removal.

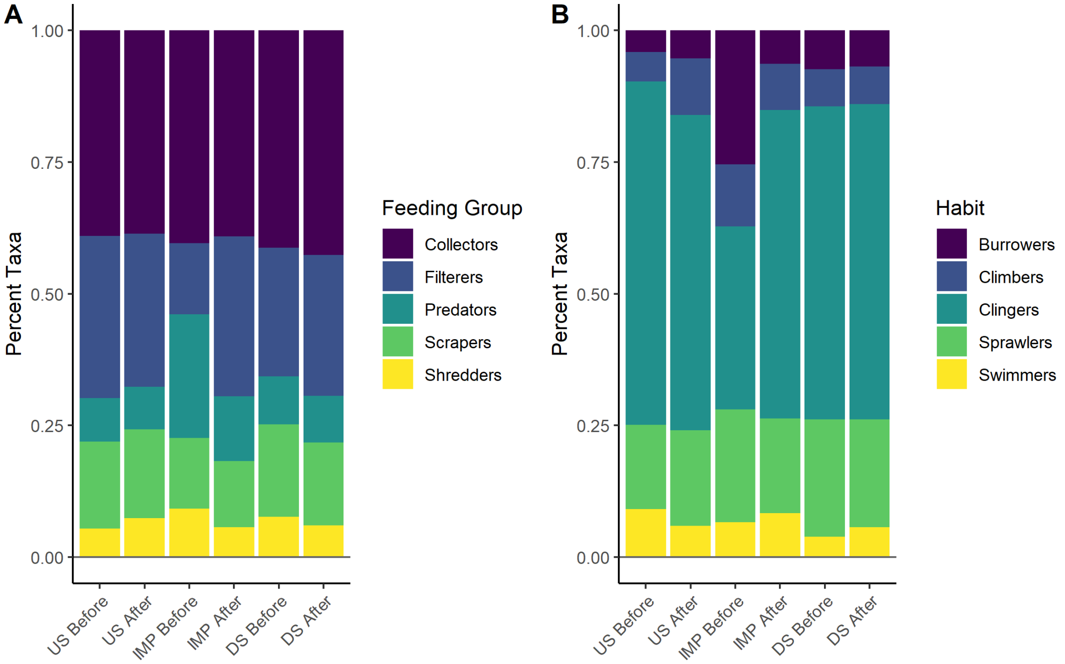


Figure A11.10) Percent of macroinvertebrate taxa by functional trait groups A) feeding group, and B) habit in upstream (US), impoundment (IMP), and downstream (DS) stream sections before and after dam removal. See Table A2.1 in Appendix 2 for information on feeding groups and habit categories.

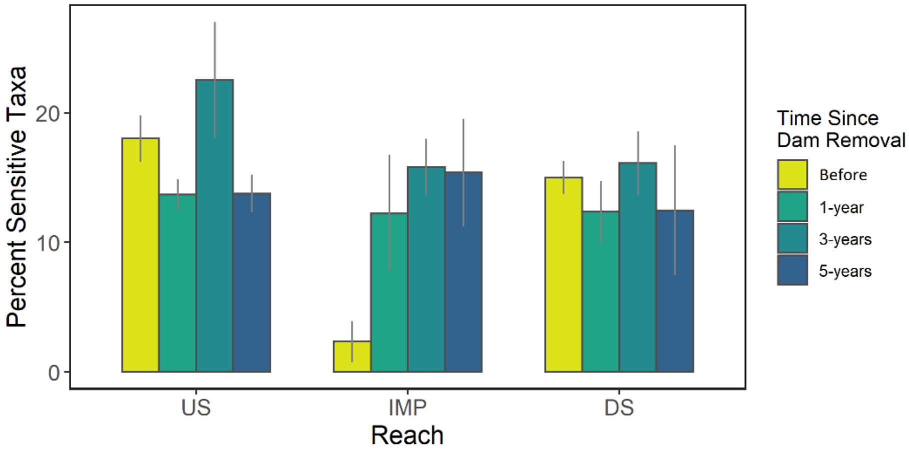


Figure A11.11) Percent of sensitive macroinvertebrate taxa in upstream (US), impoundment (IMP), and downstream (DS) stream sections before (pre) and in the years after dam removal (1, 3, and 5 years).

Table A11.1. Averages of key ecological parameters before and after dam removal in each stream section (± 1 standard deviation).

Ecological Parameter	Upstream Before	Upstream After	Impoundment Before	Impoundment After	Downstream[†] Before	Downstream After
Stream Temperature (C)	22.3 ± 2.8	22.1 ± 2.9	22.9 ± 2.6	21.9 ± 3.1	22.6 ± 2.6	22.1 ± 2.9
Dissolved Oxygen (mg/L)	8.2 ± 0.6	8.3 ± 0.4	7.3 ± 0.5	7.7 ± 0.4	8.1 ± 0.5	8.3 ± 0.5
Hilsenhoff Biotic Index[††] (HBI)	5.1 ± 0.1	5.2 ± 0.3	7.0 ± 0.3	5.3 ± 0.8	5.3 ± 0.3	5.3 ± 0.3

[†] Temperature from first downstream logger (DS1) only. [††] Higher HBI indicates a greater relative abundance of pollution-tolerant macroinvertebrate taxa and suggests poorer water quality.

APPENDIX 12: Old Mill Dam (OLD)

Sampling Overview

Old Mill Dam (Pearl Street Dam), a 13.5 ft tall (4.1 m) surface-release dam forming a 7.7-acre (3.1 ha) impoundment, was removed in late 2016. This structure, located in Bellingham, MA, was one of many barriers on the mainstem Charles River. The stream section immediately downstream of the dam location is heavily channelized and impacted by debris from an abandoned mill building. This site is located in a 25.3 mi^2 (65.5 km^2) watershed that is 46% forest cover, 21% impervious cover, and 0.01% cultivated land, with a mean elevation of 311.7 ft (95 m) above sea level. This site was monitored for temperature, dissolved oxygen, benthic macroinvertebrates, and fishes both before and after dam removal.

Figure A12.1. Map of temperature and dissolved oxygen logger locations in the Charles River, Bellingham, MA. Macroinvertebrates were sampled in approximately 100m sections around OLDUS, OLDIMP, and OLDDS1 loggers. See Figure 1 in Study Design section for location within Massachusetts. Esri World Imagery Basemap accessed 10/18/2022.

One temperature data logger was deployed upstream (OLDUS), one within the impoundment (OLDIMP), and four deployed downstream (OLDDS1-OLDDS4) of the dam, covering 0.54 mi (0.87 km) of the river downstream (Fig. A12.1). Temperature loggers were deployed in July 2015 and remained in the field until October 2021, capturing 2 years of pre-removal stream temperature and 5 years of post-removal stream temperature. Dissolved oxygen (DO) loggers were deployed upstream (OLDUS), within the impoundment (OLDIMP), and downstream (OLDDS1) of Old Mill Dam or former dam location (Fig. A12.1) for approximately week-long deployments during summer months (July, August, and September) from 2015 to 2017. Summer DO was monitored for 2 years before removal and 1 year after dam removal.

Macroinvertebrates were sampled once per summer from 2016 to 2021, capturing 1 year of pre-removal and up to 5 years of post-removal assemblages. Within impounded areas, 3 replicate Ponar sediment grab samples were collected from randomly selected locations, and along impoundment margins, 3 replicate sweeps of submerged and emergent vegetation were conducted using a rectangular net. In flowing stream sections (e.g., upstream, downstream, and former impoundment), 3 replicate Surber samples were taken in separate riffle habitats and a single representative multihabitat sample was collected throughout ~100 m of stream. All samples were preserved in 70% ethanol prior to sorting and identification by Cole Ecological, Inc. or a trained UMass researcher. Up to 300 individuals were identified to the lowest practical taxonomic unit (usually genus or species, referred to as "taxa").

Fish sampling was also conducted in upstream and downstream sections by MassWildlife intermittently before and after dam removal; data summaries are provided in the General Results section of this final report. Temperature data are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Water quality data (temperature and dissolved oxygen) are also available through ScienceBase (https://doi.org/10.5066/P9L2ATHV). Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

Results

Temperature

Prior to dam removal, mean summer temperatures within the impoundment (23.3 °C) were slightly higher than the upstream reference temperatures (22.9 °C; Fig. A12.2) and downstream temperatures decreased from 22.8 °C at DS1 to 22.4 °C at DS5. We observed a small but consistent warming pattern at the DS4 location that was indicative of beaver activity near the logger. Downstream warming—the mean difference between upstream and downstream (DS1) daily temperatures—did not occur at this site, and we actually observed slight cooling downstream in summer months (Fig. A12.3). Summer downstream temperatures were on average -0.11 °C less than upstream temperatures prior to removal, with high variability (SD= 0.33; Fig. A12.4), indicating a negligible thermal effect of the dam downstream. This may be because the section directly downstream of the dam is channelized as it runs through the remains of an abandoned mill building complex which limits solar radiation. Additionally, cooling during periods of low flows suggests a greater contribution from groundwater may be influencing temperatures downstream, likely driven in part by the hydraulic head of the dam leading to greater ground water inputs. Summer stream temperatures cooled slightly with increasing distance downstream from the dam with a slope of -0.6 °C/km (Fig. A12.5). These results suggest that Old Mill Dam had a small effect on the Charles River within the impoundment and downstream of the dam.

Following removal, it appears that the downstream groundwater contribution was reduced, potentially due to the reduction in hydraulic head, such that downstream temperatures (DS1) after removal (22.1 °C) averaged higher than upstream temperatures (21.8 °C). Across all stream sections, mean temperatures were lower following dam removal, likely due to ambient weather conditions. For example, in the former impoundment, temperatures were reduced from 23.3 °C to 22.2 °C (1.1 °C difference); during the same years, upstream reference temperatures averaged 22.9 °C before removal to 21.8 °C after removal (1.1 °C difference). This suggests that dam removal did not substantially impact impoundment temperatures. After dam removal, downstream warming increased during summer months (July-Sept), but with high variability among years (Fig. A12.3; Fig. A12.4). This may be due to the reduction of groundwater inputs downstream of the dam, and the relatively open canopy of the former impoundment. It is possible that temperatures within the former impoundment and downstream will reduce over time as riparian vegetation develops and provides more shading. After removal, summer stream temperatures decreased with increasing distance downstream, but with a lower slope (-0.19°C/km), which suggests a more natural thermal regime throughout these stream sections (Fig. A12.5). These results suggest that the Old Mill Dam removal altered the thermal regime throughout this section of river, particularly by reducing cold groundwater inputs downstream. Although downstream warming slightly increased after removal, there was a return to more consistent temperatures from the impoundment to the furthest downstream section monitored.

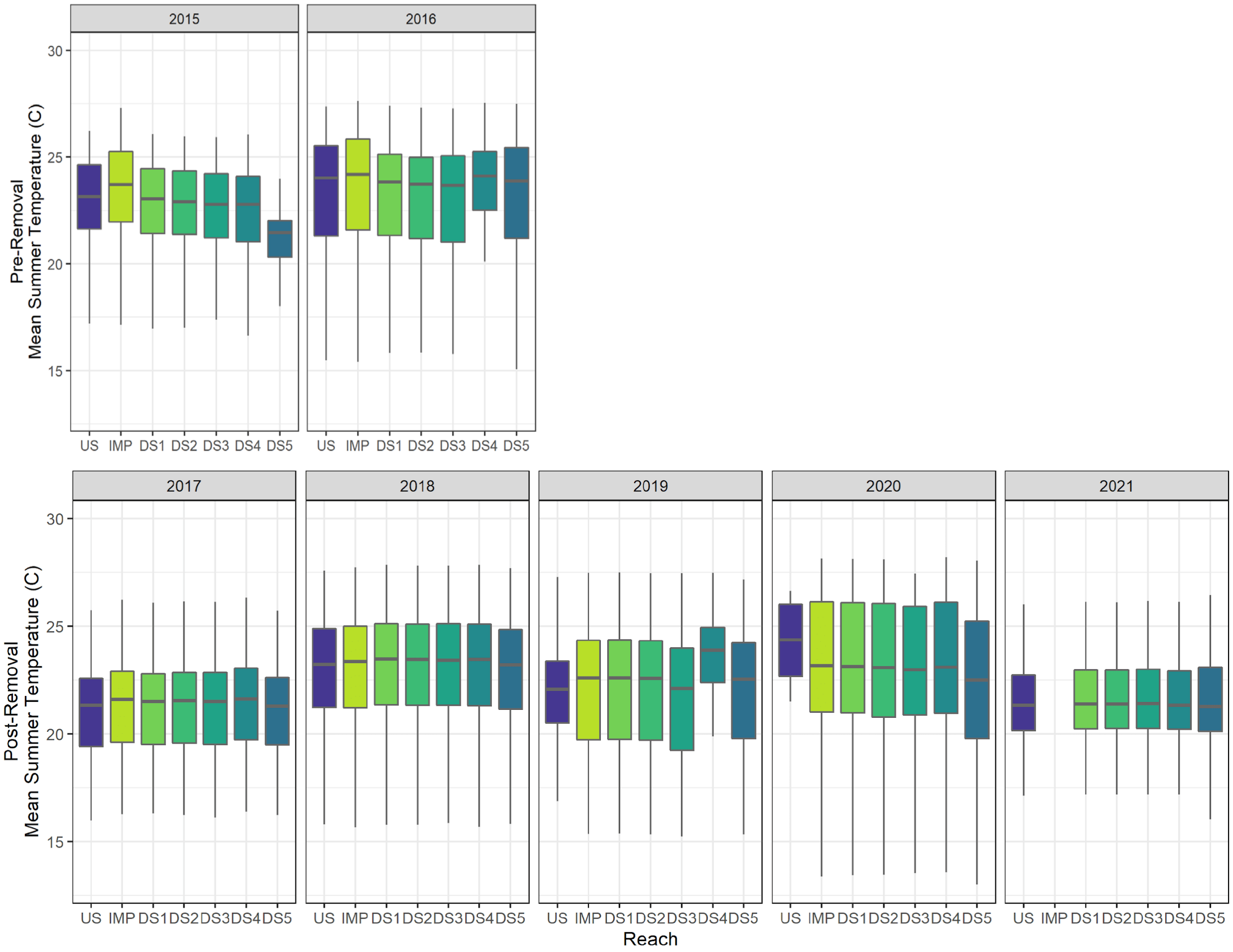


Figure A12.2) Mean summer (July-September) in-stream temperatures at each logger location A) before dam removal (2015-2016) and B) after dam removal (2017-2021). Logger locations are indicated by the following abbreviations: US = upstream, IMP = Impoundment, DS1-DS5 = Downstream 1 through Downstream 5.

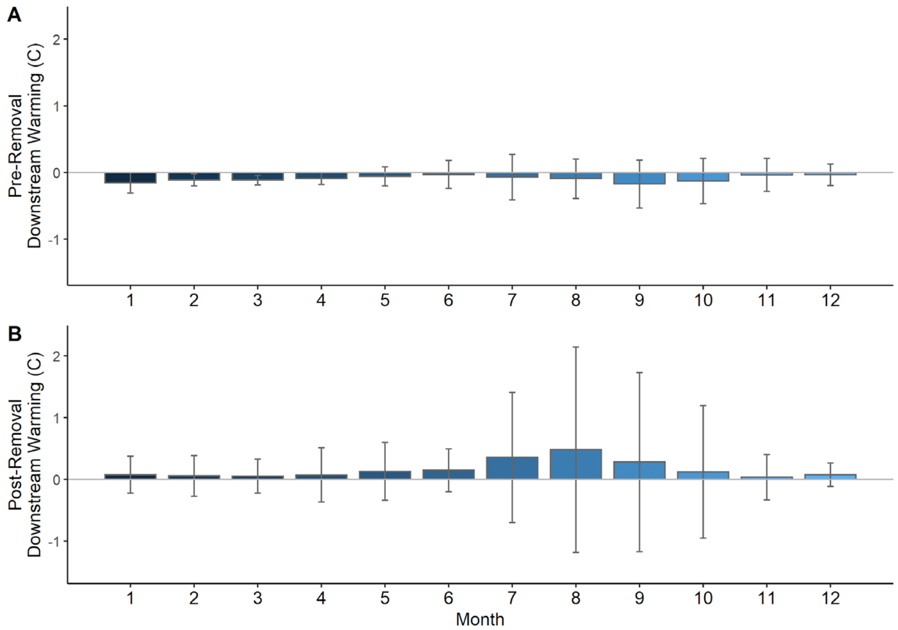


Figure A12.3) Downstream warming by month A) before (2015-2016) and B) after dam removal (2017-2021).

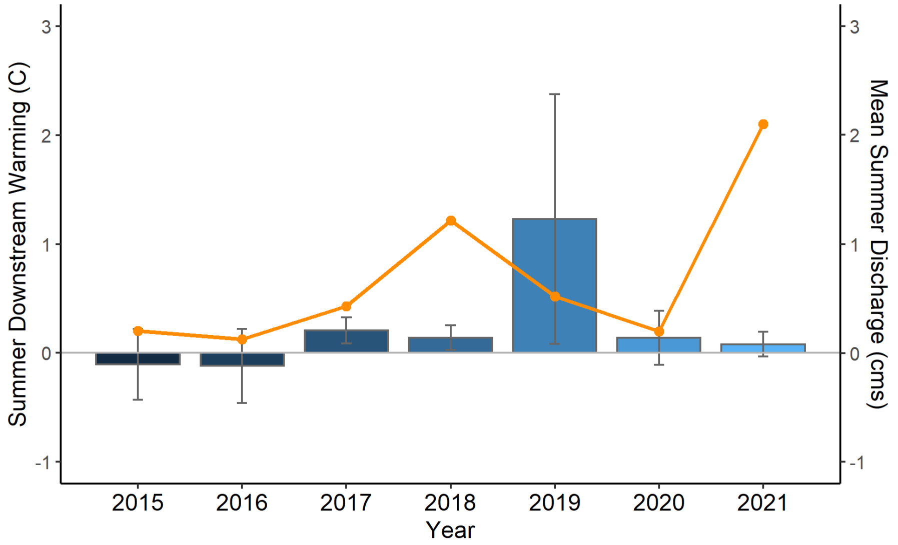


Figure A12.4) Summer (July-September) downstream warming (i.e., the difference between upstream and downstream temperatures ± SD; blue bars) and estimated mean summer discharge (orange line).

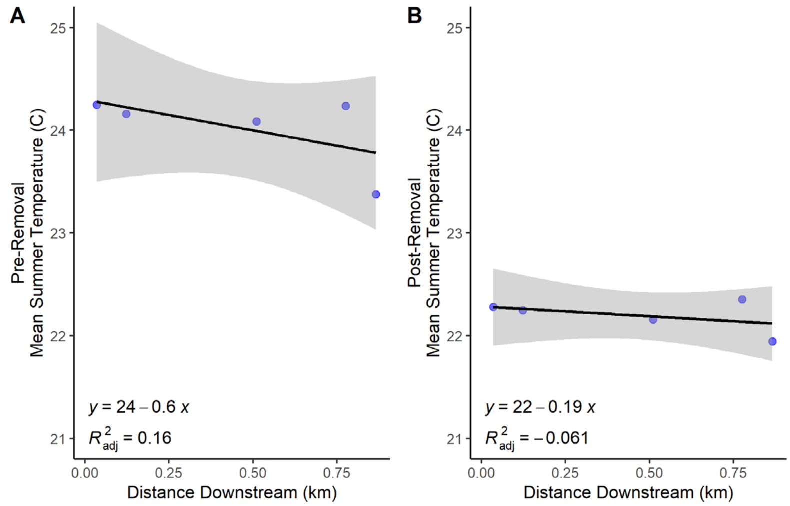


Figure A12.5) Mean summer temperature for each downstream logger (DS1-DS5) relative to the distance from the dam A) before and B) after dam removal. The black line represents the mean slope of linear temperature decay downstream of the dam and the shaded grey area represents the 95% confidence interval.

Dissolved oxygen (DO)

Prior to removal, Old Mill Dam had small negative impacts on mean surface DO within the impoundment and downstream sections (Fig. A12.6). The upstream section and impoundment had similar mean daily DO concentrations (US: 6.79 mg/L; IMP: 6.72 mg/L), although there was variation between years. The downstream section had the highest DO concentrations at an average of 8.01 mg/L, which may be related to the relatively cooler water, and turbulence due to abundant riffle habitat and water spilling from the dam. Daily ranges downstream (0.58 mg/L) were smaller than in both the upstream (1.58 mg/L) and impoundment (1.50 mg/L; Fig. A12.7). Most reaches did not experience prolonged periods of DO less than 5 mg/L (Fig. A12.8), a threshold below which waters may be considered impaired for DO (MassDEP 2016). The upstream section and impoundment experienced occasional periods of low DO only in 2016, a summer with relatively low precipitation and high air temperatures.

Following dam removal, DO concentrations within the former impoundment experienced an increase of 1.01 mg/L, from 6.72 to 7.73 mg/L on average. Mean downstream DO decreased slightly by 0.15 mg/L, while upstream DO increased by 0.13. Dissolved oxygen concentrations of the impoundment and downstream sections became more similar following dam removal. Daily ranges within the former impoundment did not change following removal, but downstream ranges increased to be more similar to the formerly impounded section, although both sections maintained slightly smaller ranges than upstream. After removal, DO impairment (i.e., concentrations less than 5 mg/L) did not occur in any stream section (Fig. A12.8).

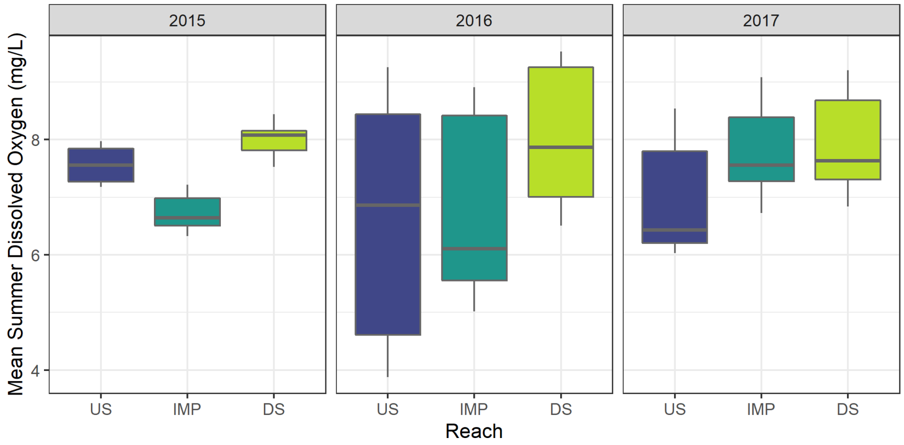


Figure A12.6) Mean summer (July-September) dissolved oxygen concentrations in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2017. Dam removal occurred in late 2016, prior to the summer deployment.

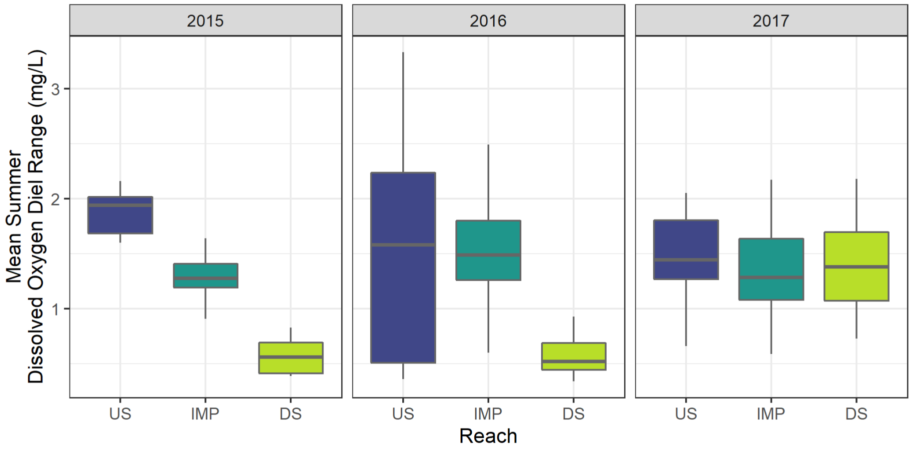


Figure A12.7) Mean summer (July-September) daily range of dissolved oxygen levels in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2017. Dam removal occurred in late 2016, prior to the summer deployment.

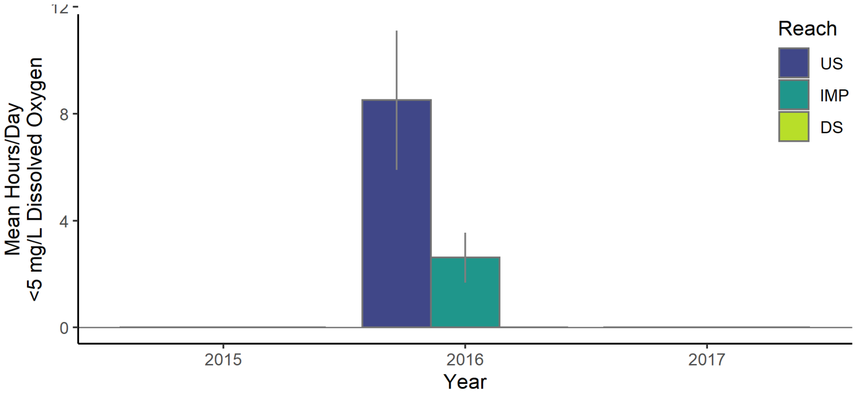


Figure A12.8) Mean and standard error (SE) hours per day that upstream (US), impoundment (IMP) and downstream (DS) stream sections spent below 5.0 mg/L, a threshold below which waters may be considered impaired for DO, prior to dam removal (MassDEP 2016). Stream sections in 2015 and 2017 did not experience any time with DO < 5 mg/L.

Macroinvertebrates

Prior to dam removal, we found that macroinvertebrate taxa differed between upstream and downstream sections, as well as between flowing water and impounded sections. For example, the percent of taxa (unique organisms) classified as coldwater (thermal optimum <18 °C) was lower downstream (2.4%) as compared to upstream (5.4%), and the percent of warmwater (>20 °C) taxa was higher upstream (6.2%) as compared to downstream (4.4%; Fig. A12.9). In general, coolwater (18-20 °C) taxa comprised most taxa at this site. We observed a much smaller percentage of sensitive taxa within the impoundments (0.3%) than the upstream section (8.9%) and a much greater percentage of pollution-tolerant taxa (35.2%) than upstream (9.5%). The Hilsenhoff Biotic Index (HBI), which estimates the overall pollution tolerance weighted by the relative abundance of each taxa (Hilsenhoff 1988), also indicated more pollution tolerant taxa within the impoundment relative to flowing water sections. The total number of taxa (taxa richness) was slightly lower in downstream sections compared to the upstream section, and diversity, which incorporates both richness and abundance of taxa, followed a similar pattern.

After dam removal, the former impoundment exhibited an increase in sensitive taxa, and a corresponding decrease in tolerant taxa (Fig. A12.9), which may reflect an improvement in water quality and habitat with the shift from stagnant to flowing water. However, thermal classes reflect a no change in coldwater taxa and an increase in warmwater taxa in the former impoundment and downstream. The downstream section also exhibited an increase in the percent sensitive taxa after dam removal (Fig. A12.9). HBI scores in the former impoundment decreased to become more similar to adjacent flowing water sections. Taxa richness and diversity in both the former impoundment and downstream sections were not substantially altered after dam removal (Fig. A12.10). Functional traits—feeding behavior and movement habits, for example—allow us to link environmental conditions to the abundance and diversity of the different functional groups sampled. In the former impoundment, we observed an increase in taxa that feed by filtering water, like Hydropsychidae caddisflies, which may reflect increased water flow and available coarser substrates. We also observed a reduction in taxa that burrow and an increase in taxa that cling to rocks in the former impoundment after removal, reflecting the shift in habitat from stagnant to flowing water and from fine sediment and organic matter to coarser substrate (Fig. A12.11). We observed increased similarity in macroinvertebrate assemblages between all stream sections after dam removal. Additionally, we observed a relatively quick recovery in impacted stream sections, with the percent of sensitive taxa within the impoundment and downstream recovering to be similar to upstream within 1 year after removal (Fig. A12.12).

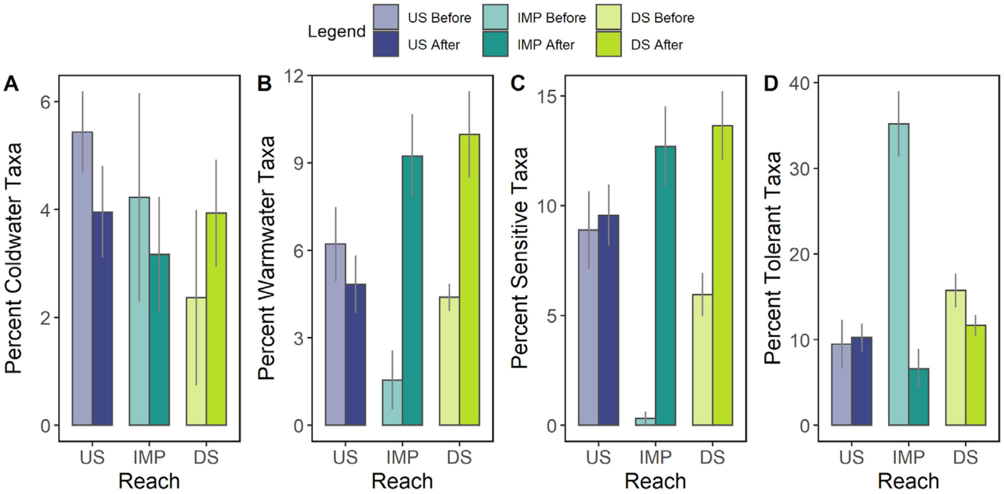


Figure A12.9) Mean percent of macroinvertebrate taxa by A) coldwater, B) warmwater, C) sensitive, and D) pollution-tolerant found within each sample in upstream (US), impoundment (IMP), and downstream (DS) stream sections before and after dam removal.

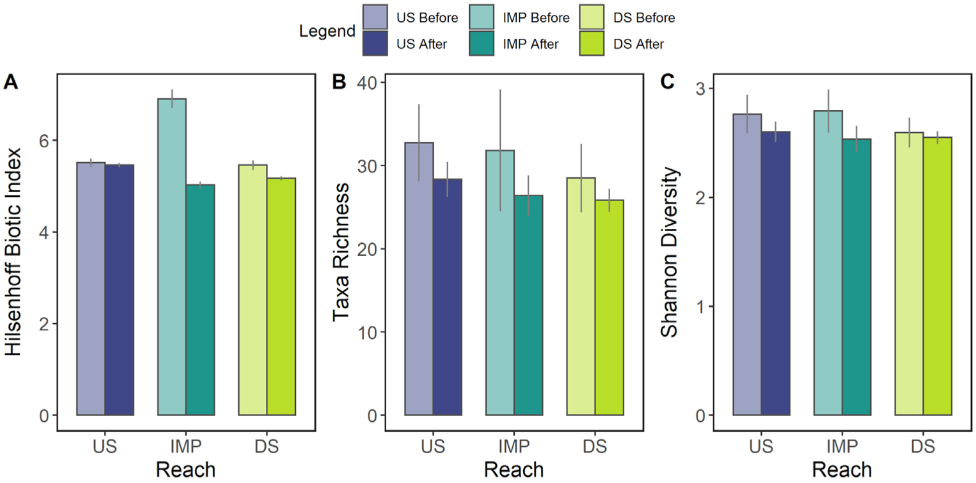


Figure A12.10) Mean macroinvertebrate biotic metric A) Hilsenhoff Biotic Index, B) total taxa richness, and C) Shannon diversity found in upstream (US), impoundment (IMP), and downstream (DS) sections before and after dam removal.

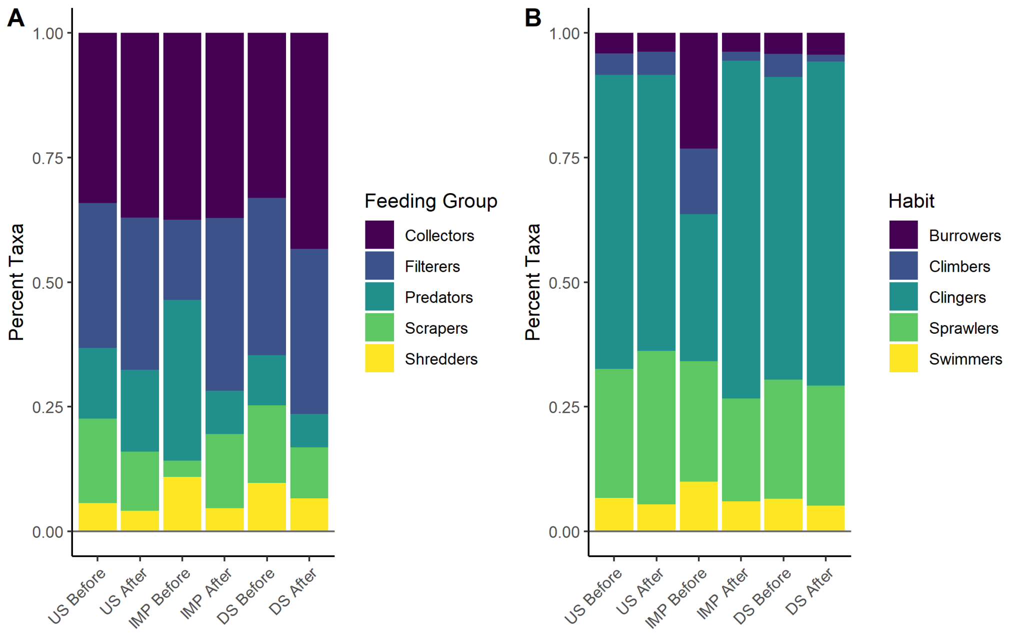


Figure A12.11) Percent of macroinvertebrate taxa by functional trait groups A) feeding group, and B) habit in upstream (US), impoundment (IMP), and downstream (DS) stream sections before and after dam removal. See Table A2.1 in Appendix 2 for information on feeding groups and habit categories.

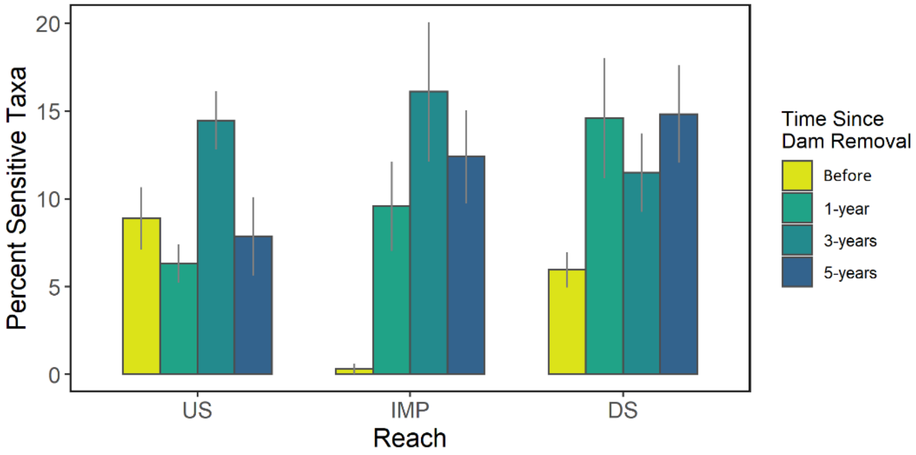


Figure A12.12) Percent of sensitive macroinvertebrate taxa in upstream (US), impoundment (IMP), and downstream (DS) stream sections before (pre) and in the years after dam removal (1 and 3 years).

Table A12.1. Averages of key ecological parameters before and after dam removal in each stream section (± 1 standard deviation).

Ecological Parameter	Upstream Before	Upstream After	Impoundment Before	Impoundment After	Downstream[†] Before	Downstream After
Stream Temperature (C)	22.9 ± 2.9	21.8 ± 2.7	23.3 ± 3	22.2 ± 3.1	22.8 ± 2.9	22.1 ± 2.9
Dissolved Oxygen (mg/L)	6.8 ± 1.7	6.9 ± 0.9	6.7 ± 1.3	7.7 ± 0.7	8.0 ± 0.9	7.9 ± 0.8
Hilsenhoff Biotic Index[††] (HBI)	5.5 ± 0.2	5.5 ± 0.2	6.9 ± 0.5	5.0 ± 0.2	5.5 ± 0.2	5.2 ± 0.2

[†] Temperature from first downstream logger (DS1) only. [††] Higher HBI indicates a greater relative abundance of pollution-tolerant macroinvertebrate taxa and suggests poorer water quality.

APPENDIX 13: Rattlesnake Dam (RAT)

Sampling Overview

Rattlesnake Brook Dam, a 3.9-ft tall (1.2 m) surface-release dam forming a 3.7-acre (1.5 ha) impoundment, was removed in late 2016. This structure, located in Fall River, MA, was the downstream-most barrier on Rattlesnake Brook. This site is located in a 6.6 mi^2 (17.1 km^2) watershed that is 90% forest cover, 1% impervious cover, and 0% cultivated land, with a mean elevation of 157 ft (47.9 m) above sea level. This site was monitored for temperature, dissolved oxygen, benthic macroinvertebrates, and fishes both before and after dam removal.

Figure A13.1. Map of temperature and dissolved oxygen logger locations in Rattlesnake Brook, Fall River, MA. Macroinvertebrates were sampled in approximately 100m sections around RATUS, RATIMP, and RATDS1 loggers. See Figure 1 in Study Design section for location within Massachusetts. Esri World Imagery Basemap accessed 10/18/2022.

Two temperature data loggers were deployed upstream of the impoundment: one in Terry Brook, a small tributary to the impoundment (RATUST), and one in Rattlesnake Brook proper (RATUSR). Temperature loggers were also deployed within the impoundment (RATIMP), and two deployed downstream (RATDS1-RATDS2) of the dam, covering 230 ft (0.07 km) of the river downstream to the Assonet River estuary (Fig. A13.1). Temperature loggers were deployed in June 2015 and remained in the field until October 2021, capturing 2 years of pre-removal stream temperature and 5 years of post-removal stream temperature. Dissolved oxygen (DO) loggers were deployed upstream (RATUS), within the impoundment (RATIMP), and downstream (RATDS1) of the Rattlesnake Brook Dam or former dam location (Fig. A13.1) for approximately week-long deployments during summer months (July, August, and September) from 2015 to 2019. Summer DO was monitored for 2 years before removal and 3 years after dam removal.

Macroinvertebrates were sampled once per summer from 2015 to 2019, and again in 2021, capturing 2 years of pre-removal and up to 5 years of post-removal assemblages. Within impounded areas, 3 replicate Ponar sediment grab samples were collected from randomly selected locations, and along impoundment margins, 3 replicate sweeps of submerged and emergent vegetation were conducted using a rectangular net. In flowing stream sections (e.g., upstream, downstream, and former impoundment), 3 replicate Surber samples were taken in separate riffle habitats and a single representative multihabitat sample was collected throughout ~100 m of stream. All samples were preserved in 70% ethanol prior to sorting and identification by Cole Ecological, Inc. or a trained UMass researcher. Up to 300 individuals were identified to the lowest practical taxonomic unit (usually genus or species, referred to as "taxa").

Fish sampling was also conducted in upstream and downstream sections by MassWildlife intermittently before and after dam removal; data summaries are provided in the General Results section of this final report. Temperature data are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Water quality data (temperature and dissolved oxygen) are also available through ScienceBase (https://doi.org/10.5066/P9L2ATHV). Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

Results

Temperature

There are 2 inflowing tributaries to this impoundment, Rattlesnake Brook and Terry Brook, which may impact the Rattlesnake Brook impoundment and downstream temperatures differently. Terry Brook flows over a surface-release dam from a larger impoundment, which may have driven the relatively high mean summer temperatures at RATUST (23.8 °C) before dam removal. Prior to dam removal, mean summer temperatures within the impoundment (21.4 °C) were higher than the upstream temperatures in Rattlesnake Brook (19.5 °C; Fig. A13.2) and downstream temperatures decreased from 20.0 °C at DS1 to 19.6 °C at DS2. It is important to note that due to a partial breach of this dam's secondary outlet, flows were bifurcated, with most water going overland through the woods and little flowing through the main channel. Thus, the downstream section often consisted of disconnected pools of water, with dense canopy cover and potential groundwater inputs. Downstream warming—the mean difference between upstream and downstream (DS1) daily temperatures—exhibited a bimodal pattern and was highest in spring and fall months, decreasing in summer (Fig. A13.3). This may be related to seasonal patterns of higher flows in the spring and fall months, which would lead to more water flowing over the dam and through the main channel. Summer downstream temperatures (July-Sept.) were on average 0.5 °C higher than upstream temperatures prior to removal, with high variability (SD= 1.4; Fig. A13.4). In 2016, a relatively dry and warm summer, downstream temperatures were cooler than upstream, potentially reflective of shading and cooler groundwater contributions constituting a larger proportion of stream flow than dam outflows. This disconnection may have also driven the rapid downstream cooling with increasing distance from the dam, at a slope of 8 °C/km (Fig. A13.5). These results suggest that Rattlesnake Brook Dam had a large thermal impact on Rattlesnake Brook temperatures within the impoundment and downstream.

Following dam removal, flow was returned to the main channel of Rattlesnake Brook downstream of the former dam, and the thermal regime of the brook was altered. For example, in the former impoundment, temperatures were reduced from 21.4 °C to 19.9 °C (1.5 °C difference); during the same years, upstream reference temperatures averaged 19.5 °C before removal to 18.9 °C after removal (0.6 °C difference). Temperatures in Terry Brook (UST) averaged 23.8 °C before removal and 23.4 after removal (0.4 °C difference). Despite the notable reduction in impoundment temperatures, downstream temperatures exhibited slight warming after dam removal. Downstream warming increased during summer months (July-Sept), and decreased in spring and fall, but with high variability among years (Fig. A13.3). Mean summer downstream warming significantly increased following dam removal, and variability also increased (before: 0.53, after: 1.77, t=10.9, $p<0.001$; Fig. A13.4). This may be due to the reconnection of flow, which may have reduced the proportion of groundwater inputs downstream of the dam, and the relatively open canopy of the former impoundment and downstream. It is possible that temperatures within the former impoundment and downstream will reduce over time as riparian vegetation develops and provides more shading. After removal, summer stream temperatures decreased with increasing distance downstream, but with a lower slope (-2.1 °C/km), which suggests a more natural thermal regime throughout these stream sections (Fig. A13.5). These results suggest that the Rattlesnake Brook Dam removal altered the thermal regime throughout this section of river, particularly by reconnecting flow between upstream and downstream sections. Although temperatures downstream increased relative to the upstream section after removal, there was a return to more consistent temperatures from the impoundment to the furthest downstream section monitored.

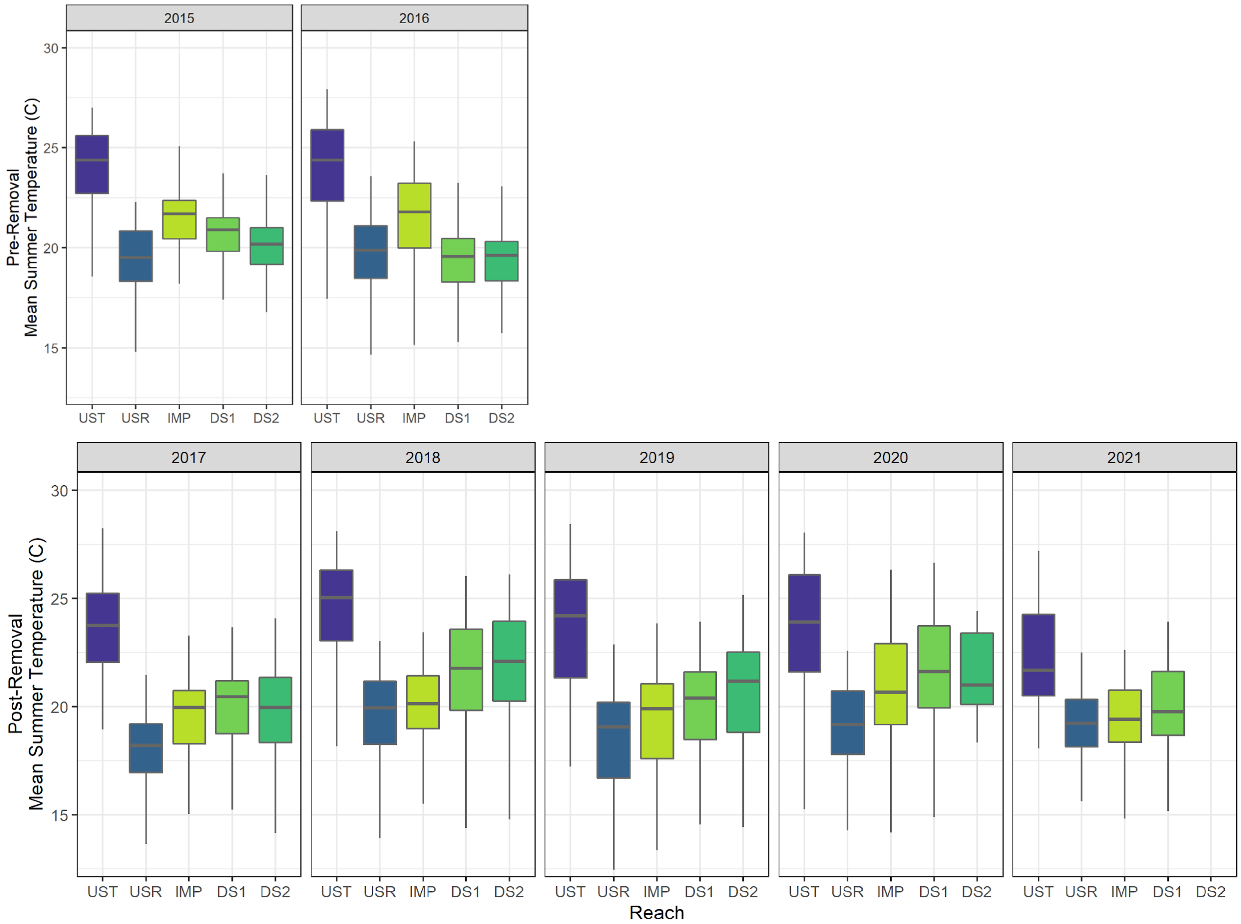


Figure A13.2) Mean summer (July-September) in-stream temperatures at each logger location A) before dam removal (2015-2016) and B) after dam removal (2017-2021). Logger locations are indicated by the following abbreviations: UST = upstream of Terry Brook, USR = upstream of Rattlesnake Brook, IMP = Impoundment, DS1-DS2 = Downstream 1 through Downstream 2.

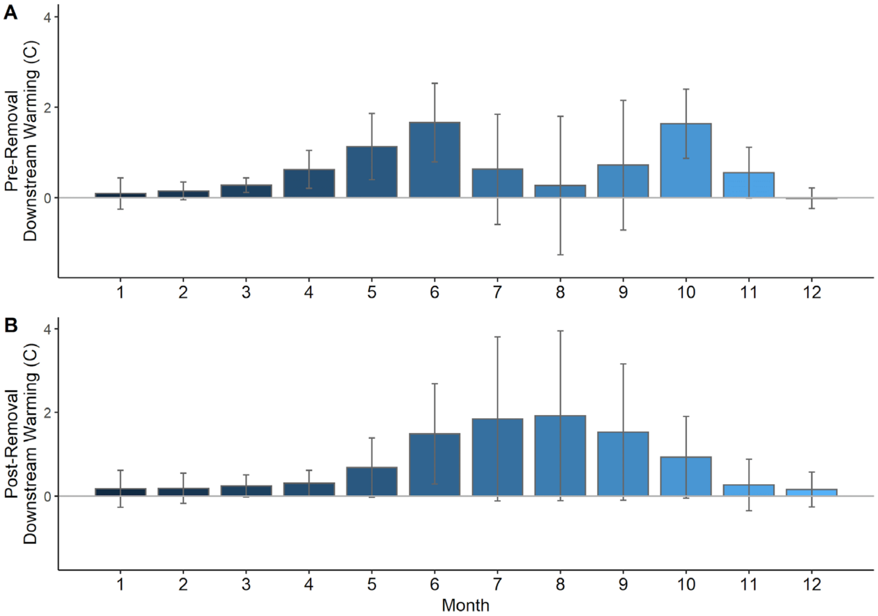


Figure A13.3) Downstream warming by month A) before (2015-2016) and B) after dam removal (2017-2021).

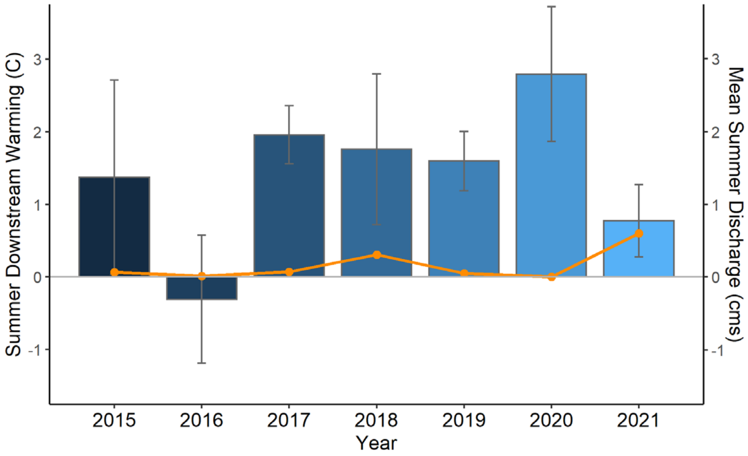


Figure A13.4) Summer (July-September) downstream warming (i.e., the difference between upstream and downstream temperatures ± SD; blue bars) and estimated mean summer discharge (orange line).

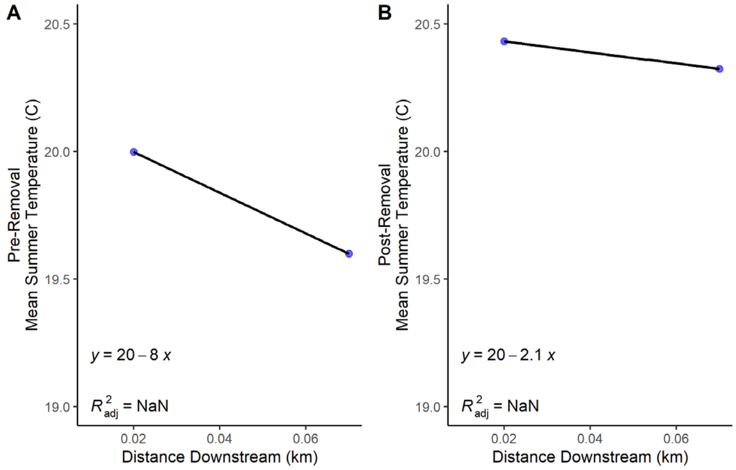


Figure A13.5) Mean summer temperature for each downstream logger (DS1-DS2) relative to the distance from the dam A) before and B) after dam removal. The black line represents the mean slope of linear temperature decay downstream of the dam.

Dissolved oxygen (DO)

Prior to removal, Rattlesnake Brook Dam had large negative impacts on stream DO, particularly in the downstream section due to limited water flowing over the dam. The downstream section averaged only 0.04 mg/L prior to removal (Fig. A13.6). The impoundment was not monitored for DO in summer 2015 due to limited access; however, in 2016, it exhibited a slightly lower mean DO (7.25 mg/L) than the upstream section (8.30 mg/L). The daily DO range within the impoundment (2.60 mg/L) was almost 3 times that of the daily range within the upstream section (0.92 mg/L), suggesting more eutrophic conditions within the impoundment. Daily ranges downstream (0.21 mg/L) were smaller than in both the upstream and impoundment (Fig A13.7). The downstream reach experienced consistent DO less than 5 mg/L (Fig. A13.8), a threshold below which waters may be considered impaired for DO (MassDEP 2016). The impoundment experienced minimal periods of low DO in 2016, a summer with relatively low precipitation and high air temperatures.

Following dam removal, DO concentrations within the former impoundment experienced an increase of 1.06 mg/L, from 7.25 to 8.31 mg/L on average, while upstream DO increased by 0.34 mg/L. Mean downstream DO increased dramatically from 0.04 mg/L to 8.27 mg/L, resulting in a relatively consistent DO regime from upstream to downstream sections. Daily ranges within the former impoundment decreased following dam removal, and downstream ranges increased to be more similar to the formerly impounded section, although both sections maintained slightly larger ranges than upstream (Fig. A13.8). In the 3 years monitored after dam removal, DO impairment (i.e., concentrations less than 5 mg/L) did not occur in any stream section (Fig, A13.4).

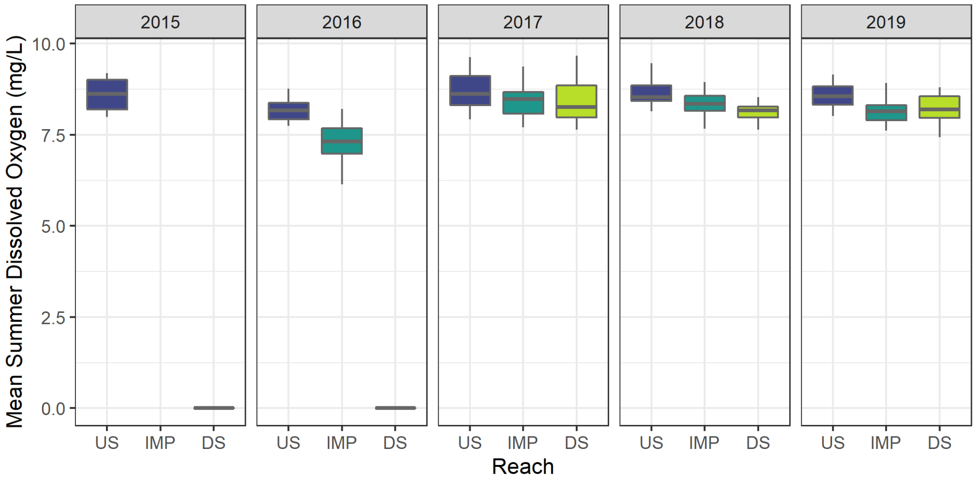


Figure A13.6) Mean summer (July-September) dissolved oxygen concentrations in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2019. Dam removal occurred in late 2016, prior to the 2017 deployment.

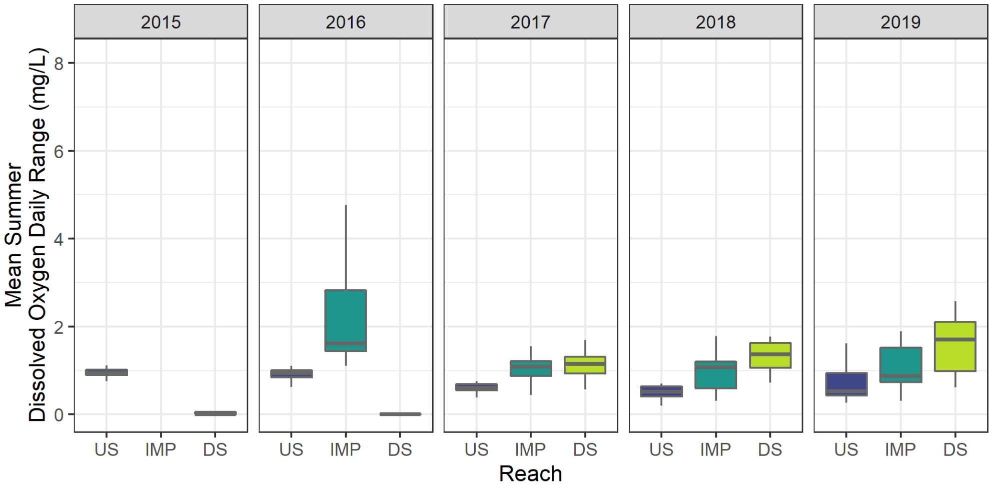


Figure A13.7) Mean summer (July-September) daily range of dissolved oxygen levels in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2019. Dam removal occurred in late 2016, prior to the 2017 deployment.

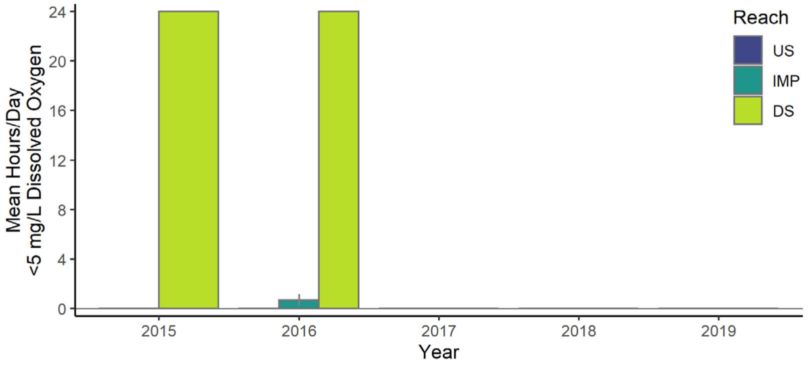


Figure A13.8) Mean and standard error (SE) hours per day that upstream (US), impoundment (IMP) and downstream (DS) stream sections spent below 5.0 mg/L, a threshold below which waters may be considered impaired for DO (MassDEP 2016). No impoundment data were collected in 2015, and no reaches in 2017-2019 spent any time with DO < 5 mg/L.

Macroinvertebrates

Prior to dam removal, we found that macroinvertebrate taxa differed between upstream and downstream sections, as well as between flowing water and impounded sections. For example, the percent of taxa (unique organisms) classified as coldwater (thermal optimum <18 °C) was lower downstream (19.0%) as compared to upstream (29.9%), and the percent of warmwater (>20 °C) taxa was higher upstream (3.6%) as compared to downstream (1.8%). In general, coolwater (18-20 °C) and coldwater taxa comprised most taxa at this site. We observed a much smaller percentage of sensitive taxa within the impoundment (5.2%) than the upstream section (37.5%) and a much greater percentage of pollution-tolerant taxa (34.4%) than upstream (5.9%; Fig. A13.9). The Hilsenhoff Biotic Index (HBI), which estimates the overall pollution tolerance weighted by the relative abundance of each taxa (Hilsenhoff 1988), also indicated more pollution tolerant taxa within the impoundment relative to flowing water sections. The total number of taxa (taxa richness) was much lower in downstream sections compared to the upstream section, and diversity, which incorporates both richness and abundance of taxa, followed a similar pattern. This is likely due to the lack of flowing water downstream, as described in previous sections.

After dam removal, the former impoundment exhibited an increase in sensitive taxa, and a corresponding decrease in tolerant taxa (Figure A13.9), which may reflect an improvement in water quality and habitat with the shift from stagnant to flowing water. Thermal classes reflect an increase in both coldwater and warmwater taxa within the impoundment, indicating a reduced percent of coolwater taxa. The downstream section also experienced an increase in the percentage of warmwater taxa, possibly corresponding to the warming downstream temperatures after dam removal (Fig. A13.9). The downstream section also exhibited a decrease in the percent tolerant taxa after dam removal, but no change in sensitive taxa (Figure A13.9). HBI scores in the former impoundment decreased to become more similar to adjacent flowing water sections, though the impoundment and downstream maintained a slightly higher HBI than upstream. Taxa richness and diversity in the downstream section were both increased after dam removal (Figure A13.10). Functional traits—feeding behavior and movement habits, for example—allow us to link environmental conditions to the abundance and diversity of the different functional groups sampled. In the former impoundment, we observed a decrease in predators, which may reflect the change from lentic habitat suitable for Odonata (e.g., dragonflies and damselflies) to habitat suitable for more riverine taxa. We also observed an increase in taxa that cling to rocks in the former impoundment after removal, reflecting the shift in habitat from stagnant to flowing water and from fine sediment and organic matter to coarser substrate (Fig. A13.11). In general, macroinvertebrate assemblages in the impoundment and downstream sections shifted to become more similar to the upstream section of Rattlesnake Brook, and this shift occurred within one year after dam removal (Fig. A13.12). The sections remain impacted by warmer temperatures, likely due to inputs from Terry Brook as well as increased solar radiation near the former dam location, and this may influence the macroinvertebrate assemblages found in these stream sections.

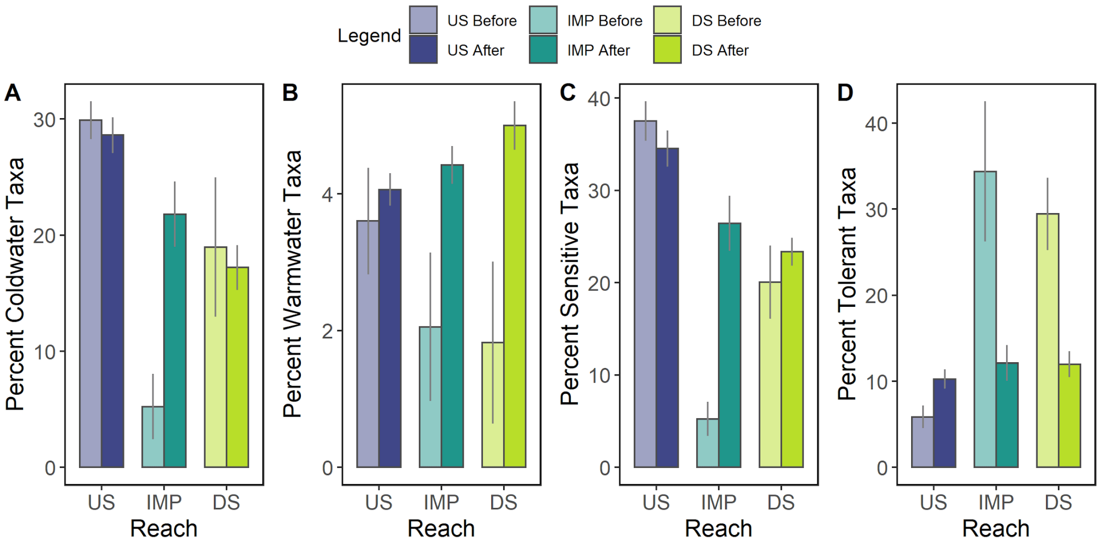


Figure A13.9) Mean percent of macroinvertebrate taxa by A) coldwater, B) warmwater, C) sensitive, and D) pollution-tolerant found within each sample in upstream (US), impoundment (IMP), and downstream (DS) stream sections before and after dam removal.

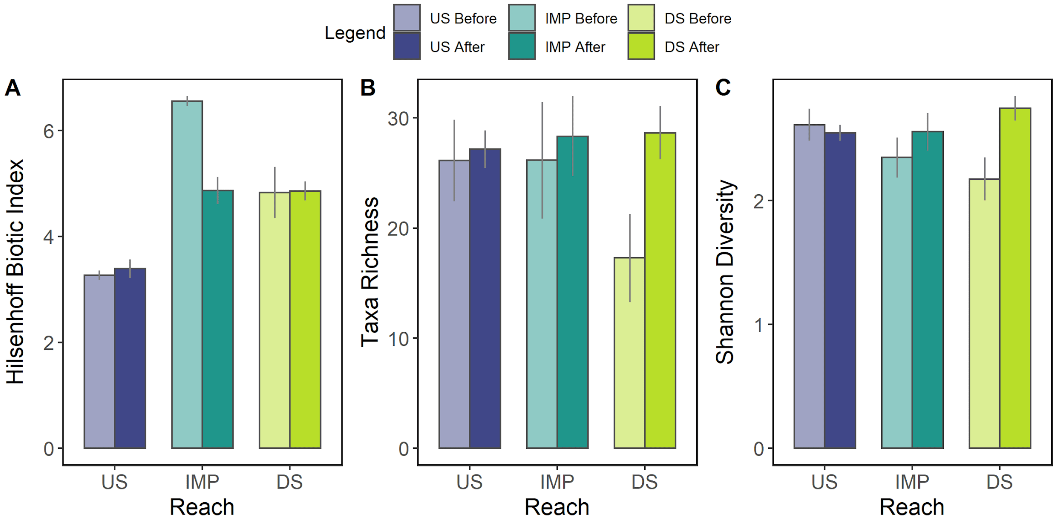


Figure A13.10) Mean macroinvertebrate biotic metric A) Hilsenhoff Biotic Index, B) total taxa richness, and C) Shannon diversity found in upstream (US), impoundment (IMP), and downstream (DS) sections before and after dam removal.

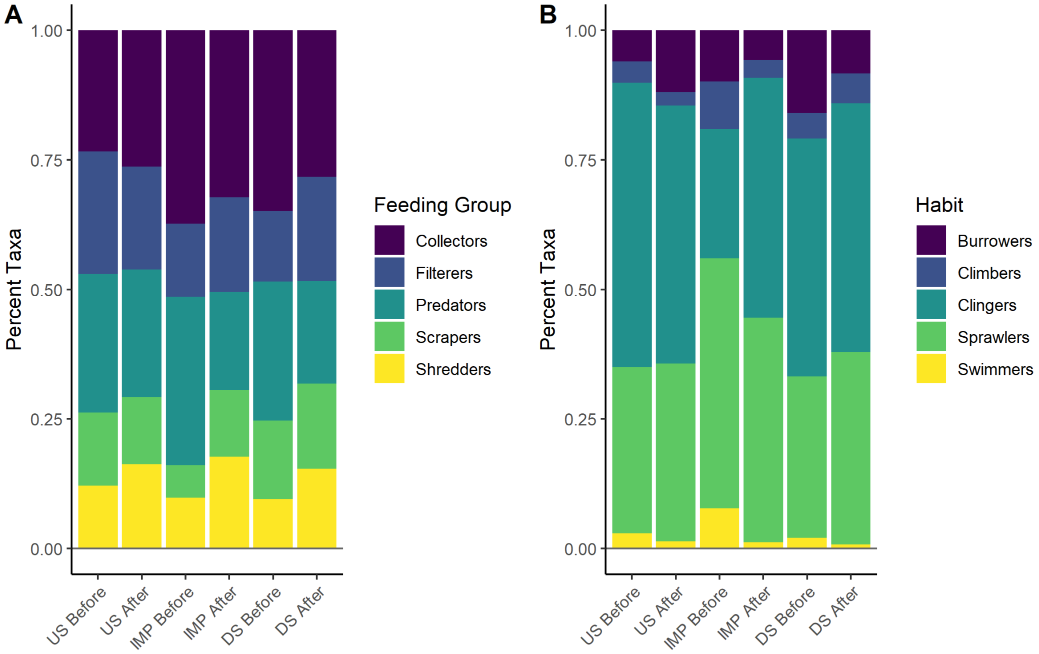


Figure A13.11) Percent of macroinvertebrate taxa by functional trait groups A) feeding group, and B) habit in upstream (US), impoundment (IMP), and downstream (DS) stream sections before and after dam removal. See Table A2.1 in Appendix 2 for information on feeding groups and habit categories.

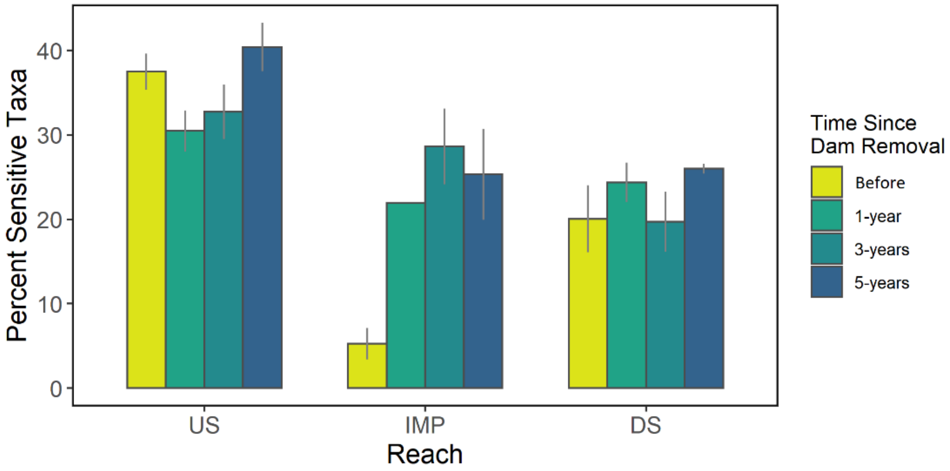


Figure A13.12) Percent of sensitive macroinvertebrate taxa in upstream (US), impoundment (IMP), and downstream (DS) stream sections before (pre) and in the years after dam removal (1, 3, and 5 years).

Table A13.1. Averages of key ecological parameters before and after dam removal in each stream section (± 1 standard deviation).

Ecological Parameter	Upstream Before	Upstream After	Impoundment Before	Impoundment After	Downstream[†] Before	Downstream After
Stream Temperature (C)	19.5 ± 2.1	18.9 ± 2.2	21.4 ± 2.1	19.9 ± 2.3	20.0 ± 2.0	20.6 ± 2.5
Dissolved Oxygen (mg/L)	8.3 ± 0.4	8.6 ± 0.4	7.3 ± 0.7	8.3 ± 0.4	0.0 ± 0.1	8.3 ± 0.5
Hilsenhoff Biotic Index[†] (HBI)	3.3 ± 0.2	3.4 ± 0.6	6.6 ± 0.2	4.9 ± 0.8	4.8 ± 1.3	4.9 ± 0.6

[†] Temperature from first downstream logger (DS1) only. [††] Higher HBI indicates a greater relative abundance of pollution-tolerant macroinvertebrate taxa and suggests poorer water quality.

APPENDIX 14: Sucker Brook Dam (SUC)

Sampling Overview

Sucker Brook Dam, located in Pepperell, MA, was a 3.9 ft tall (1.2 m) surface-release dam forming a 3.2-acre (1.3 ha) impoundment which was removed in October 2021. This structure was the only known dam encountered on Sucker Brook, a tributary to the Nissitissit River. The dam removal occurred concurrently with a culvert replacement at the first upstream road crossing, which was causing some flow backup. This site is located in a 2.6 mi^2 (6.8 km^2) watershed that is 50% forest cover, 4% impervious cover, and 2.6% cultivated land, with a mean elevation of 338 ft (103 m) above sea level. This site was monitored for temperature, dissolved oxygen, benthic macroinvertebrates, and fishes to determine the ecological impacts of the dam and to provide a baseline for future assessments of dam removal responses.

Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure A14.1. Map of temperature and dissolved oxygen logger locations in Sucker Brook, Pepperell, MA. Macroinvertebrates were sampled in approximately 100m sections around SUCUS, SUCIMP, and SUCDS1 loggers. See Figure 1 in Study Design section for location within Massachusetts. Esri World Imagery Basemap accessed 10/18/2022.

One temperature data logger was deployed upstream (SUCUS), one within the impoundment (SUCIMP), and six deployed downstream (SUCDS1-SUCDS6) of the dam, covering roughly 0.9 mi (1.4 km) downstream to the confluence with the Nissitissit River (Fig. A14.1). Temperature loggers were deployed in June 2018 and have remained in the field through the present (Spring 2022), capturing 4 years of pre-removal stream temperature. Dissolved oxygen (DO) loggers were deployed upstream (SUCUS), within the impoundment (SUCIMP), and downstream (near SUCDS1) of Sucker Brook Dam (Fig. A14.1) for approximately week-long deployments during summer months (July, August, and September) from 2018 to 2021, capturing 4 years of pre-removal DO concentrations.

Macroinvertebrates were sampled once per summer from 2018 to 2020, capturing 3 years of pre-removal assemblages. Within impounded areas, 3 replicate Ponar sediment grab samples were collected from randomly selected locations, and along impoundment margins, 3 replicate sweeps of submerged and emergent vegetation were conducted using a rectangular net. In flowing stream sections (e.g., upstream, downstream), 3 replicate Surber samples were taken in separate riffle habitats and a single representative multihabitat sample was collected throughout ~100 m of stream. All samples were preserved in 70% ethanol prior to sorting and identification by Cole Ecological, Inc. or a trained UMass researcher. Up to 300 individuals were identified to the lowest practical taxonomic unit (usually genus or species, referred to as "taxa").

Temperature data are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Water quality data (temperature and dissolved oxygen) are also available through ScienceBase (https://doi.org/10.5066/P9L2ATHV). Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

Results

Temperature

Prior to the removal of Sucker Brook Dam, we observed large differences in summer mean temperatures between the impoundment (21.2 °C) and the upstream section (16.9 °C), suggesting the dam had a large impact on stream temperatures. Summer temperatures were highest in the impoundment and decreased downstream from 21.1 °C at DS1 to 19.8 °C at DS6. We observed interannual variability in thermal impacts, potentially related to annual precipitation and air temperature conditions (Fig. A14.2). For example, in 2020—a year with relatively low precipitation and high air temperatures— upstream temperatures were lowest and impoundment temperatures were highest. During these low flow conditions, the upstream section was likely receiving a greater proportion of cooler groundwater input, while the impoundment warmed due to increased solar radiation and ambient temperatures. Conversely, periods of higher precipitation (e.g., 2021), may have resulted in more consistent temperatures throughout the stream due to higher flows and reduced residence times. Downstream warming—the mean difference between upstream and downstream (DS1) daily temperatures—was highest during spring and summer months (June-August; Fig. A14.3). Summer downstream warming (July-Sept.) was on average 4.21 °C, with high variability (SD= 3.03; Fig. A14.4). August stream temperatures cooled with increasing distance downstream from the dam with a slope of -0.89 °C/km (Fig. A14.5), although downstream temperatures did not recover to meet upstream conditions. Overall, results suggest that Sucker Brook Dam had large impacts on impoundment and downstream temperatures, with impacts varying due to flows and air temperatures. It is important to note that an undersized culvert immediately upstream of the impoundment, which backed up flows, was also replaced in Fall 2021. Further upstream, another culvert and a large wetland complex may have also contributed to the warmer temperatures within the impoundment. Monitoring within the impoundment after dam removal should help to clarify how much warming was due to instream infrastructure (i.e., dam and undersized culvert) and how much may have been natural warming due to more open wetland habitat.

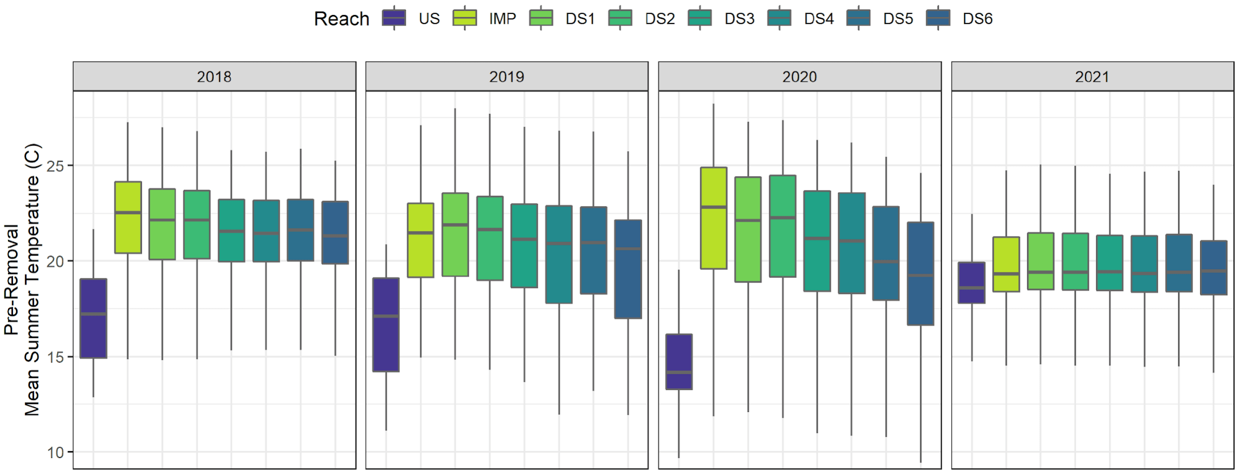


Figure A14.2) Mean summer (July-September) in-stream temperatures at each logger location during 2018-2021. Logger locations are indicated by the following abbreviations: US = upstream, IMP = Impoundment, DS1-DS6 = Downstream 1 through Downstream 6.

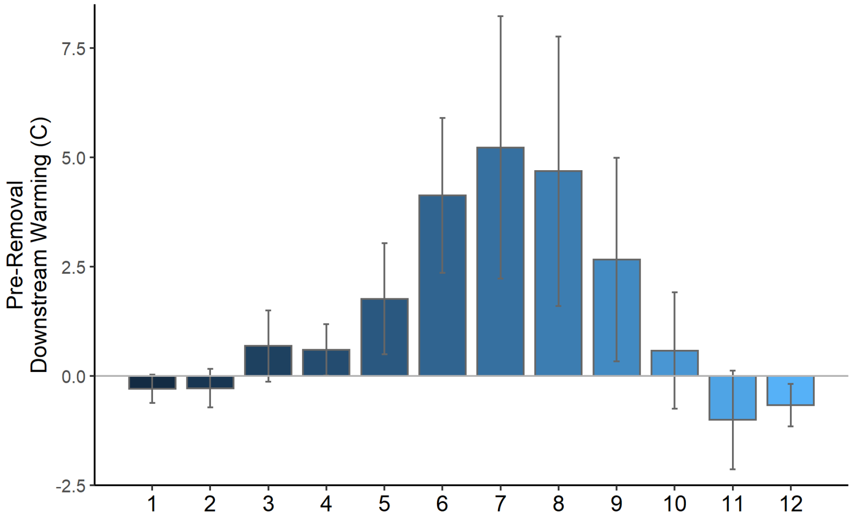


Figure A14.3) Mean downstream warming (i.e., downstream temperature minus upstream temperature) by month, across all years (2018-2021).

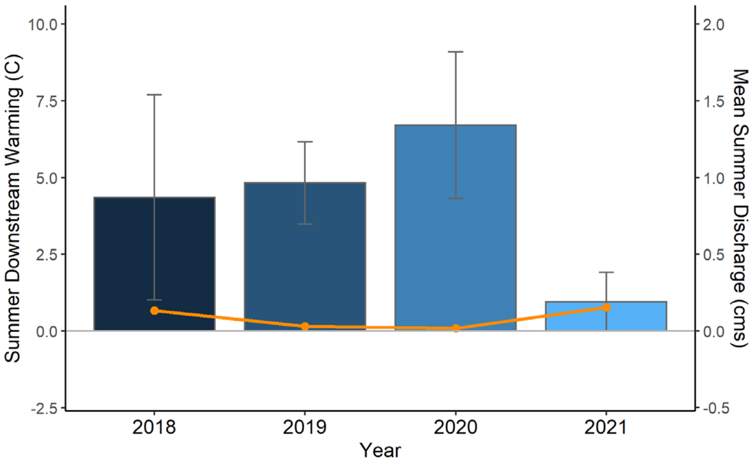


Figure A14.4) Summer (July-September) downstream warming (i.e., the difference between upstream and downstream temperatures ± SD; blue bars) and estimated mean summer discharge (orange line).

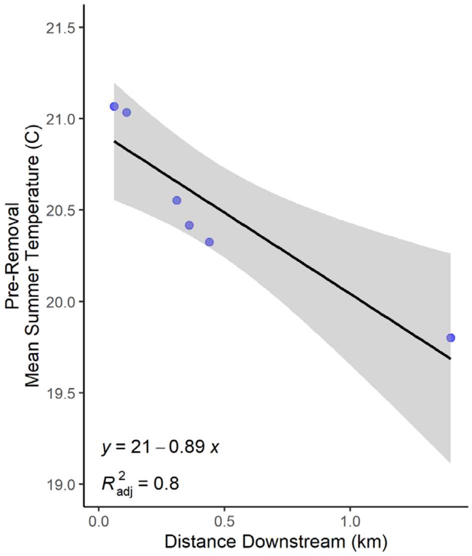


Figure A14.5) Mean summer temperature for each downstream logger (DS1-DS5) relative to the distance from the dam. The black line represents the mean slope of linear temperature decay downstream of the dam and the shaded grey area represents the 95% confidence interval.

Dissolved oxygen (DO)

Average surface DO within the impoundment of Sucker Brook Dam (5.91 mg/L) was lower than both the upstream (8.79 mg/L) and downstream (7.14 mg/L) section (Fig. A14.5). Although this pattern was consistent across all years monitored, the magnitude of differences between stream sections were variable among years (Fig. A14.6). For example, in 2018, low precipitation and high temperatures may have resulted in lower DO within the impoundment. However, this pattern was not observed in 2020. Higher-than-normal precipitation in 2021 may have led to relatively high DO across all stream sections, and more water spilling from the dam potentially contributing to slightly higher downstream DO. One of the most notable impacts to DO was observed with the extremely high mean daily range within the impoundment (4.80 mg/L) as compared to downstream (1.40 mg/L) and upstream (0.80 mg/L; Fig. A14.7). Larger daily ranges typically indicate more plant and algal growth, as high rates of oxygen production during daytime photosynthesis and oxygen consumption via nighttime respiration result in larger daily oxygen fluxes (Diamond et al. 2021). This is consistent with the dense emergent and submerged macrophyte and algal growth within the Sucker Brook impoundment. The impoundment consistently experienced some hours per day of DO less than 5 mg/L (Fig. A14.8), a threshold below which waters may be considered impaired for DO (MassDEP 2016). These results suggest Sucker Brook Dam had a large impact on the dissolved oxygen regime of Sucker Brook, with particularly extreme impacts within the impoundment.

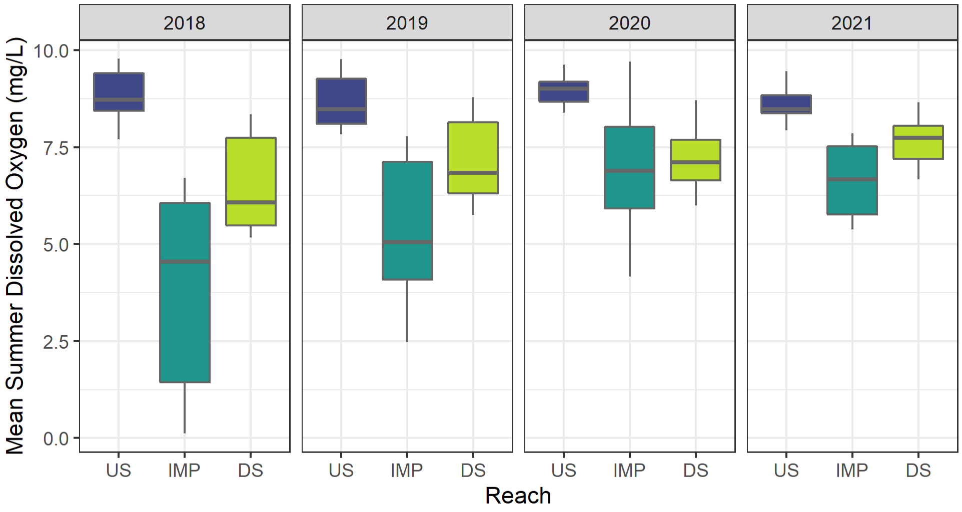


Figure A14.6) Mean summer (July-September) dissolved oxygen concentrations in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2018-2021.

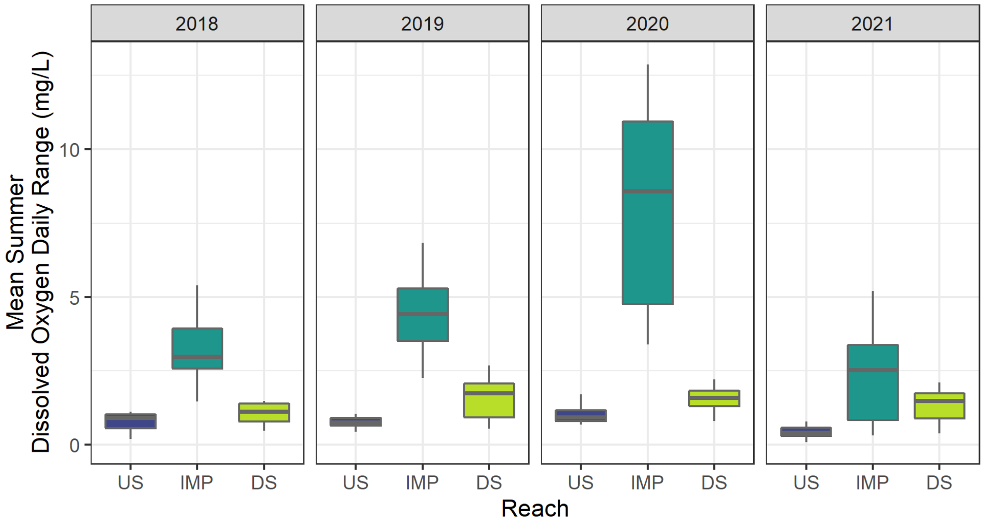


Figure A14.7) Mean summer (July-September) daily range of dissolved oxygen levels in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2018-2021.

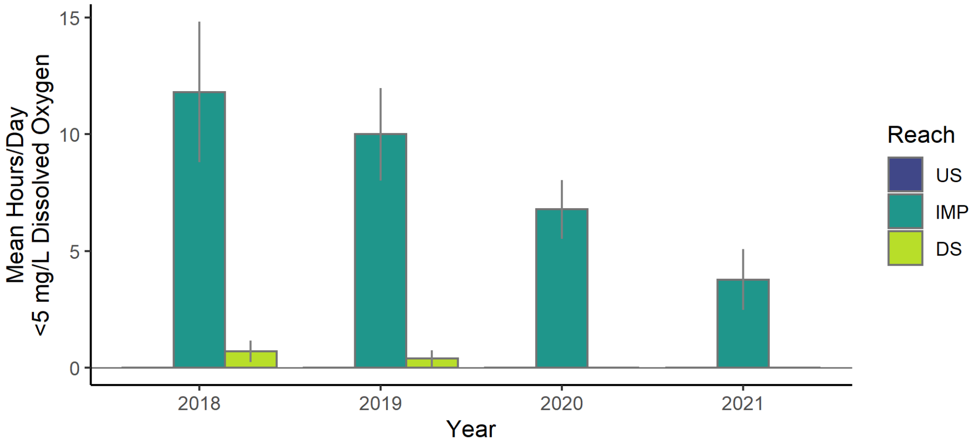


Figure A14.8) Mean and standard error (SE) hours per day that upstream (US), impoundment (IMP) and downstream (DS) stream sections spent below 5.0 mg/L, a threshold below which waters may be considered impaired for DO (MassDEP 2016). The upstream reach did not experience any time with DO < 5 mg/L.

Macroinvertebrates

At this site, we found that macroinvertebrate assemblages differed between upstream and downstream sections, as well as between flowing water and impounded sections. For example, the percent of taxa (unique organisms) classified as coldwater (thermal optimum <18 °C) was much lower within the impoundment (5.5%) and downstream (14.5%) as compared to upstream (33.6%), while warmwater taxa (>20 °C) were more prevalent downstream (1%). In general, coolwater (18-20 °C) taxa dominated all sections at this site. We observed a greater percentage of pollution-tolerant taxa within the impoundment (51.6%) section than in downstream (19%) and upstream sections (11.2%), and fewer sensitive taxa (1.9%; Fig. A14.9). The Hilsenhoff Biotic Index (HBI), which estimates the overall pollution tolerance weighted by the relative abundance of each taxa (Hilsenhoff 1988), also indicated more pollution-tolerant taxa within the impoundment relative to flowing water sections (Fig. A14.10), and downstream had a lower HBI than upstream. The total number of taxa (taxa richness) and the diversity, which incorporates both richness and abundance of taxa, were both lowest within the impoundment (Fig. A14.10). Functional traits—feeding behavior and movement habits, for example—allow us to link environmental conditions to the abundance and diversity of the different functional groups sampled. In the impoundment, we observed a lower proportion of taxa that feed by "shredding" and "scraping", like stoneflies (Plecoptera) and some riffle beetles (Elmidae), which may indicate less coarse particulate matter is available to feed on (Fig. A14.11). In the impoundment, we also found a higher percentage of taxa that burrow and a lower percentage of clingers than both flowing-water sections, reflecting the shift to stagnant waters and to finer sediment and organic matter (Fig. A14.11). These results suggest that Sucker Brook Dam may be impacting macroinvertebrate assemblages by inducing changes in temperature and habitat availability within the impoundment and downstream.

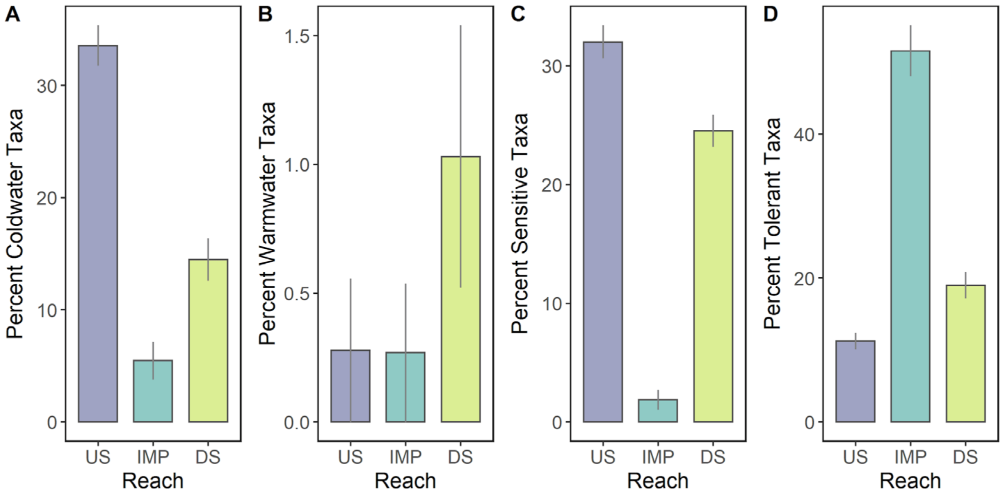


Figure A14.9) Mean percent of macroinvertebrate taxa by A) coldwater, B) warmwater, C) sensitive, and D) pollution-tolerant found within each sample in upstream (US), impoundment (IMP), and downstream (DS) stream sections.

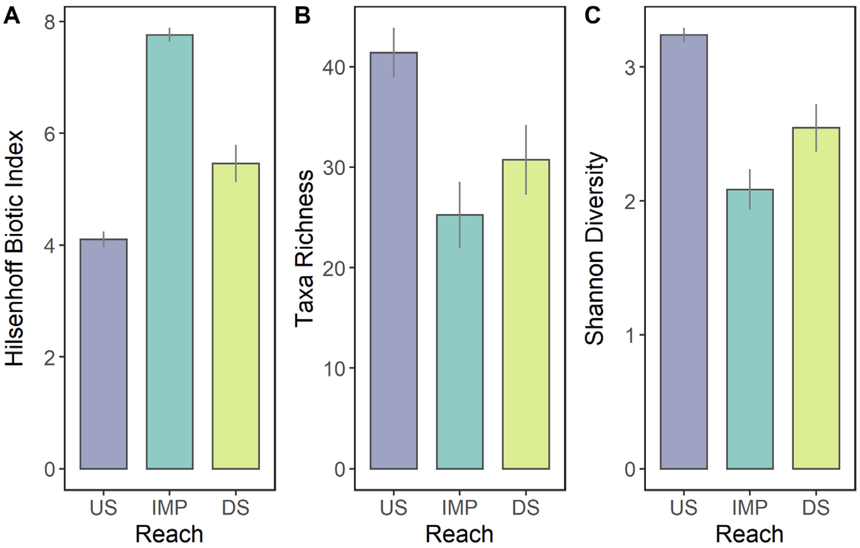


Figure A14.10) Mean macroinvertebrate biotic metric A) Hilsenhoff Biotic Index, B) total taxa richness, and C) Shannon diversity found in upstream (US), impoundment (IMP), and downstream (DS) sections.

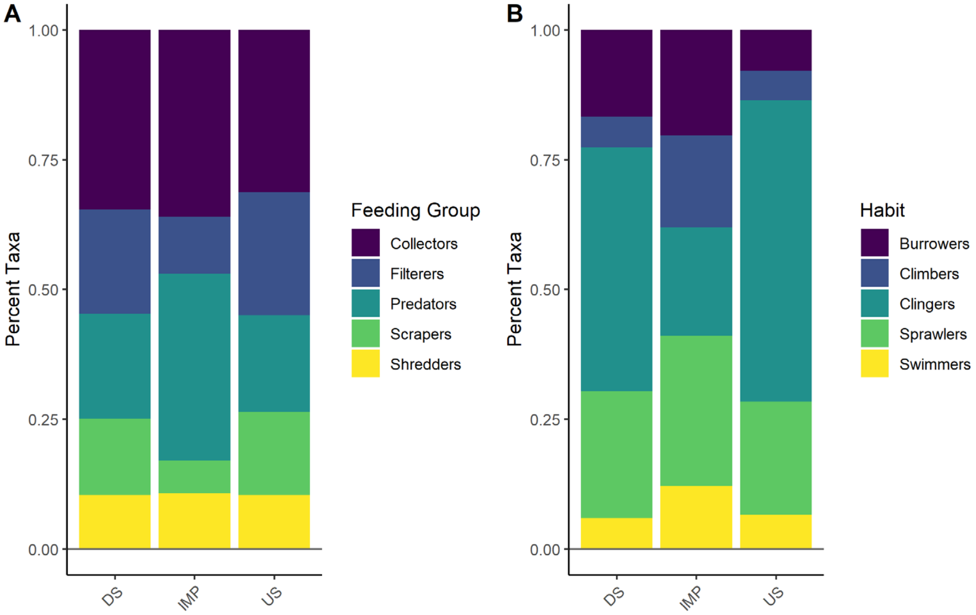


Figure A14.11) Percent of macroinvertebrate taxa by functional trait groups A) feeding group, and B) habit in upstream (US), impoundment (IMP), and downstream (DS) stream sections. See Table A2.1 in Appendix 2 for information on feeding groups and habit categories.

Table A14.1. Averages of key ecological parameters before dam removal in each stream section (± 1 standard deviation).

Ecological Parameter	**Upstream Before**	**Upstream After**	**Impoundment Before**	**Impoundment After**	**Downstream[†] Before**	**Downstream After**
Stream Temperature (C)	16.9 ± 2.7	-	21.2 ± 3.2	-	21.1 ± 3.2	-
Dissolved Oxygen (mg/L)	8.8 ± 0.5	-	5.9 ± 2.0	-	7.1 ± 1.0	-
Hilsenhoff Biotic Index[††] (HBI)	4.1 ± 0.4	-	7.8 ± 0.4	-	5.5 ± 0.9	-

[†] Temperature from first downstream logger (DS1) only. [††] Higher HBI indicates a greater relative abundance of pollution-tolerant macroinvertebrate taxa and suggests poorer water quality.

APPENDIX 15: Tel-Electric Dam (TEL)

Sampling Overview

Tel-Electric Dam, a 20 ft tall (6.1 m) surface-release dam forming a 10.9-acre (4.4 ha) impoundment, was removed in early 2020. This structure, located in Pittsfield, MA, was the downstream-most barrier on the West Branch Housatonic River. This site is located in a 36.1 mi^2 (93.5 km^2) watershed that is 59% forest cover, 5% impervious cover, and 0.3% cultivated land, with a mean elevation of 1420 ft (432.8 m) above sea level. This site was monitored for temperature, dissolved oxygen, benthic macroinvertebrates, and fishes both before and after dam removal.

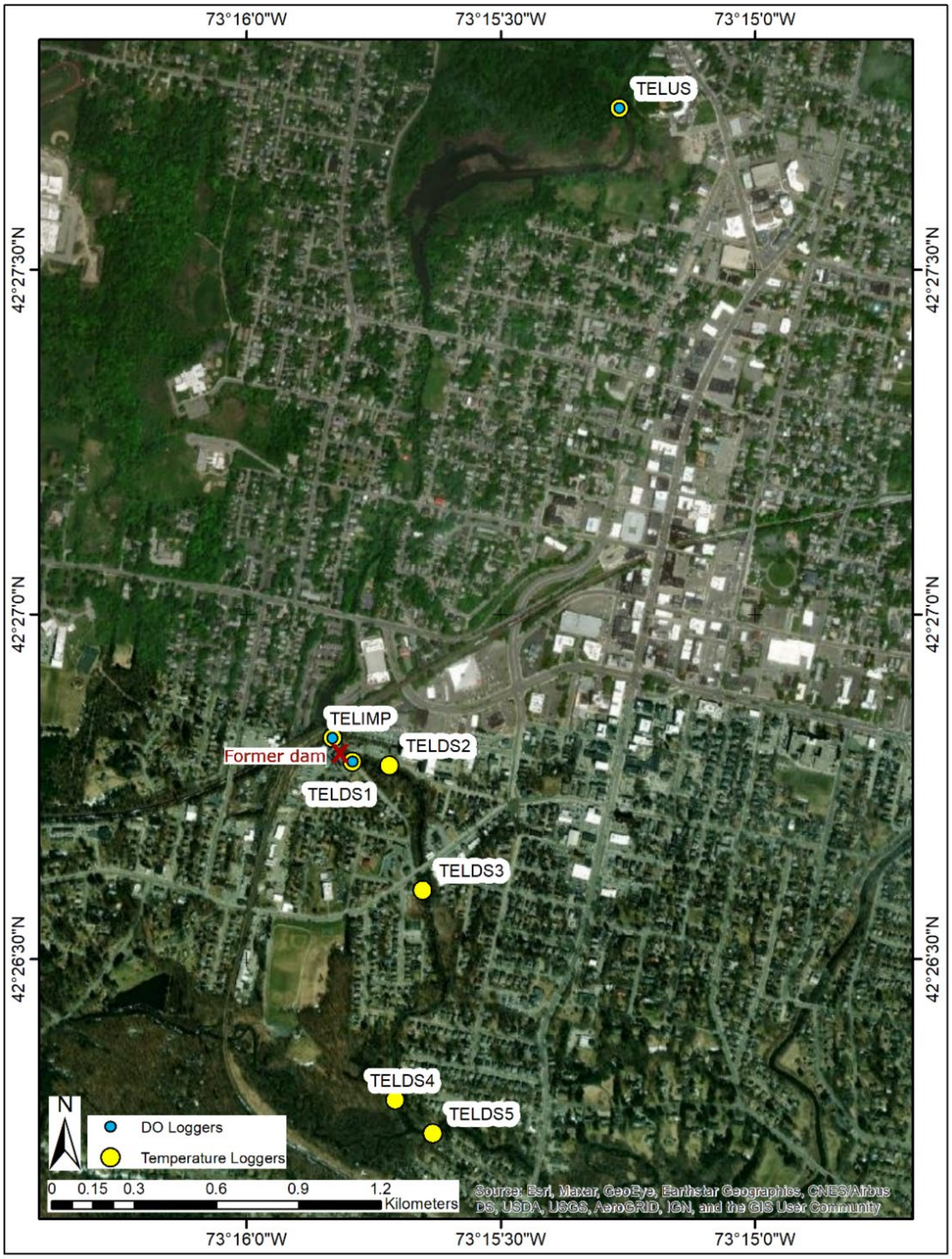


Figure A15.1. Map of temperature and dissolved oxygen logger locations in the West Branch Housatonic River, Pittsfield, MA. Macroinvertebrates were sampled in approximately 100m sections around TELUS, TELIMP, and TELDS1 loggers. See Figure 1 in Study Design section for location within Massachusetts. Esri World Imagery Basemap accessed 10/18/2022.

Temperature data loggers were deployed upstream of the impoundment (TELUS), within the impoundment (TELIMP), and five deployed downstream (TELDS1-TELDS5) of the dam, covering 0.82 mi (1.34 km) of the river downstream (Fig. A15.1). Temperature loggers were deployed in July 2015 and are currently still deployed, capturing 5 years of pre-removal stream temperature and 2 years of post-removal stream temperature. Dissolved oxygen (DO) loggers were deployed upstream (TELUS), within the impoundment (TELIMP), and downstream (TELDS1) of Tel-Electric Dam or former dam location (Fig. A15.1) for approximately week-long deployments during summer months (July, August, and September) in 2015, 2016, 2018, and 2020. Summer DO was monitored for 3 years before removal and 1 year after dam removal.

Macroinvertebrates were sampled once per summer in 2015, 2016, 2018, and again in 2020, capturing 3 years of pre-removal and 1 year of post-removal assemblages. Within impounded areas, 3 replicate Ponar sediment grab samples were collected from randomly selected locations, and along impoundment margins, 3 replicate sweeps of submerged and emergent vegetation were conducted using a rectangular net. In flowing stream sections (e.g., upstream, downstream, and former impoundment), 3 replicate Surber samples were taken in separate riffle habitats and a single representative multihabitat sample was collected throughout ~100 m of stream. All samples were preserved in 70% ethanol prior to sorting and identification by Cole Ecological, Inc. or a trained UMass researcher. Up to 300 individuals were identified to the lowest practical taxonomic unit (usually genus or species, referred to as "taxa").

Fish sampling was also conducted in upstream and downstream sections by MassWildlife intermittently before and after dam removal; data summaries are provided in the General Results Section of this final report. Temperature data are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Water quality data (temperature and dissolved oxygen) are also available through ScienceBase (https://doi.org/10.5066/P9L2ATHV). Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

Results

Temperature

Prior to dam removal, the Tel-Electric dam had a small thermal impact on the West Branch Housatonic River. Mean summer temperatures within the impoundment (22.7 °C) were slightly higher than upstream temperatures (22.2 °C; Fig. A15.2) and downstream temperatures ranged from 22.3 °C to 20.4 °C, similar or slightly cooler than upstream temperatures. Downstream warming—the mean difference between upstream and downstream (DS1) daily temperatures—was highest in April and May (Fig. A15.3). During the summer of 2019, the impoundment was drawn down in preparation for dam removal. The impoundment logger was removed prior to draw down, and some downstream loggers were partially buried, resulting in an inconsistent thermal regime downstream. This impoundment was relatively narrow and constrained by development, and downstream sections were well-shaded by riparian trees and some channelization; these characteristics likely moderated solar radiation and prevented warming. The upstream section is relatively shallow with less dense canopy cover, potentially leading to the lack of difference between upstream and dam-adjacent stream sections. Summer downstream temperatures (July-Sept.) were on average 0.29 °C lower than upstream, with high variability (SD= 0.64; Fig. A15.4). Temperatures continued to cool with increasing distance from the dam, at a slope of -0.81 °C/km (Fig. A15.5). These results suggest that Tel-Electric Dam had a small thermal impact on West Branch Housatonic River temperatures within the impoundment and downstream.

After dam removal, we observed minimal changes in the thermal regime, likely because of the small impact before removal. Across all loggers, temperatures were slightly lower after removal, potentially due to ambient weather conditions. In the former impoundment, temperatures were reduced from 22.7 °C to 21.9 °C (0.8 °C difference); during the same years, upstream reference temperatures averaged 22.2 °C before removal to 21.7 °C after removal (0.5 °C difference). The magnitude of downstream warming remained fairly consistent across months (Fig. A15.3). Temperatures decreased slightly downstream relative to upstream, but with high variability among years (Fig. A15.4). Mean summer temperatures downstream decreased relative to upstream temperatures (-0.53 °C), and variability also increased (SD = 0.75). After removal, summer stream temperatures decreased with increasing distance downstream, but with a slightly steeper slope (-0.95 °C/km), driven by cooler water at the furthest downstream loggers (DS3-DS5; Fig. A15.5). These results suggest that the Tel-Electric Dam removal did not substantially alter the thermal regime throughout this section of river. This river is impacted by a number of anthropogenic stressors, including industrial contamination, dumping, upstream barriers, and urbanization; thus, the thermal impacts of this dam and dam removal may be obscured.

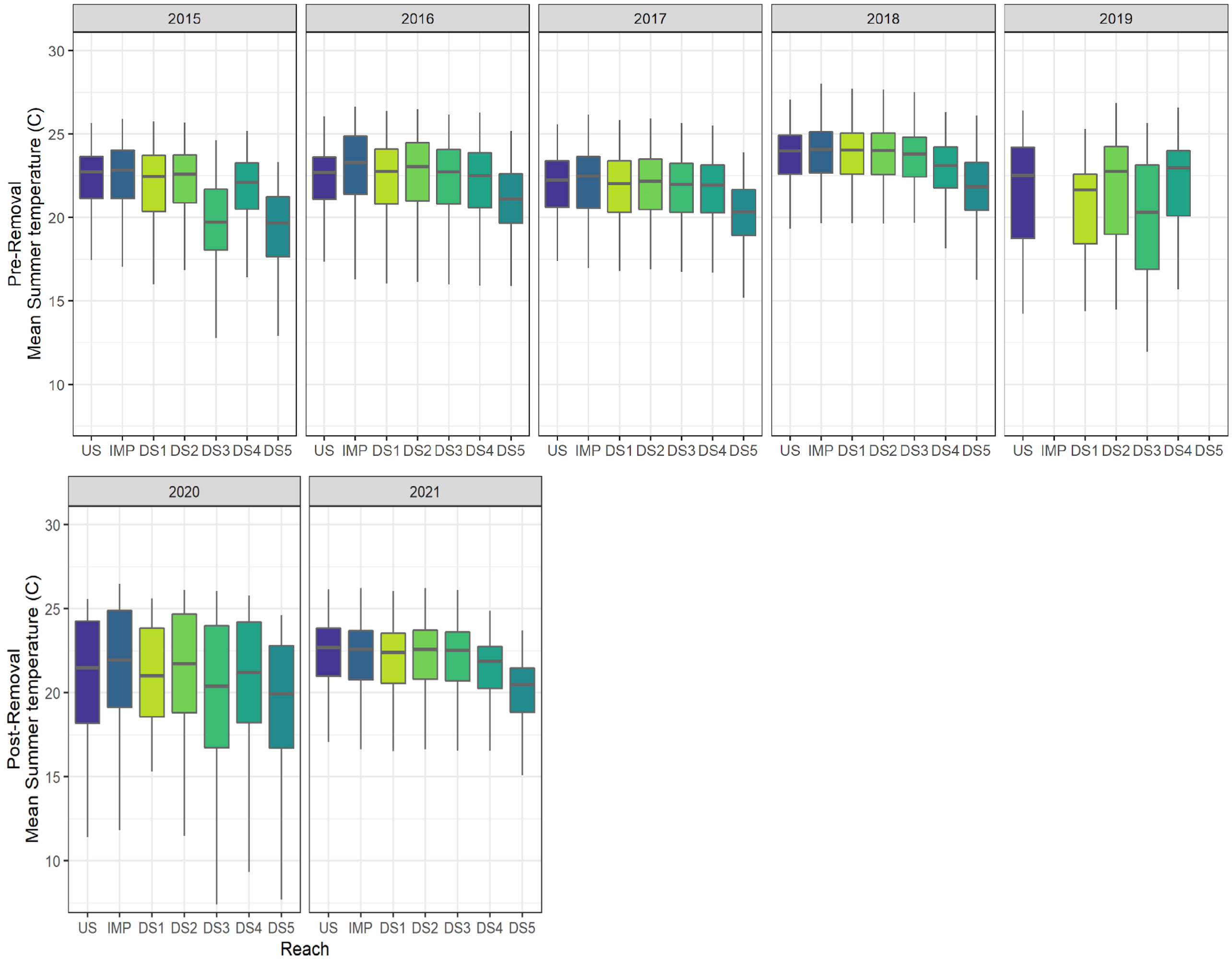


Figure A15.2) Mean summer (July-September) in-stream temperatures at each logger location A) before dam removal (2015-2019) and B) after dam removal (2020-2021). Logger locations are indicated by the following abbreviations: US = upstream, IMP = Impoundment, DS1-DS5 = Downstream 1 through Downstream 5.

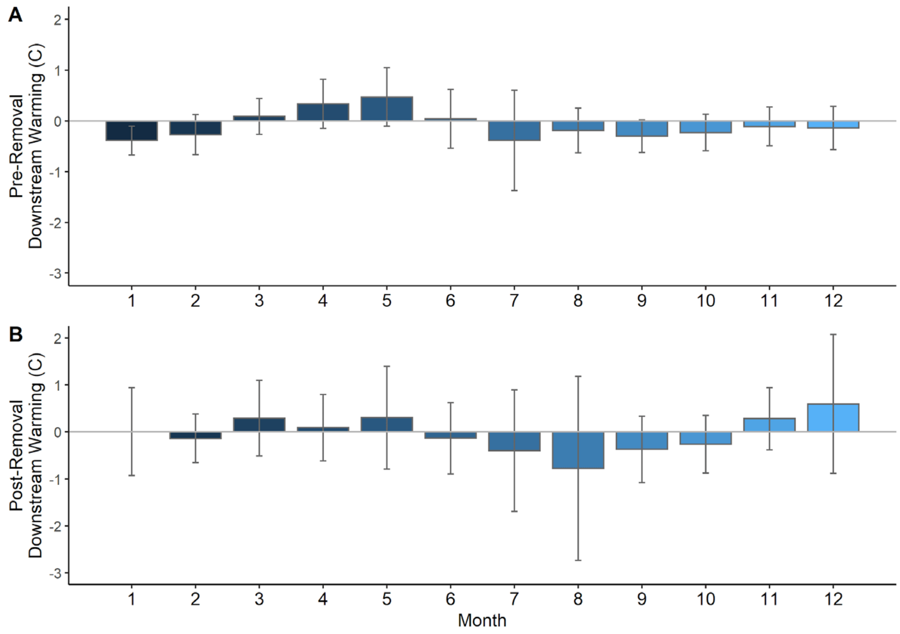


Figure A15.3) Downstream warming by month A) before (2015-2019) and B) after dam removal (2020-2021).

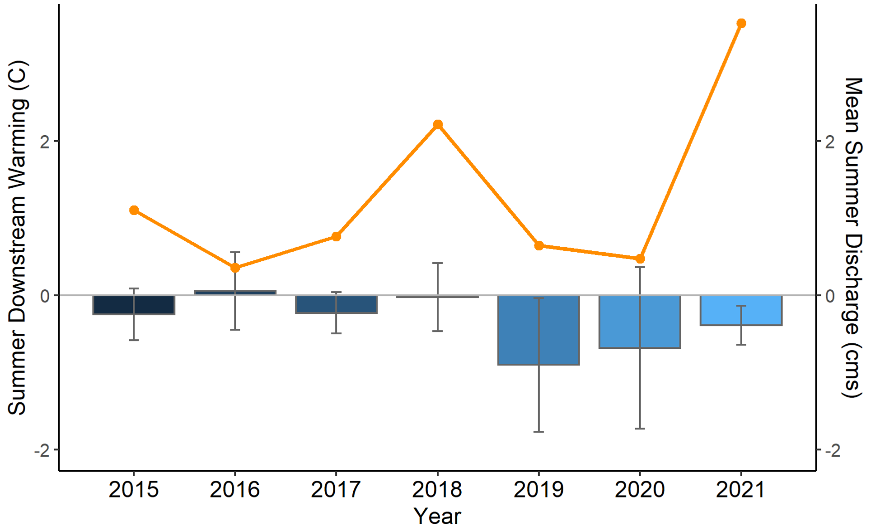


Figure A15.4) Summer (July-September) downstream warming (i.e., the difference between upstream and downstream temperatures ± SD; blue bars) and estimated mean summer discharge (orange line).

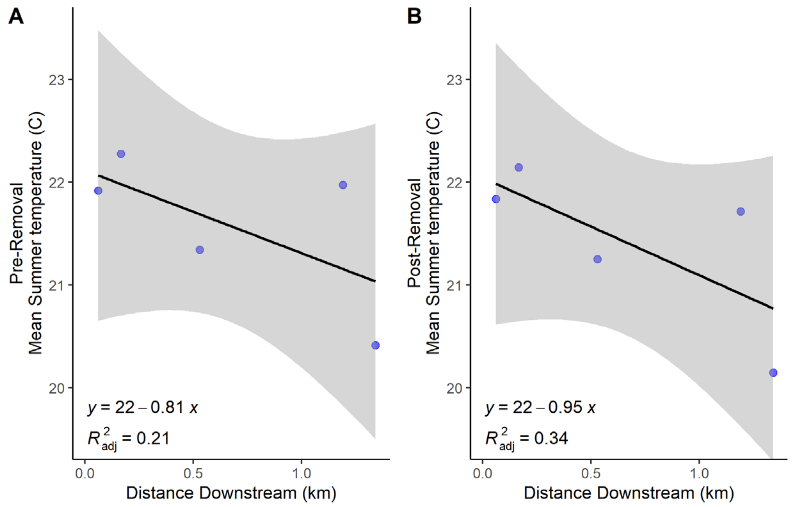


Figure A15.5) Mean summer temperature for each downstream logger (DS1-DS2) relative to the distance from the dam A) before and B) after dam removal. The black line represents the mean slope of linear temperature decay downstream of the dam.

Dissolved oxygen (DO)

Prior to removal, the Tel-Electric Dam had large negative impacts on stream DO, particularly within the impoundment. The impoundment averaged 7.04 mg/L prior to removal, which was consistently lower than DO concentrations within the upstream section (7.99 mg/L). Downstream DO averaged slightly higher (8.12 mg/L) than both upstream and impoundment sections (Fig. A15.6). The more extreme impacts to DO were observed in the differences in daily range among stream sections. Within the impoundment, the DO daily range (4.13 mg/L) was 4 times that of the daily range within the upstream section (0.98 mg/L), suggesting eutrophic conditions within the impoundment. Larger daily ranges typically indicate more plant and algal growth, as high rates of oxygen production during daytime photosynthesis and oxygen consumption via nighttime respiration result in larger daily oxygen fluxes (Diamond et al. 2021). At this site, organic pollution was likely driving high algal growth. Daily ranges downstream (0.65 mg/L) were smaller than in both the upstream and impoundment (Fig A15.7). In 2015 and 2016, the impoundment experienced periods of time with DO less than 5 mg/L (Fig. A15.8), a threshold below which waters may be considered impaired for DO (MassDEP 2016).

Following dam removal, DO concentrations within the former impoundment experienced an increase of 0.78 mg/L, from 7.04 to 7.82 mg/L on average, while upstream DO increased by 0.17 mg/L. Mean downstream DO decreased by 0.58 mg/L, resulting in a relatively consistent DO regime from upstream to downstream sections. Across all stream sections, daily ranges of DO became more similar after dam removal. The average daily range within the former impoundment decreased by 2.27 mg/L following dam removal, and downstream ranges increased by 1.06 to be more similar to the formerly impounded section and upstream (Fig. A15.8). In the year after dam removal, DO impairment (i.e., concentrations less than 5 mg/L) did not occur in any stream section (Fig. A15.8).

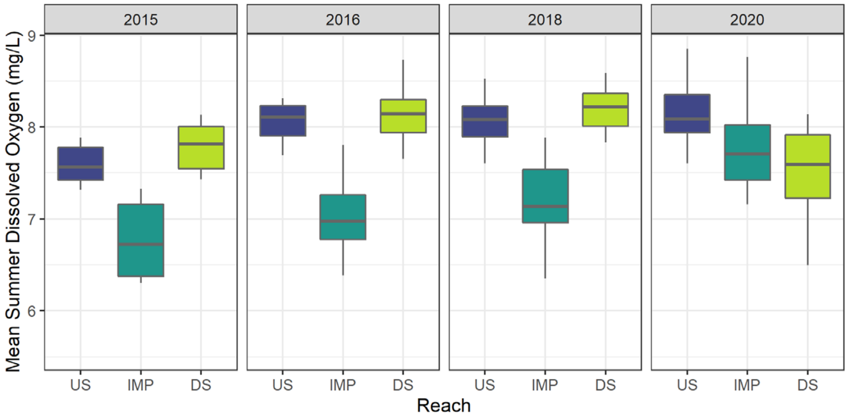


Figure A15.6) Mean summer (July-September) dissolved oxygen concentrations in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2021. Dam removal occurred in early 2020, prior to the summer deployment.

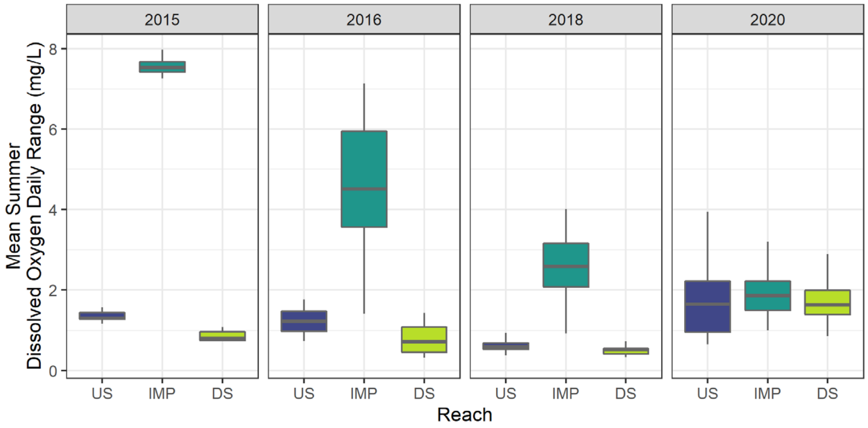


Figure A15.7) Mean summer (July-September) daily range of dissolved oxygen levels in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2021. Dam removal occurred in late 2020, prior to the summer deployment.

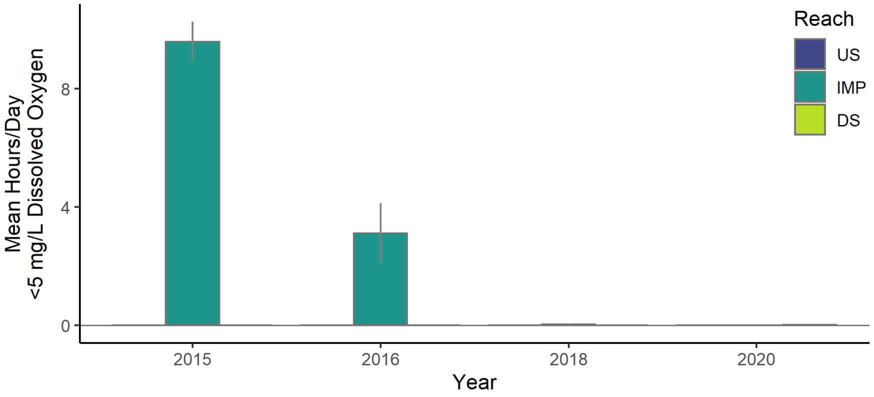


Figure A15.8) Mean and standard error (SE) hours per day that upstream (US), impoundment (IMP) and downstream (DS) stream sections spent below 5.0 mg/L, a threshold below which waters may be considered impaired for DO (MassDEP 2016).

Macroinvertebrates

Prior to dam removal, we found that macroinvertebrate taxa differed between upstream and downstream sections, as well as between flowing water and impounded sections. For example, the percent of taxa (unique organisms) classified as coldwater (thermal optimum <18 °C) was higher downstream (3.0%) as compared to upstream (1.4%). In general, coolwater (18-20 °C) taxa comprised most taxa at this site. We observed a smaller percentage of sensitive taxa within the impoundments (0.5%) than the upstream section (7.2%), although the downstream section contained the greatest percent of sensitive taxa (17.7%). The impoundment contained the greatest percentage of pollution-tolerant taxa (56.9%) than upstream (15.0%) and downstream (10.5%) sections (Fig. A15.9). The Hilsenhoff Biotic Index (HBI), which estimates the overall pollution tolerance weighted by the relative abundance of each taxa (Hilsenhoff 1988), also indicated more pollution tolerant taxa within the impoundment relative to flowing water sections. The total number of taxa (taxa richness) was slightly lower in the impoundment compared to the flowing water sections, and diversity, which incorporates both richness and abundance of taxa, followed a similar pattern. At this heavily impacted site, most stream sections contained abundant trash, and there is stormwater runoff along the length of this study area. Along the west bank of the upstream section, a former unlined landfill ("King Street Dump") may be contributing to poor water quality in this area. It is likely that the recovery of macroinvertebrate assemblages will be constrained by these water quality and habitat impacts, and why we may have observed fewer sensitive taxa upstream than downstream.

One year after dam removal, the former impoundment exhibited an increase in sensitive taxa, and a corresponding decrease in tolerant taxa to become more similar to the upstream assemblage (Fig. A15.9). Thermal classes reflect a decrease in coldwater taxa and an increase in warmwater taxa in the former impoundment (Fig. A15.9). HBI scores in the former impoundment decreased to become more similar to adjacent flowing water sections. Taxa richness and diversity in both the former impoundment and downstream sections increased after dam removal to become similar to the upstream section (Fig. A15.10). Functional traits—feeding behavior and movement habits, for example—allow us to link environmental conditions to the abundance and diversity of the different functional groups sampled. In the former impoundment, we observed an increase in taxa that feed by filtering water, like Hydropsychidae caddisflies, which may reflect increased water flow and available coarser substrates. We also observed a reduction in taxa that burrow and an increase in taxa that cling to rocks in the former impoundment after removal, reflecting the shift in habitat from stagnant to flowing water and from fine sediment and organic matter to coarser substrate (Fig. A15.11). These data suggest that macroinvertebrate assemblages have begun to recover within one year after dam removal, although the taxa present may be constrained by other negative anthropogenic impacts in this river. Additionally, reconstruction of the Mill St. Bridge (downstream of the former dam) in 2022 may impact downstream assemblages, making it difficult to determine whether future assemblages reflect the dam removal or other intensive construction taking place at this site.

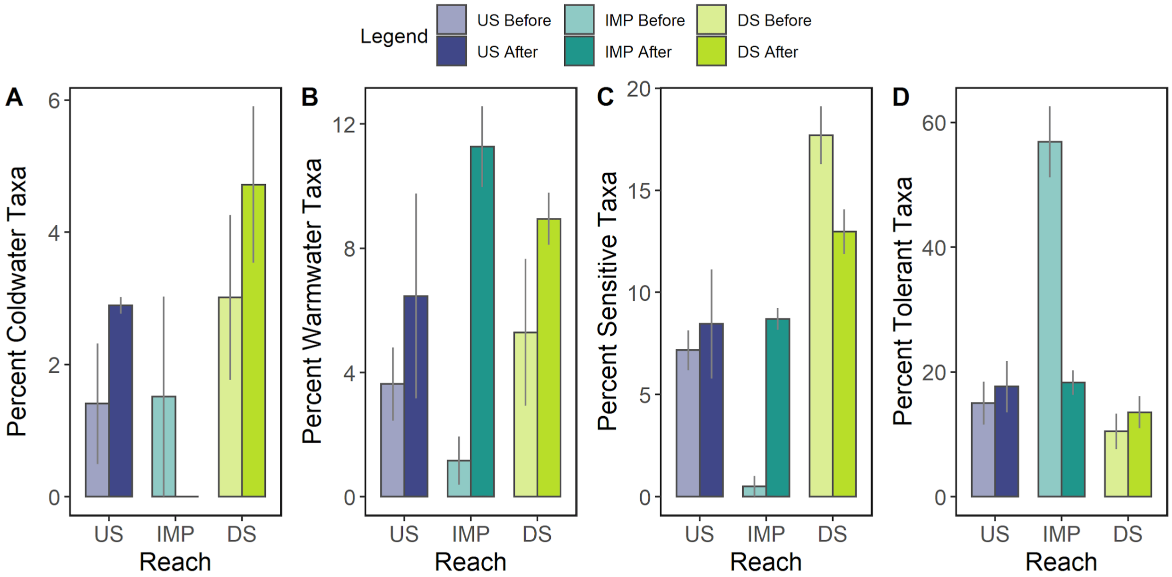


Figure A15.9) Mean percent of macroinvertebrate taxa by A) coldwater, B) warmwater, C) sensitive, and D) pollution-tolerant found within each sample in upstream (US), impoundment (IMP), and downstream (DS) stream sections before and after dam removal.

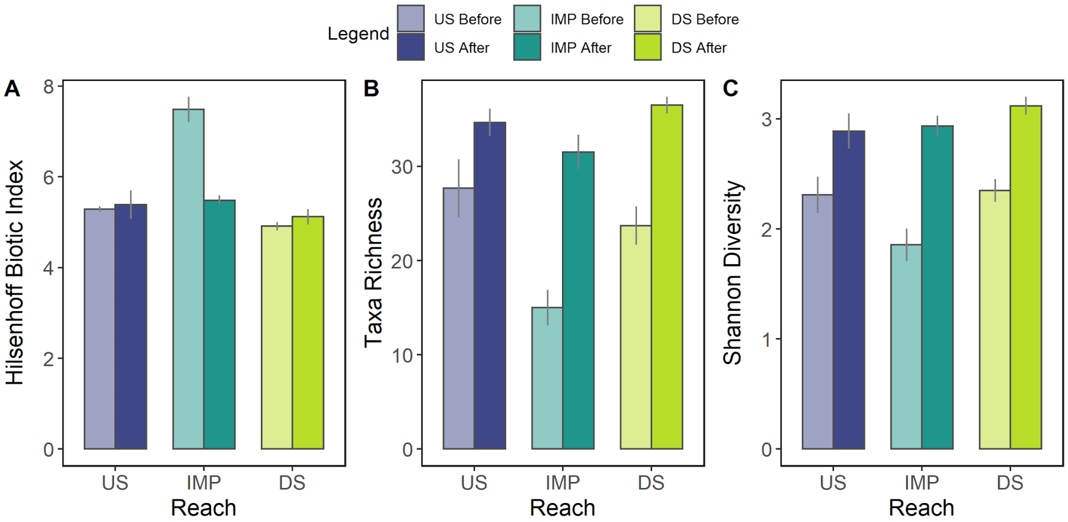


Figure A15.10) Mean macroinvertebrate biotic metric A) Hilsenhoff Biotic Index, B) total taxa richness, and C) Shannon diversity found in upstream (US), impoundment (IMP), and downstream (DS) sections before and after dam removal.

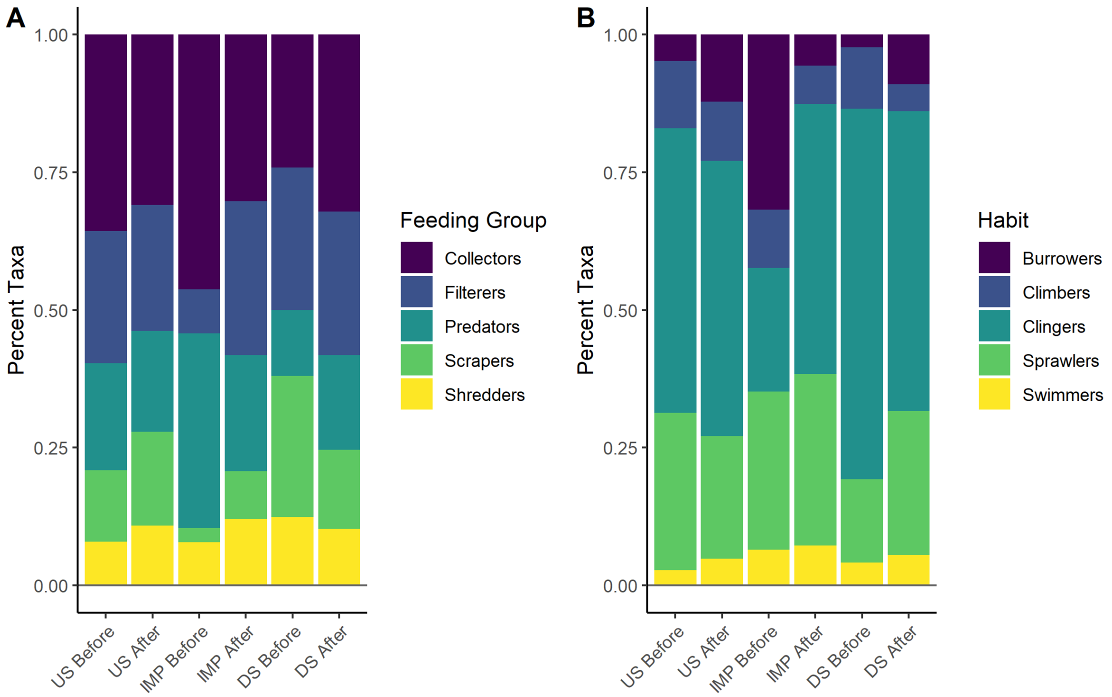


Figure A15.11) Percent of macroinvertebrate taxa by functional trait groups A) feeding group, and B) habit in upstream (US), impoundment (IMP), and downstream (DS) stream sections before and after dam removal. See Table A2.1 in Appendix 2 for information on feeding groups and habit categories.

Table A15.1. Averages of key ecological parameters before and after dam removal in each stream section (± 1 standard deviation).

Ecological Parameter	**Upstream Before**	**Upstream After**	**Impoundment Before**	**Impoundment After**	**Downstream† Before**	**Downstream After**
Stream Temperature (C)	22.2 ± 2.5	21.7 ± 3.1	22.7 ± 2.6	21.9 ± 3.0	21.9 ± 2.7	21.7 ± 2.4
Dissolved Oxygen (mg/L)	8.0 ± 0.3	8.2 ± 0.3	7.0 ± 0.5	7.8 ± 0.5	8.1 ± 0.3	7.5 ± 0.5
Hilsenhoff Biotic Index†† (HBI)	5.3 ± 0.2	5.4 ± 0.5	7.5 ± 0.8	5.5 ± 0.2	4.9 ± 0.2	5.1 ± 0.3

†Temperature from first downstream logger (DS1) only. ††Higher HBI indicates a greater relative abundance of pollution-tolerant macroinvertebrate taxa and suggests poorer water quality.

APPENDIX 16: Millie Turner Dam (TUR)

Sampling Overview

The Millie Turner Dam, a 10.2 ft tall (3.1 m) surface-release dam forming a 17.1-acre (6.9 ha) impoundment, was removed in fall 2015. This structure, located in Pepperell, MA, was the only remaining barrier on the Nissitissit River, a tributary to the Nashua River; however, there appear to be remains of an additional small defunct dam ~0.87 km upstream of this study area. This site is located in a 59.9 mi^2 (155.1 km^2) watershed that is 79% forest cover, 1.5% impervious cover, and 0.46% cultivated land, with a mean elevation of 448 ft (136.5 m) above sea level. This site was monitored for temperature, dissolved oxygen, benthic macroinvertebrates, and fishes both before and after dam removal.

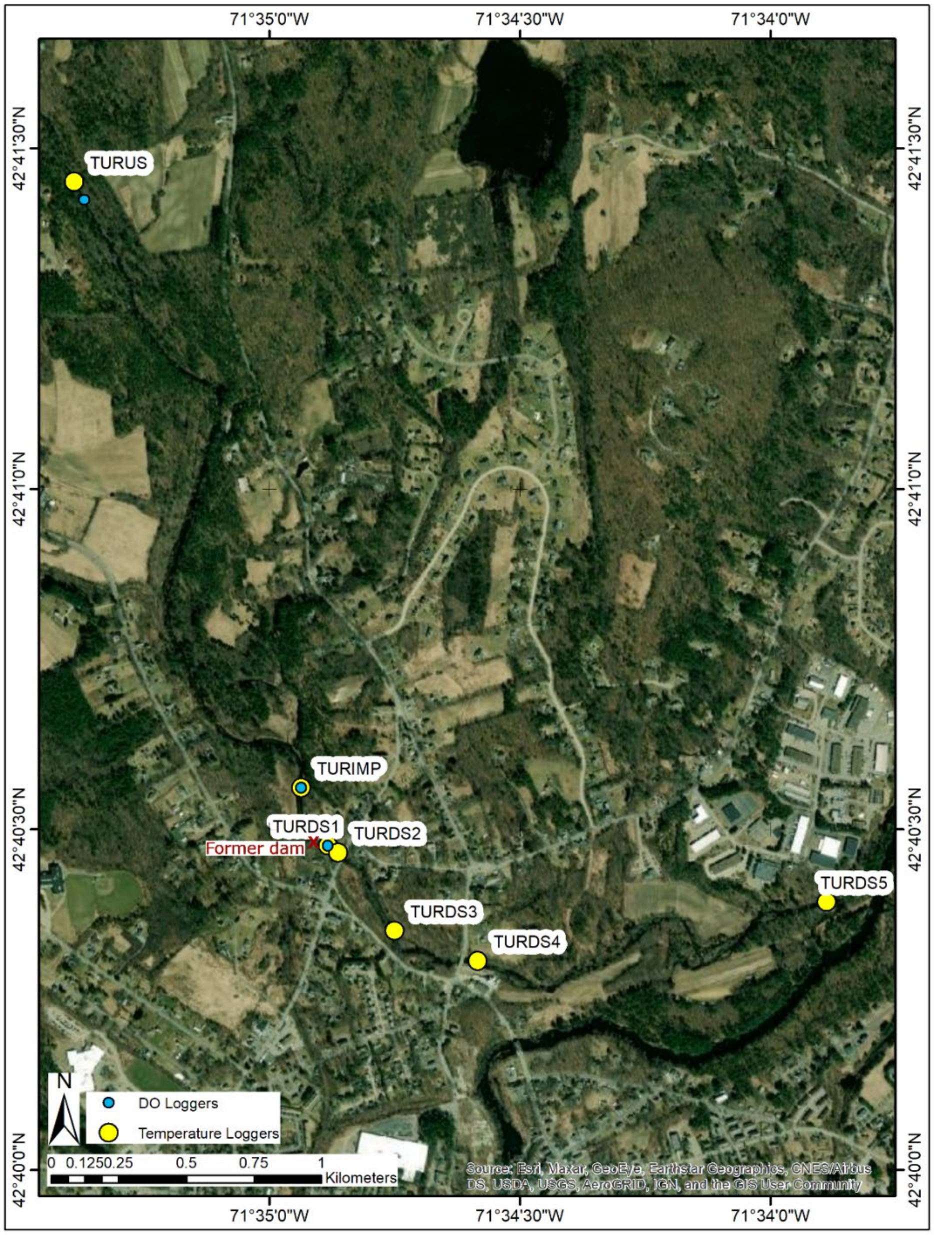


Figure A16.1. Map of temperature and dissolved oxygen logger locations in the Nissitissit River, Pittsfield, MA. Macroinvertebrates were sampled in approximately 100m sections around TURUS, TURIMP, and TURDS1 loggers. See Figure 1 in Study Design section for location within Massachusetts. Esri World Imagery Basemap accessed 10/18/2022.

One temperature data logger was deployed upstream of the impoundment (TURUS), within the impoundment (TURIMP), and five deployed downstream (TURDS1-TURDS5) of the dam, covering 1.1 mi (1.77 km) of the river downstream (Fig. A16.1). Temperature loggers were deployed in July 2015 and were retrieved in October 2020, capturing 1 year of pre-removal stream temperature and 5 years of post-removal stream temperature. Dissolved oxygen (DO) loggers were deployed upstream (TURUS), within the impoundment (TURIMP), and downstream (TURDS1) of Tel-Electric Dam or former dam location (Fig. A16.1) for approximately week-long deployments during summer months (July, August, and September) in 2015 and 2016. Summer DO was monitored for 1 year before removal and 1 year after dam removal.

Macroinvertebrates were sampled once per summer from 2015 to 2018, and again in 2020, capturing 1 year of pre-removal and up to 5 years of post-removal assemblages. In flowing stream sections (e.g., upstream, downstream, and former impoundment), 3 replicate Surber samples were taken in separate riffle habitats and a single representative multihabitat sample was collected throughout ~100 m of stream. Impoundment samples were not collected at this site. All samples were preserved in 70% ethanol prior to sorting and identification by Cole Ecological, Inc. or a trained UMass researcher. Up to 300 individuals were identified to the lowest practical taxonomic unit (usually genus or species, referred to as "taxa").

Fish sampling was also conducted in upstream and downstream sections by MassWildlife intermittently before and after dam removal; data summaries are provided in the General Results section of this final report. Temperature data are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Water quality data (temperature and dissolved oxygen) are also available through ScienceBase (https://doi.org/10.5066/P9L2ATHV). Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

Results

Temperature

Prior to dam removal, Millie Turner dam had a negative thermal impact on the Nissitissit River. Mean summer temperatures within the impoundment (21.8 °C) were higher than upstream temperatures (20.7 °C; Figure A16.2) and downstream temperatures ranged from 21.4 °C to 22.2 °C. The stream section near the DS4 logger had the highest stream temperature prior to dam removal (22.2 °C). Downstream warming—the mean difference between upstream and downstream (DS1) daily temperatures—was highest during summer months (July-Sept), although the spring temperature were not monitored at this site before removal (Fig. A16.3). September exhibited the highest downstream warming, with the downstream section over 1.2 °C warmer than the upstream section. Summer downstream temperatures (July-Sept.) were on average 0.89 °C higher than upstream, with moderate variability (SD= 0.5; Fig. A16.4). Temperatures generally cooled with increasing distance from the dam, at a slope of -0.15 °C/km (Fig. A16.5). These results suggest that the Millie Turner Dam had a small to moderate thermal impact on Nissitissit River temperatures within the impoundment and downstream, potentially altering thermally sensitive biotic assemblages, such as brook trout, during critical spawning periods (e.g., September).

After dam removal, we observed improvements in the thermal regime of the Nissitissit River. In the former impoundment, temperatures were reduced from 21.8 °C to 20.7 °C (1.1 °C difference); during the same years, upstream reference temperatures increased from 20.7 °C before removal to 21.1 °C after removal (0.4 °C difference). The magnitude of downstream warming decreased after dam removal and continued to improve over the 5 years monitored, eventually showing cooler temperatures downstream than upstream (Fig. A16.3). Summer downstream warming decreased from an average of 0.89 °C before removal to an average of -0.02 °C after removal. After removal, summer stream temperatures became cooler immediately downstream of the former impoundment and increased with increasing distance downstream (0.3 °C/km; Fig. A16.5). These results suggest that the Millie Turner Dam removal substantially improved the thermal regime throughout this section of river, and that stream temperatures recovered within 5 years after dam removal.

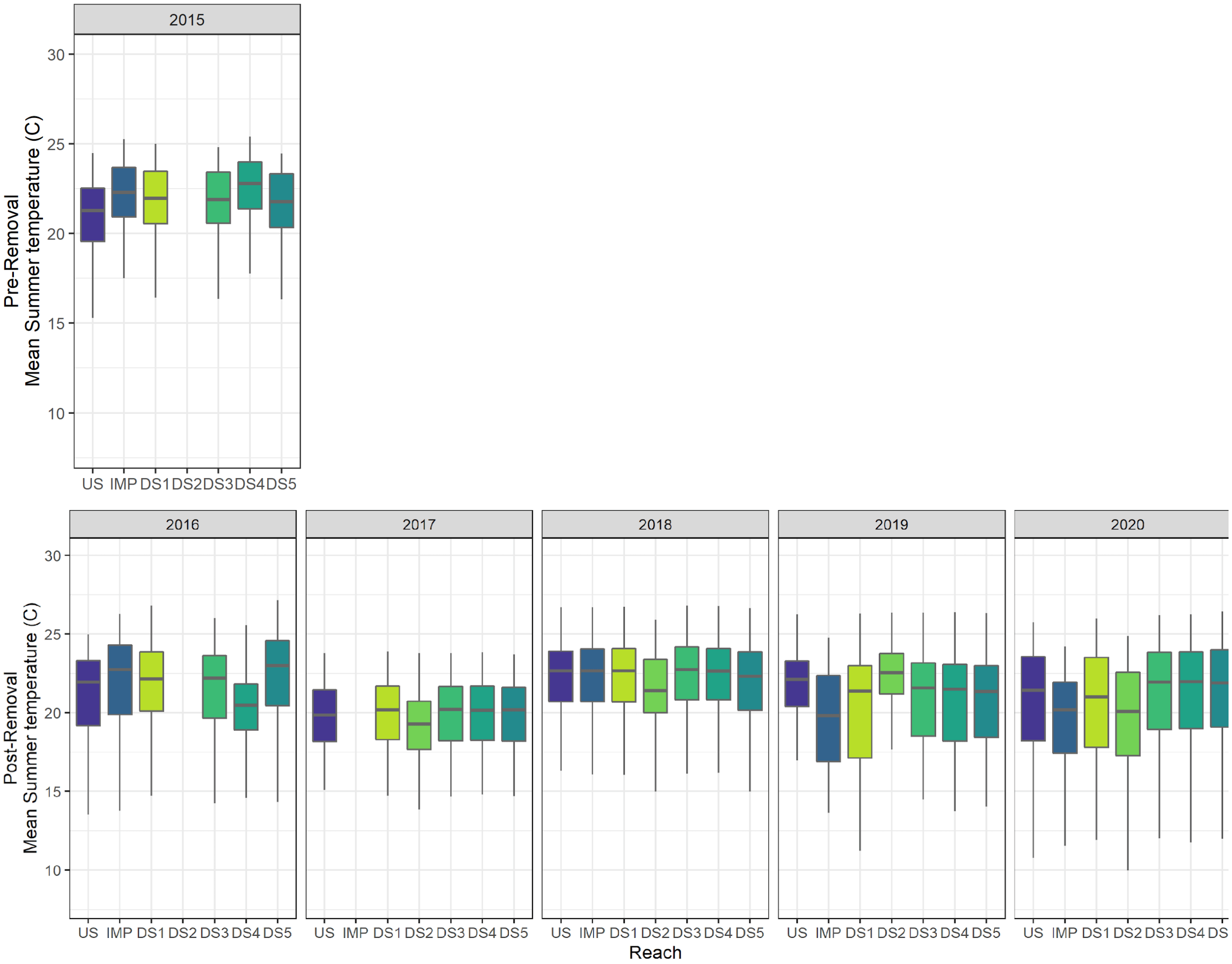


Figure A16.2) Mean summer (July-September) in-stream temperatures at each logger location A) before dam removal (2015) and B) after dam removal (2016-2020). Logger locations are indicated by the following abbreviations: US = upstream, IMP = Impoundment, DS1-DS5 = Downstream 1 through Downstream 5.

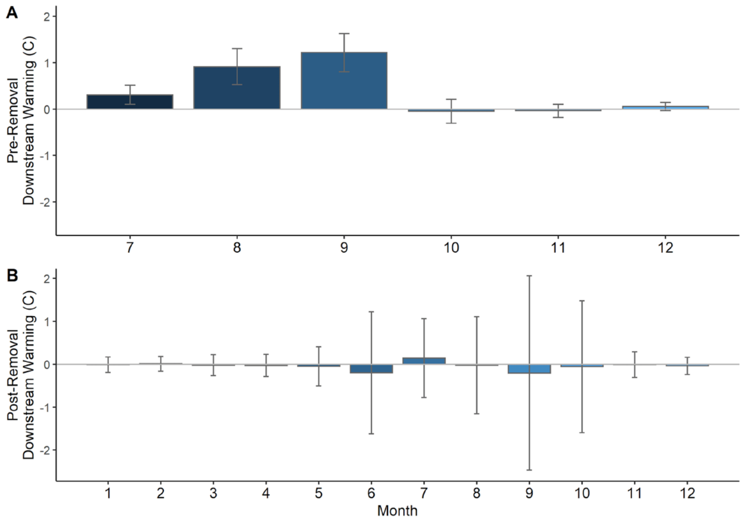


Figure A16.3) Downstream warming by month A) before (2015) and B) after dam removal (2016-2020).

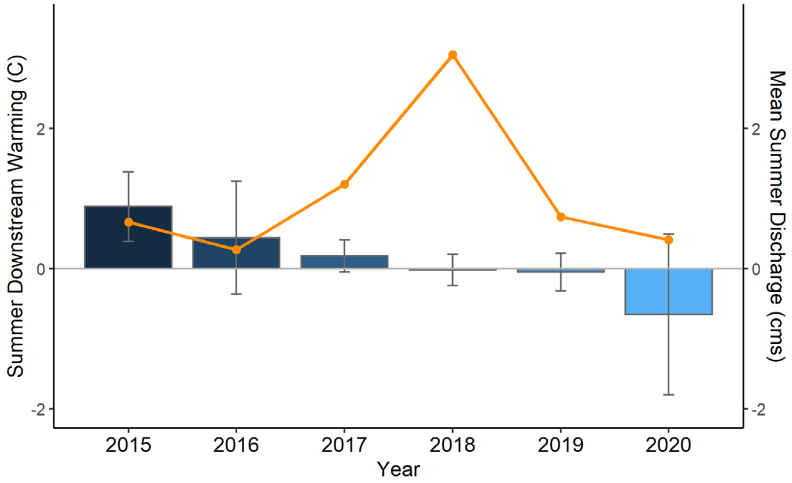


Figure A16.4) Summer (July-September) downstream warming (i.e., the difference between upstream and downstream temperatures ± SD; blue bars) and estimated mean summer discharge (orange line).

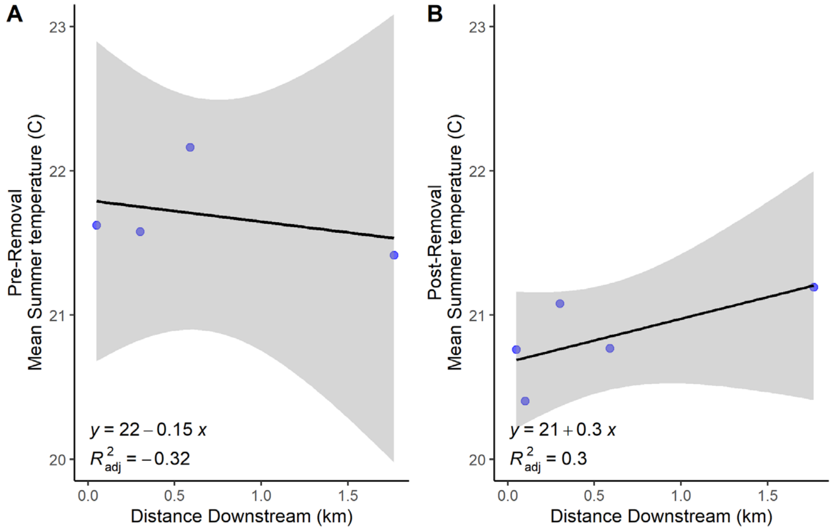


Figure A16.5) Mean summer temperature for each downstream logger (DS1-DS2) relative to the distance from the dam A) before and B) after dam removal. The black line represents the mean slope of linear temperature decay downstream of the dam.

Dissolved oxygen (DO)

Prior to removal, the Millie Turner Dam had moderate to large negative impacts on stream DO, particularly within the impoundment. The impoundment averaged 7.40 mg/L prior to removal, which was lower than DO concentrations within the upstream section (8.59 mg/L). Mean downstream DO (8.33 mg/L) was similar to the upstream concentrations (Fig. A16.6). Differences in DO daily ranges were observed among stream sections, with the impoundment exhibiting slightly higher daily ranges (0.86 mg/L) than that of the downstream (0.54 mg/L) and upstream (0.53 mg/L) sections (Fig. A16.7). Larger daily ranges typically indicate more plant and algal growth, as high rates of oxygen production during daytime photosynthesis and oxygen consumption via nighttime respiration result in larger daily oxygen fluxes (Diamond et al. 2021). No stream section monitored experienced DO less than 5 mg/L, a threshold below which waters may be considered impaired for DO (MassDEP 2016).

Following dam removal, DO concentrations within the former impoundment experienced an increase of 1.04 mg/L, from 7.40 to 8.44 mg/L on average, while upstream DO decreased by 0.25 mg/L. Mean downstream DO increased slightly by 0.34 mg/L, resulting in a relatively consistent DO regime from upstream to downstream sections (Fig. A16.6). Daily ranges exhibited a different response to dam removal, with an increase in DO daily ranges in both the former impoundment and downstream sections (Fig. A16.7). 2016 was a relatively dry, hot summer, and these high ranges may be reflective of those conditions, as well as the developing channel within the former impoundment. After dam removal, the channel contained more fine sediment and organic matter, which was gradually exported in the following years. In the year after dam removal, DO impairment (i.e., concentrations less than 5 mg/L) did not occur in any stream section.

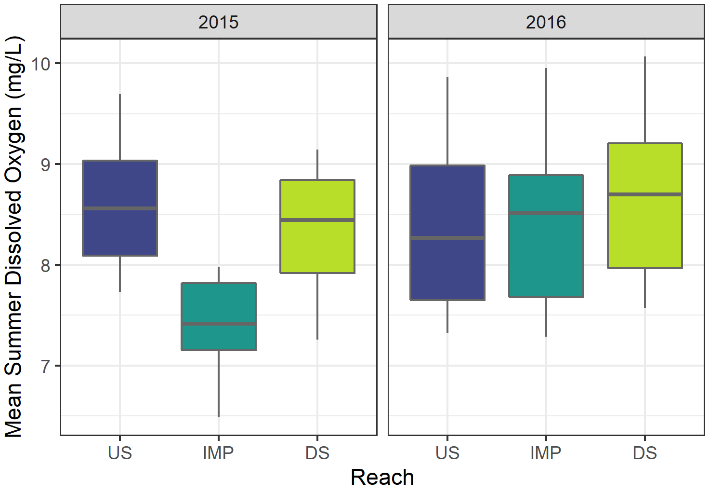


Figure A16.6) Mean summer (July-September) dissolved oxygen concentrations in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2016. Dam removal occurred in fall 2015, after the summer deployment.

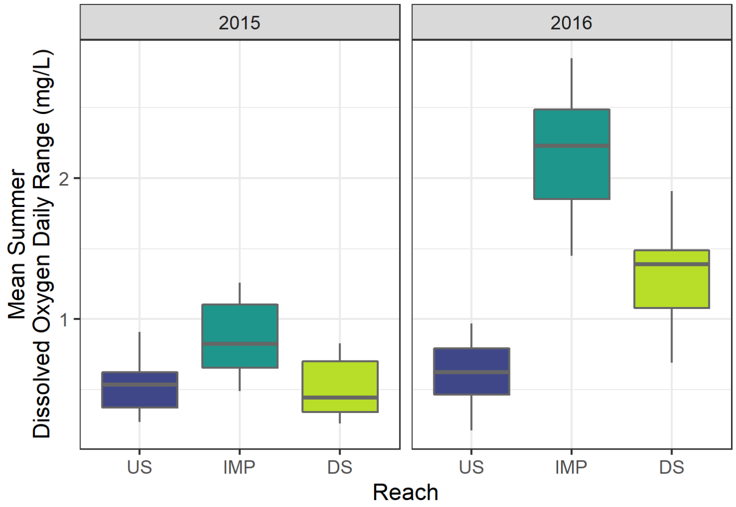


Figure A16.7) Mean summer (July-September) daily range of dissolved oxygen levels in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2016. Dam removal occurred in fall 2015, after the summer deployment.

Macroinvertebrates

Prior to dam removal, we found that macroinvertebrate taxa differed slightly between upstream and downstream sections, which may reflect differences in water quality or habitat availability. For example, the percent of taxa (unique organisms) classified as coldwater (thermal optimum <18 °C) was lower downstream (5.1%) as compared to upstream (7.1%), and the percent of warmwater (>20 °C) taxa was slightly higher downstream (9.6%) as compared to upstream (8.4%). In general, coolwater (18-20 °C) taxa comprised most taxa at this site. We observed a slightly greater percentage of pollution-tolerant taxa in the downstream section (8.1%) than in the upstream section (6.1%; Fig. A16.8). The Hilsenhoff Biotic Index (HBI), which estimates the overall pollution tolerance weighted by the relative abundance of each taxa (Hilsenhoff 1988), also indicated more pollution tolerant taxa within the downstream section relative upstream. The total number of taxa (taxa richness) and diversity, which incorporates both richness and abundance of taxa, were both similar in upstream and downstream sections (Fig. A16.9).

After dam removal, the percent of warm and coldwater taxa in the downstream section did not substantially change. Both very sensitive and very tolerant taxa decreased downstream, suggesting an increase in moderately tolerant taxa (Fig. A16.8). Downstream HBI scores and diversity did not substantially change after dam removal, but taxa richness slightly decreased to be more similar to the upstream section (Fig. A16.9). Functional traits—feeding behavior and movement habits, for example—allow us to link environmental conditions to the abundance and diversity of the different functional groups sampled. There were relatively minor differences between upstream and downstream sections in functional feeding groups. The downstream section had slightly more "scrapers", which are taxa that feed on detritus and algae growing on rocks, and slightly fewer "filterers" than upstream (Fig A16.10). This suggests the dam was likely trapping fine organic matter and silt that filterers feed on, and the water clarity facilitated periphyton growth on substrates. These stream sections became more similar following dam removal. There was little change in the movement habits of macroinvertebrate taxa (Fig. A16.10), suggesting minimal habitat alteration downstream after dam removal. Though on average, the percent of sensitive taxa decreased downstream after dam removal, there was variability between years, with sensitive taxa recovering to upstream levels within 3 years after dam removal and decreasing again at 5 years after (Fig. A16.11). This may be related to drought conditions experienced during the final year of sampling, which reduced flows downstream.

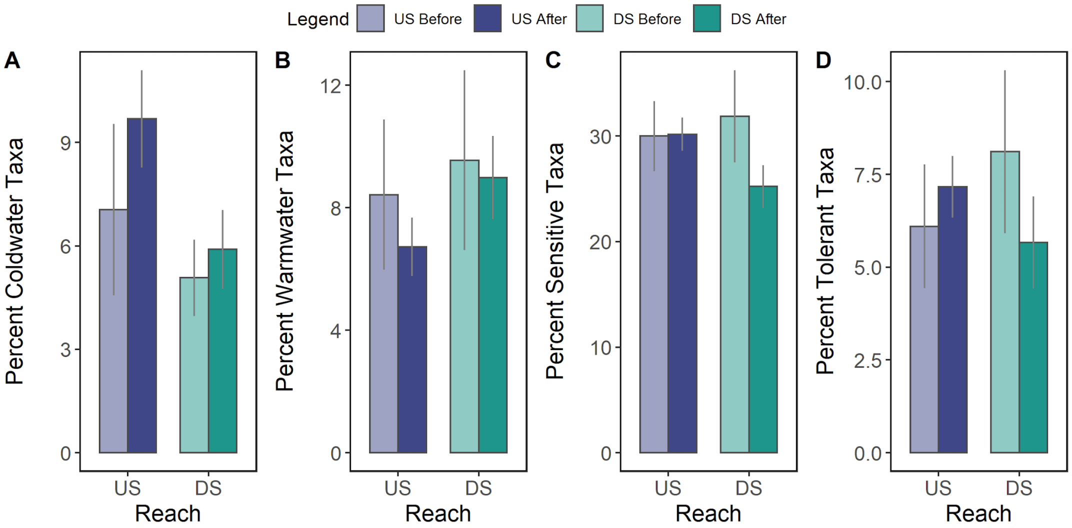


Figure A16.8) Mean percent of macroinvertebrate taxa by A) coldwater, B) warmwater, C) sensitive, and D) pollution-tolerant found within each sample in upstream (US) and downstream (DS) stream sections before and after dam removal.

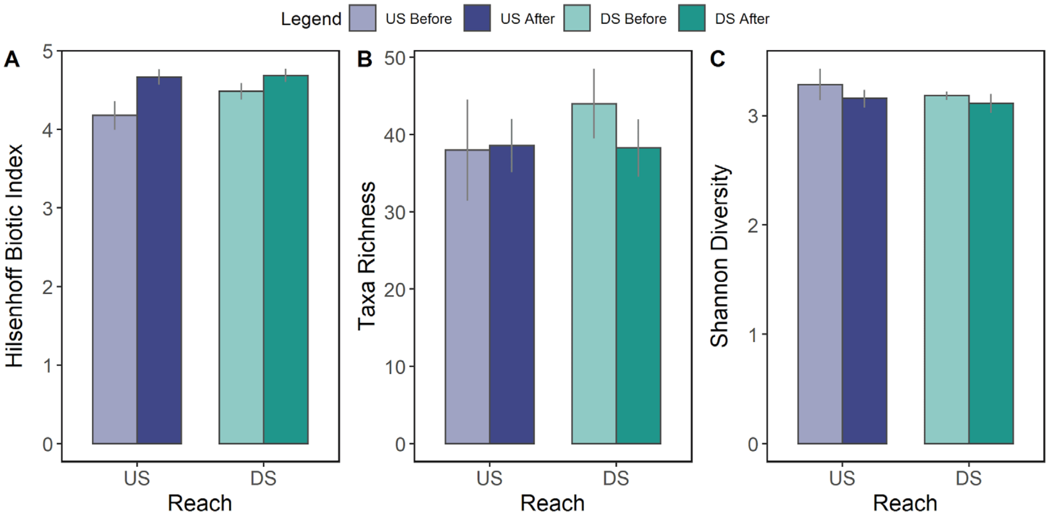


Figure A16.9) Mean macroinvertebrate biotic metric A) Hilsenhoff Biotic Index, B) total taxa richness, and C) Shannon diversity found in upstream (US) and downstream (DS) sections before and after dam removal.

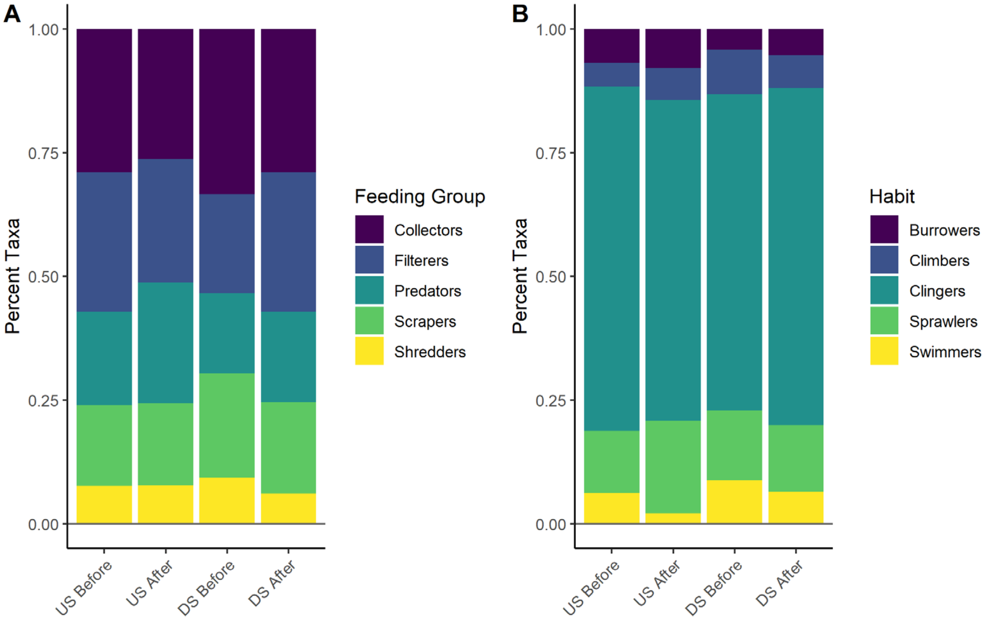


Figure A16.10) Percent of macroinvertebrate taxa by functional trait groups A) feeding group, and B) habit in upstream (US) and downstream (DS) stream sections before and after dam removal. See Table A2.1 in Appendix 2 for information on feeding groups and habit categories.

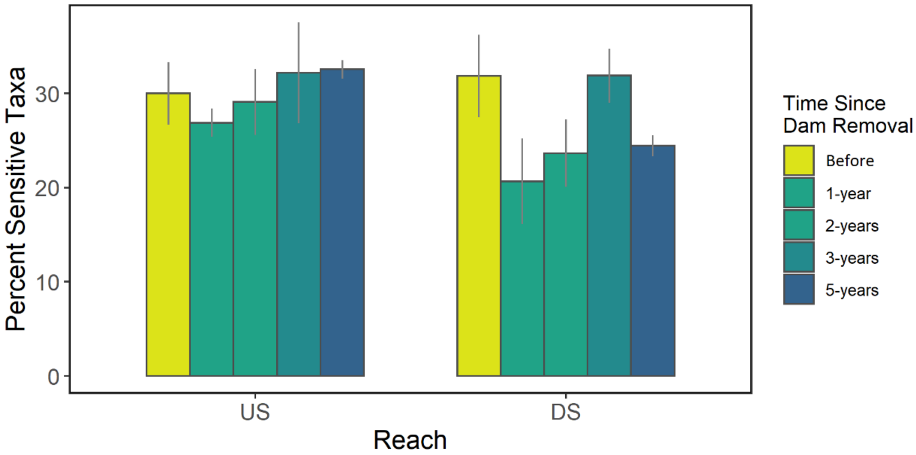


Figure A16.11) Percent of sensitive macroinvertebrate taxa in upstream (US) and downstream (DS) stream sections before (pre) and in the years after dam removal (1, 2, 3, and 5 years).

Table A16.1. Averages of key ecological parameters before and after dam removal in each stream section (± 1 standard deviation).

Ecological Parameter	Upstream Before	Upstream After	Impoundment Before	Impoundment After	Downstream[†] Before	Downstream After
Stream Temperature (C)	20.7 ± 2.7	21.1 ± 2.9	21.8 ± 2.5	20.7 ± 3.3	21.6 ± 2.5	20.8 ± 3.4
Dissolved Oxygen (mg/L)	8.6 ± 0.6	8.3 ± 0.8	7.4 ± 0.5	8.4 ± 0.8	8.3 ± 0.6	8.7 ± 0.8
Hilsenhoff Biotic Index[††] (HBI)	4.2 ± 0.3	4.7 ± 0.3	-	-	4.5 ± 0.2	4.7 ± 0.3

[†] Temperature from first downstream logger (DS1) only. [††] Higher HBI indicates a greater relative abundance of pollution-tolerant macroinvertebrate taxa and suggests poorer water quality.

APPENDIX 17: Upper Roberts Meadow Brook Dam (URM)

Sampling Overview

Upper Roberts Meadow Brook Dam, a 35.1-ft tall (10.7 m) surface-release dam forming a 4.2-acre (1.7 ha) impoundment, was removed in summer/fall 2018. This structure, located in Northampton, MA, was the upstream-most barrier on Roberts Meadow Brook, and there are 2 remaining dams downstream. This site is located in an 8.8 mi^2 (22.8 km^2) watershed that is 87% forest cover, 0.2% impervious cover, and 0.35% cultivated land, with a mean elevation of 922 ft (281 m) above sea level. This site was monitored for temperature, dissolved oxygen, benthic macroinvertebrates, and fishes both before and after dam removal.

One temperature data logger was deployed upstream of the impoundment (URMUS), one within the impoundment (URMIMP), and five deployed downstream (URMDS1-URMDS5) of the dam, covering 1.1 mi (1.75 km) of the river to the upper extent of Middle Roberts Meadow Reservoir (Fig. A17.1). Temperature loggers were deployed in June 2015 and remain in the field until present, capturing 4 years of pre-removal stream temperature and 3 years of post-removal stream temperature. The dam removal occurred in summer 2018, so data from this removal period are not presented. Dissolved oxygen (DO) loggers were deployed upstream (URMUS), within the impoundment (URMIMP), and downstream (URMDS1) of the Upper Roberts Meadow Brook Dam or former dam location (Fig. A17.1) for approximately week-long deployments during summer months (July, August, and September) from 2015 to 2019. Summer DO was monitored for 3 years before removal and 1 year after dam removal.

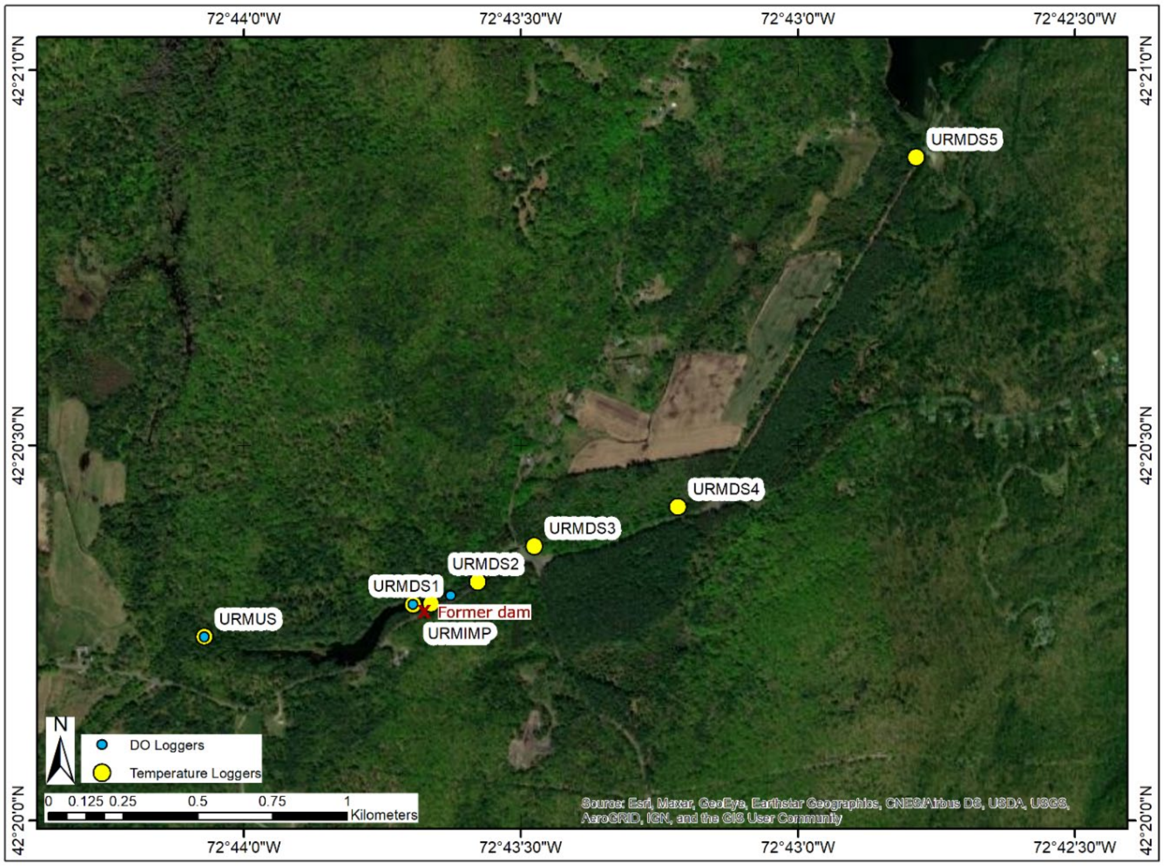


Figure A17.1. Map of temperature and dissolved oxygen logger locations in Roberts Meadow Brook, Northampton, MA. Macroinvertebrates were sampled in approximately 100m sections around URMUS, URMIMP, and URMDS1 loggers. See Figure 1 in Study Design section for location within Massachusetts. Esri World Imagery Basemap accessed 10/18/2022.

Macroinvertebrates were sampled once per summer from 2016 to 2021, capturing 2 years of pre-removal and up to 3 years of post-removal assemblages. Within impounded areas, 3 replicate Ponar sediment grab samples were collected from randomly selected locations, and along impoundment margins, 3 replicate sweeps of submerged and emergent vegetation were conducted using a rectangular net. In flowing stream sections (e.g., upstream, downstream, and former impoundment), 3 replicate Surber samples were taken in separate riffle habitats and a single representative multihabitat sample was collected throughout ~100 m of stream. All samples were preserved in 70% ethanol prior to sorting and identification by Cole Ecological, Inc. or a trained UMass researcher. Up to 300 individuals were identified to the lowest practical taxonomic unit (usually genus or species, referred to as "taxa").

Fish sampling was also conducted in upstream and downstream sections by MassWildlife intermittently before and after dam removal; data summaries are provided in the General Results section of this final report. Temperature data are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Water quality data (temperature and dissolved oxygen) are also available through ScienceBase (https://doi.org/10.5066/P9L2ATHV). Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

Results

Temperature

Prior to removal, the Upper Roberts Meadow Brook Dam had large negative impacts on the thermal regime of this small, coldwater stream, particularly within the impoundment. Mean summer temperatures within the impoundment (20.0 °C) were higher than the upstream temperatures (17.0 °C; Fig. A17.2) and downstream temperatures ranged from 19.6 °C to 18.6 °C. Downstream warming—the mean difference between upstream and downstream (DS1) daily temperatures—was highest during summer months (July-Sept.) but persisted into the spring and fall as well. Summer downstream temperatures (July-Sept.) were on average 2.43 °C higher than upstream temperatures prior to removal, with high variability (SD= 1.05; Fig. A17.4). In 2016, a relatively dry and warm summer, downstream temperatures were over 3 °C warmer than upstream, suggesting that flow and ambient air temperatures may drive interannual variability in thermal impacts. Summer downstream temperatures cooled with increasing distance from the dam, with a slope of -0.52 °C/km (Fig. A17.5). These results suggest that Upper Roberts Meadow Brook Dam had a large thermal impact on stream temperatures within the impoundment and downstream.

Following dam removal, a more natural thermal regime was restored to the upper section of Roberts Meadow Brook. In the former impoundment, temperatures were reduced from 20.0 °C to 17.6 °C (2.4 °C difference); during the same years, upstream reference temperatures averaged 17.0 °C before removal to 16.9 °C after removal (0.1 °C difference). Downstream warming continued to be highest during summer months (July-Sept), but the magnitude was greatly reduced following dam removal (Fig. A17.3). Mean summer downstream warming significantly decreased following dam removal (before: 2.43, after: 0.81, $t=-23.3$, $p<0.001$), although did not recover to meet upstream temperatures. It is possible that temperatures within the former impoundment and downstream will reduce over time as riparian vegetation develops and provides more shading. After removal, summer stream temperatures decreased with increasing distance downstream, but with a lower slope (-0.3 °C/km), which suggests a more natural thermal regime throughout these stream sections (Fig. A17.5). These results suggest that this dam removal improved the thermal regime throughout this section of river, particularly by reducing impoundment temperatures and inducing more consistent temperatures from the upstream to the furthest downstream sections. In 2021, the upstream temperature logger was lost due to high flows, so downstream warming could not be calculated. It is possible we will observe further cooling downstream with continued monitoring in 2022.

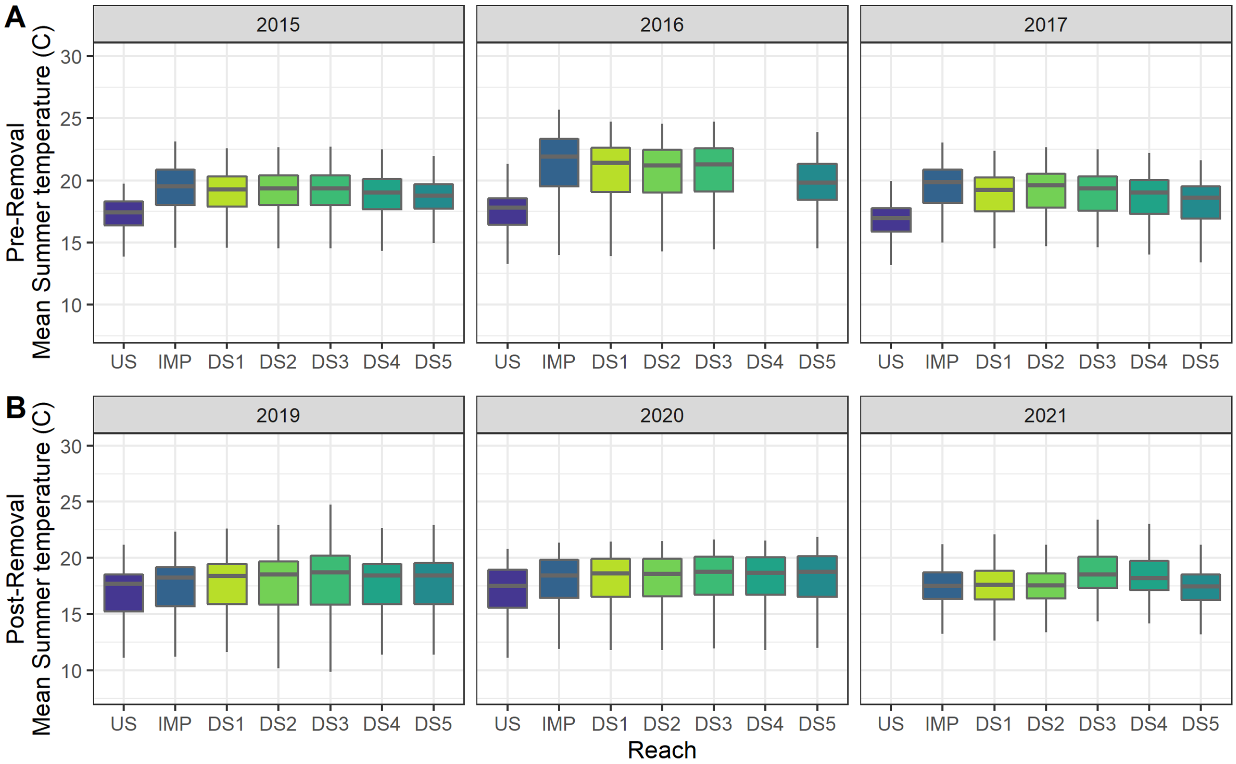


Figure A17.2) Mean summer (July-September) in-stream temperatures at each logger location A) before dam removal (2015-2017) and B) after dam removal (2019-2021). Logger locations are indicated by the following abbreviations: US = upstream, IMP = Impoundment, DS1-DS5 = Downstream 1 through Downstream 5.

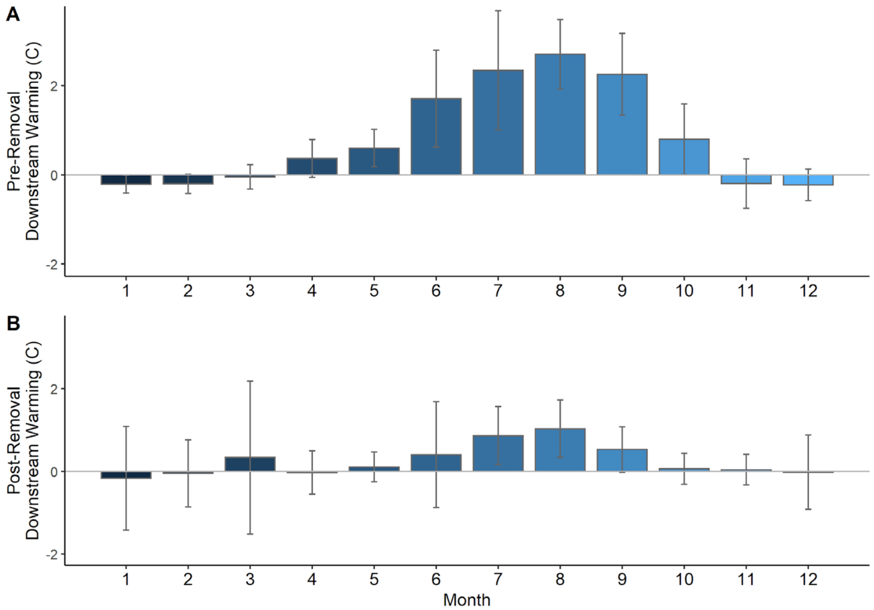


Figure A17.3) Downstream warming by month A) before (2015-2017) and B) after dam removal (2019-2021).

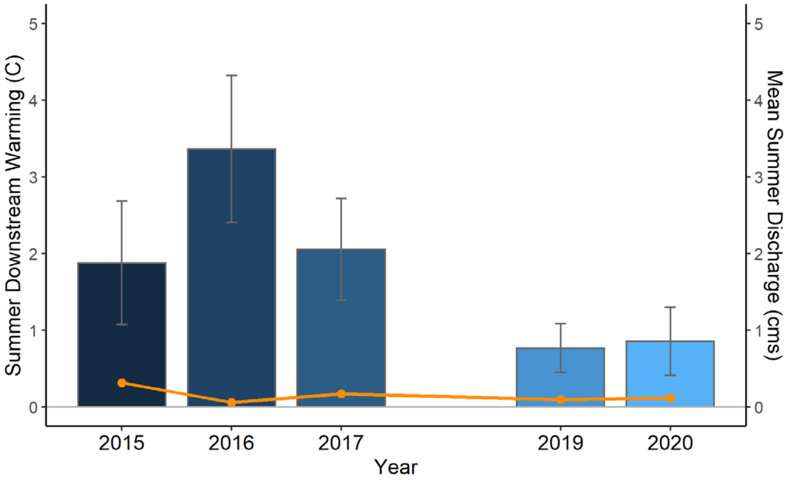


Figure A17.4) Summer (July-September) downstream warming (i.e., the difference between upstream and downstream temperatures ± SD; blue bars) and estimated mean summer discharge (orange line).

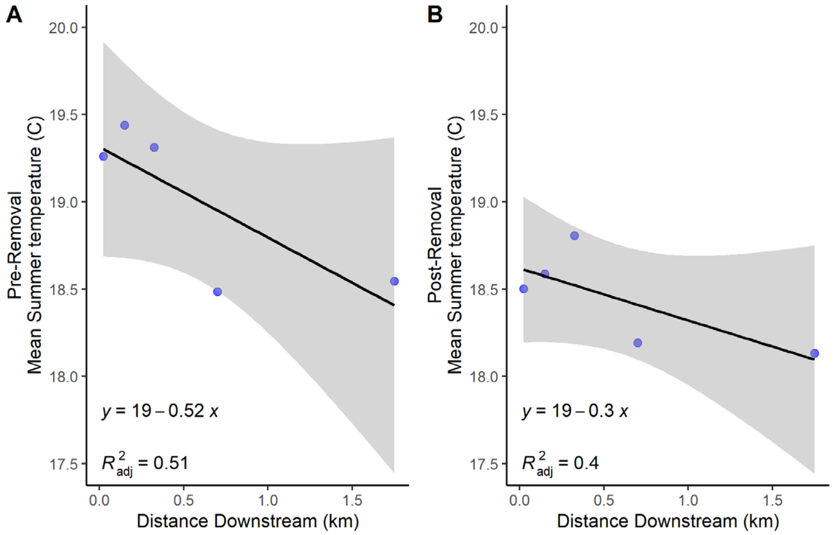


Figure A17.5) Mean summer temperature for each downstream logger (DS1-DS5) relative to the distance from the dam A) before and B) after dam removal. The black line represents the mean slope of linear temperature decay downstream of the dam.

Dissolved oxygen (DO)

Prior to removal, Upper Roberts Meadow Brook Dam had large negative impacts on stream DO, particularly in the impoundment and downstream sections. The impoundment averaged 7.92 mg/L prior to removal (Fig. A17.6), compared to 9.44 mg/L within the upstream section. Downstream DO concentrations averaged slightly lower than upstream concentrations, at 8.73 mg/L. This pattern remained consistent across years. The daily DO range within the impoundment (2.35 mg/L) was more than 4 times larger than the daily range within the upstream section (0.49 mg/L), suggesting more eutrophic conditions within the impoundment. Daily ranges downstream (0.68 mg/L) were slightly greater than in the upstream section (Fig A17.7). We observed some variability in DO impact from year to year, with lower DO and larger ranges in 2016, a relatively hot and dry summer. During 2016 and 2017, the impoundment experienced some duration of DO less than 5 mg/L (Fig. A17.8), a threshold below which waters may be considered impaired for DO (MassDEP 2016).

Following dam removal, DO concentrations within the former impoundment experienced an increase of 1.33 mg/L, from 7.92 to 9.25 mg/L on average, while upstream DO remained fairly consistent, decreasing only by 0.05 mg/L. Mean downstream DO increased by 0.45 mg/L, resulting in a relatively consistent DO regime from upstream to downstream sections. Daily ranges within the former impoundment decreased following dam removal, and downstream ranges increased to be more similar to the formerly impounded section, although both sections maintained slightly larger ranges than upstream (Fig. A17.7). In the year monitored after dam removal, DO impairment (i.e., concentrations less than 5 mg/L) did not occur in any stream section (Fig. A17.8).

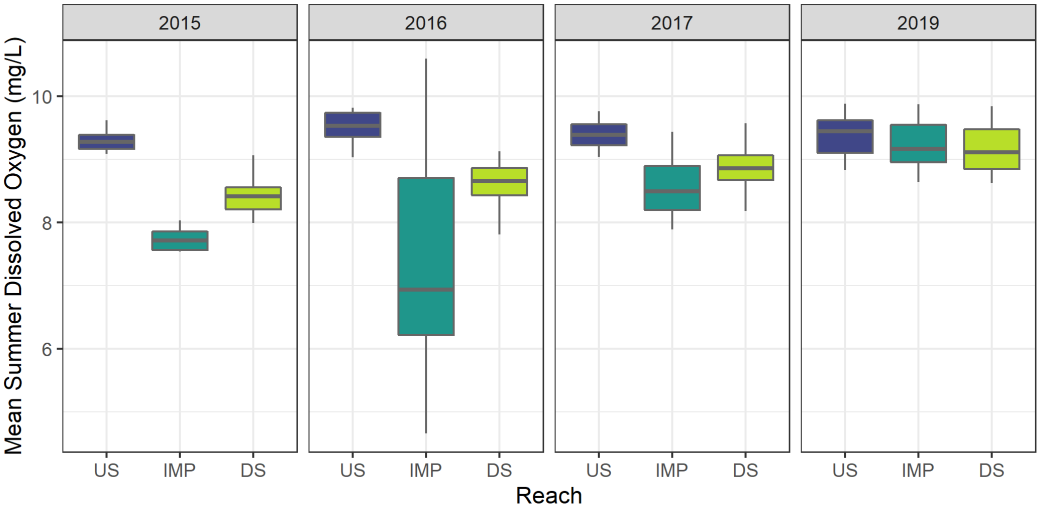


Figure A17.6) Mean summer (July-September) dissolved oxygen concentrations in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2019. Dam removal occurred in summer 2018.

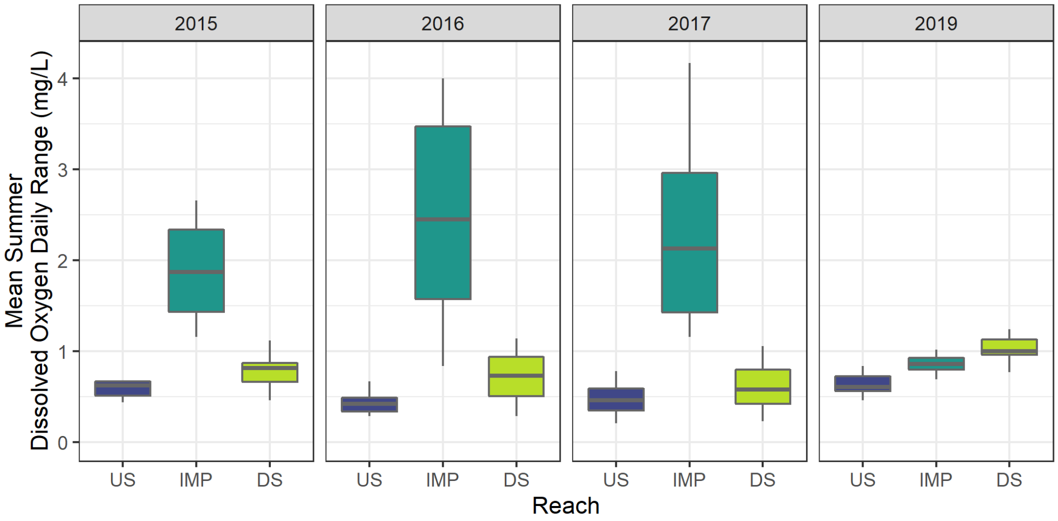


Figure A17.7) Mean summer (July-September) daily range of dissolved oxygen levels in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2015-2019. Dam removal occurred in summer 2018.

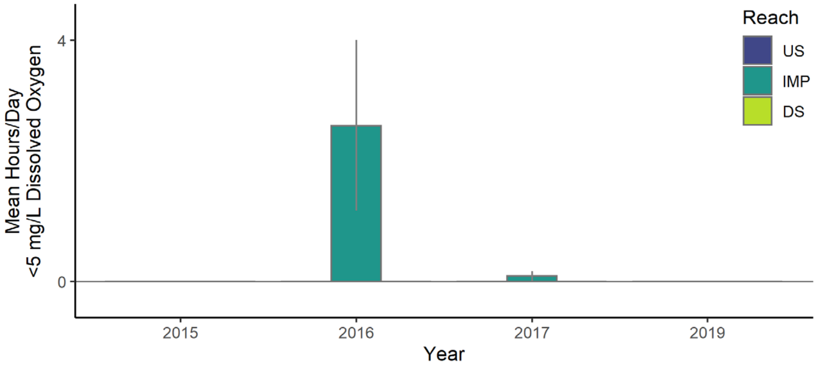


Figure A17.8) Mean and standard error (SE) hours per day that upstream (US), impoundment (IMP) and downstream (DS) stream sections spent below 5.0 mg/L, a threshold below which waters may be considered impaired for DO (MassDEP 2016). Few stream sections experienced DO < 5 mg/L for any time, except the impoundment in 2016 and 2017.

Macroinvertebrates

Prior to dam removal, we found that the Upper Roberts Meadow Dam had a larger impact on the macroinvertebrate assemblages found within the impoundment and downstream, likely due to changes in water quality (e.g., temperature) and habitat availability. For example, the percent of taxa (unique organisms) classified as coldwater (thermal optimum <18 °C) was lower within the impoundment (11.4%) and downstream (11.5%) as compared to upstream (30.1%; Fig. A17.9). In general, coolwater (18-20 °C) taxa comprised most taxa at this site, and a few warmwater taxa were observed in the impoundment and downstream, while no warmwater taxa were found upstream before dam removal. We observed a much smaller percentage of sensitive taxa within the impoundments (6.5%) than the upstream section (40.8%) and a much greater percentage of pollution-tolerant taxa (57.6%) than upstream (6.5%; Fig. A17.9). The Hilsenhoff Biotic Index (HBI), which estimates the overall pollution tolerance weighted by the relative abundance of each taxa (Hilsenhoff 1988), also indicated more pollution tolerant taxa within the impoundment relative to flowing water sections. The total number of taxa (taxa richness) was lower within the impoundment compared to the flowing water sections, and diversity, which incorporates both richness and abundance of taxa, followed a similar pattern (Fig. A17.10).

After dam removal, the former impoundment exhibited a dramatic increase in sensitive taxa, and a corresponding decrease in tolerant taxa (Fig. A17.9), which may reflect an improvement in water quality and habitat with the shift from stagnant to flowing water. There also was an increase in coldwater taxa within both the former impoundment and downstream sections, and a loss of warmwater taxa that were present prior to removal (Fig. A17.9). This may reflect the reduction in stream temperature in those sections due to dam removal and reduced solar radiation. HBI scores in the former impoundment decreased to become more similar to adjacent flowing water sections, while downstream HBI scores did not change. Taxa richness in both the former impoundment and downstream sections became more similar to the upstream section, while diversity in the former impoundment increased slightly (Fig. A17.10). Functional traits—feeding behavior and movement habits, for example—allow us to link environmental conditions to the abundance and diversity of the different functional groups sampled. In the former impoundment, we observed an increase in taxa that feed by filtering water, like Hydropsychidae caddisflies, which may reflect increased water flow and available coarser substrates. We also observed a reduction in taxa that burrow and sprawl and an increase in taxa that cling to rocks in the former impoundment after removal, reflecting the shift in habitat from stagnant to flowing water and from fine sediment and organic matter to coarser substrate (Fig. A17.11). The percent of sensitive taxa within the impoundment and downstream recovered to be similar to upstream levels within 1 year after dam removal (Fig. A17.12), which is especially notable because this dam removal involved a passive sediment release. Macroinvertebrate densities downstream were also similar before and after dam removal, suggesting minimal negative impacts from dam removal. These data suggest that this dam removal led to more similar macroinvertebrate assemblages from upstream to downstream sections and improved water quality for thermally sensitive taxa within 1 year.

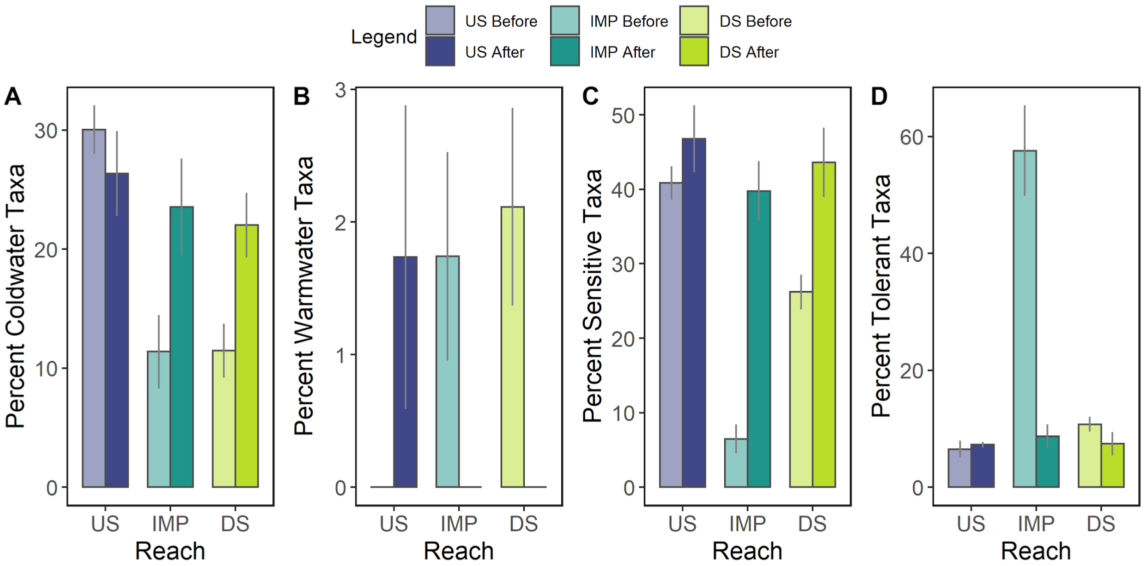


Figure A17.9) Mean percent of macroinvertebrate taxa by A) coldwater, B) warmwater, C) sensitive, and D) pollution-tolerant found within each sample in upstream (US), impoundment (IMP), and downstream (DS) stream sections before and after dam removal.

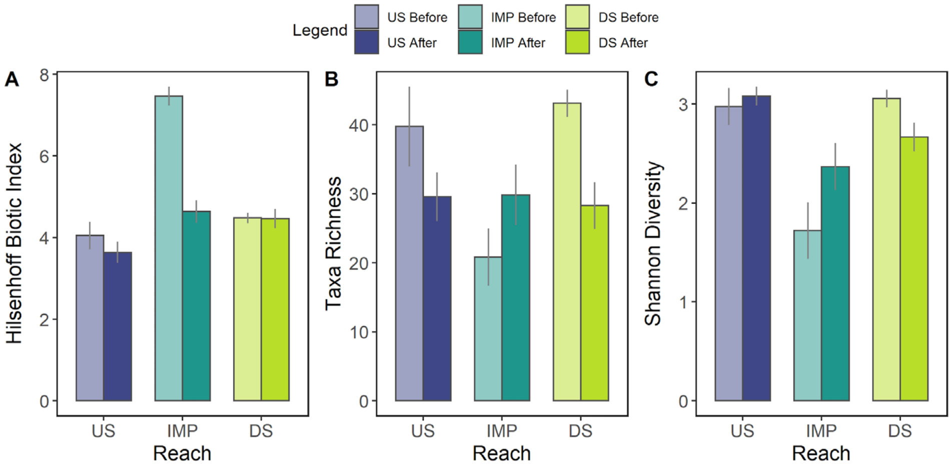


Figure A17.10) Mean macroinvertebrate biotic metric A) Hilsenhoff Biotic Index, B) total taxa richness, and C) Shannon diversity found in upstream (US), impoundment (IMP), and downstream (DS) sections before and after dam removal.

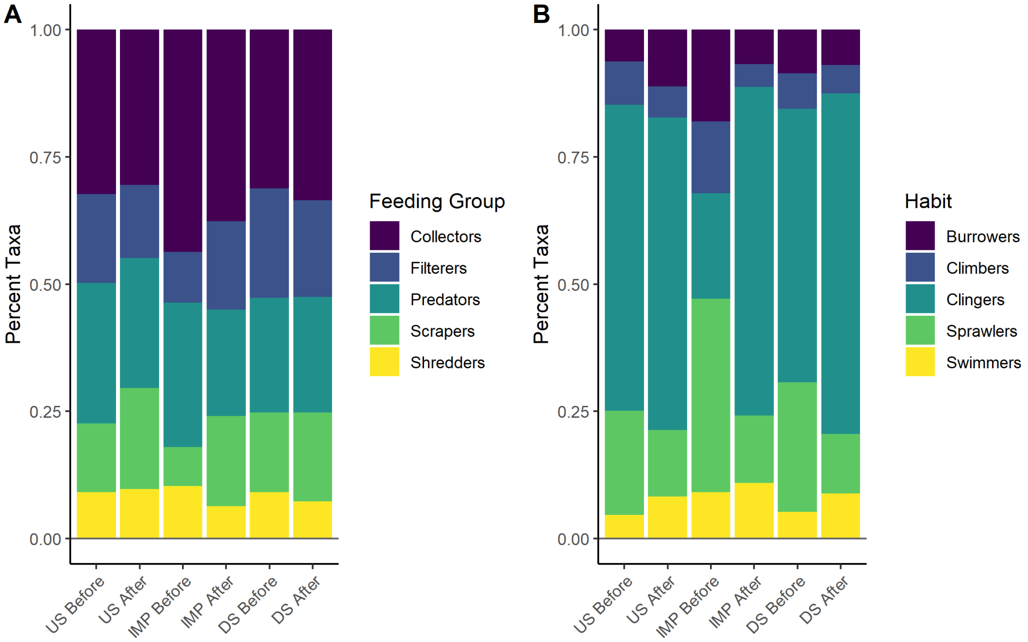


Figure A17.11) Percent of macroinvertebrate taxa by functional trait groups A) feeding group, and B) habit in upstream (US), impoundment (IMP), and downstream (DS) stream sections before and after dam removal. See Table A2.1 in Appendix 2 for information on feeding groups and habit categories.

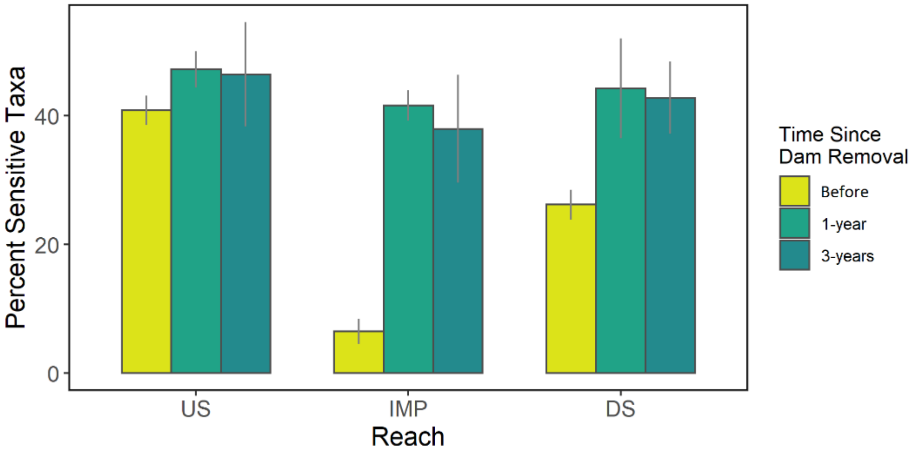


Figure A17.12) Percent of sensitive macroinvertebrate taxa in upstream (US), impoundment (IMP), and downstream (DS) stream sections before (pre) and in the years after dam removal (1 and 3 years).

Table A17.1. Averages of key ecological parameters before and after dam removal in each stream section (± 1 standard deviation).

Ecological Parameter	**Upstream Before**	**Upstream† After**	**Impoundment Before**	**Impoundment After**	**Downstream Before**	**Downstream After**
Stream Temperature (C)	17.4 ± 1.9	16.8 ± 2.4	20 ± 2.4	17.6 ± 2.4	19.5 ± 2.4	17.6 ± 2.4
Dissolved Oxygen (mg/L)	9.4 ± 0.3	9.4 ± 0.3	7.9 ± 1.3	9.3 ± 0.4	8.7 ± 0.4	9.2 ± 0.4
Hilsenhoff Biotic Index†† (HBI)	4.1 ± 1.0	3.7 ± 0.8	7.5 ± 0.8	4.6 ± 0.8	4.5 ± 0.4	4.4 ± 0.6

†Temperature from first downstream logger (DS1) only. ††Higher HBI indicates a greater relative abundance of pollution-tolerant macroinvertebrate taxa and suggests poorer water quality.

APPENDIX 18: Wheelwright Dam (WHE)

Sampling Overview

Wheelwright Dam, located in the village of Wheelwright, town of Hardwick, MA, is a 17.1 ft tall (5.2 m) surface-release dam forming a 52.9-acre (21.4 ha) impoundment. This structure is one of several remaining barriers on the Ware River. This site is located in a 129 mi^2 (334 km^2) watershed that is 74% forest cover, 1.2% impervious cover, and 0.3% cultivated land, with a mean elevation of 953 ft (290.5 m) above sea level. This site was monitored for temperature, dissolved oxygen, benthic macroinvertebrates, and fishes to determine the ecological impacts of the dam and to provide a baseline for future assessments of dam removal responses.

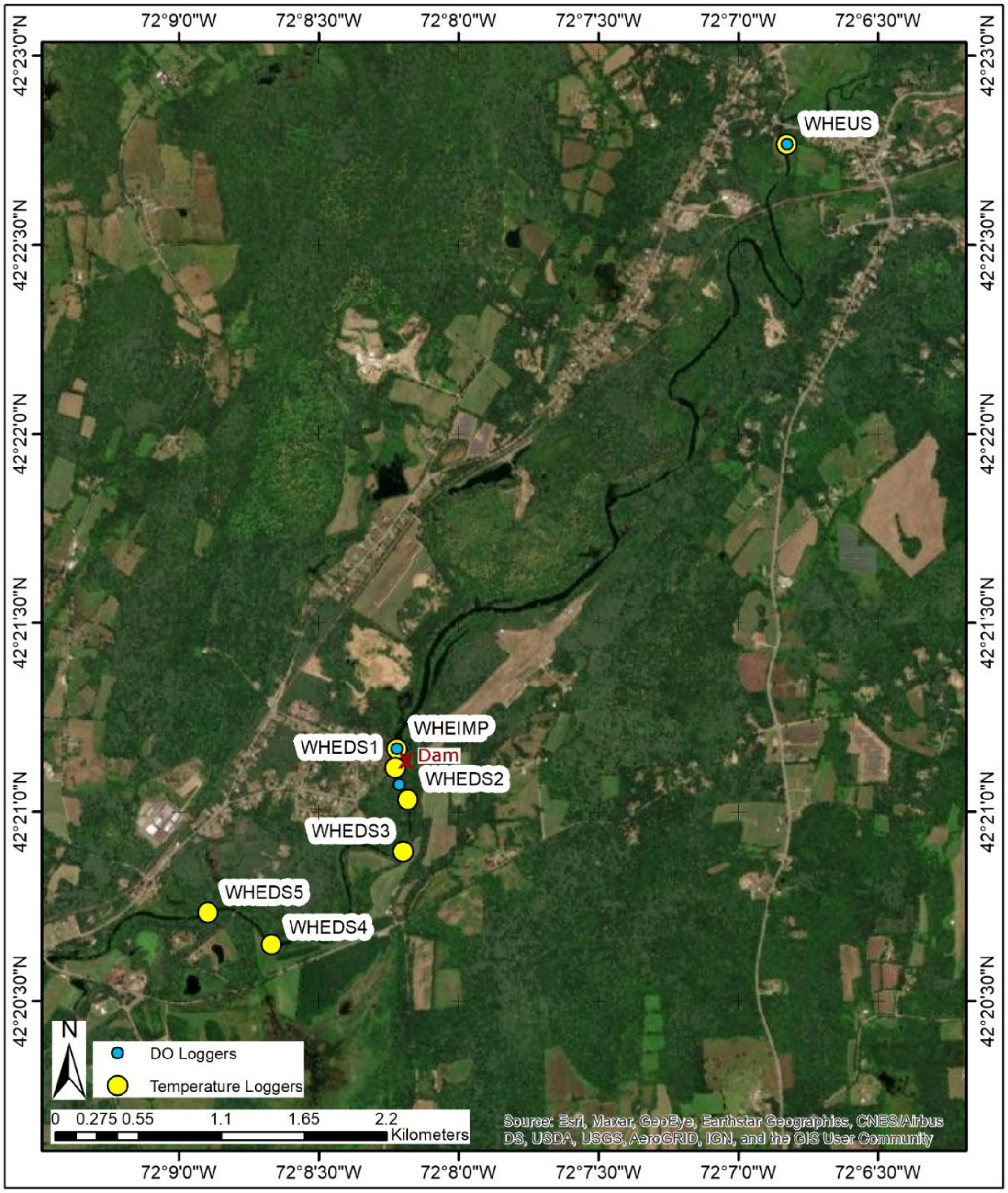


Figure A18.1. Map of temperature and dissolved oxygen logger locations in the Ware River, Wheelwright, MA. Macroinvertebrates were sampled in approximately 100m sections around WHEUS, WHEIMP, and WHEDS1 loggers. See Figure 1 in Study Design section for location within Massachusetts. Esri World Imagery Basemap accessed 10/18/2022.

One temperature data logger was deployed upstream (WHEUS), one within the impoundment (WHEIMP), and five deployed downstream (WHEDS1-WHEDS5) of the dam, covering 1.2 mi (1.94 km) downstream (Fig. A18.1). Temperature loggers were deployed in June 2019 and have remained in the field through present (Spring 2022), capturing 3 years of pre-removal stream temperature. Dissolved oxygen (DO) loggers were deployed upstream (WHEUS), within the impoundment (WHEIMP), and downstream (WHEDS1) of Wheelwright Dam (Fig. A18.1) for approximately week-long deployments during summer months (July, August, and September) from 2019 to 2021, capturing 3 years of pre-removal DO concentrations.

Macroinvertebrates were sampled once per summer from 2019 to 2020, capturing 2 years of pre-removal assemblages. Within impounded areas, 3 replicate Ponar sediment grab samples were collected from randomly selected locations, and along impoundment margins, 3 replicate sweeps of submerged and emergent vegetation were conducted using a rectangular net. In flowing stream sections (e.g., upstream, downstream), 3 replicate Surber samples were taken in separate riffle habitats and a single representative multihabitat sample was collected throughout ~100 m of stream. All samples were preserved in 70% ethanol prior to sorting and identification by Cole Ecological, Inc. or a trained UMass researcher. Up to 300 individuals were identified to the lowest practical taxonomic unit (usually genus or species, referred to as “taxa”).

Temperature data are publicly available through the SHEDS Stream Temperature Database (Agency: UMASS_USGS, http://db.ecosheds.org/). Water quality data (temperature and dissolved oxygen) are also available through ScienceBase (https://doi.org/10.5066/P9L2ATHV). Site-specific and benthic macroinvertebrate data are available upon request from Katherine Abbott (kmabbott@umass.edu).

Results

Temperature

These data currently suggest that Wheelwright Dam has a small negative impact on the thermal regime of the Ware River. Mean summer impoundment temperatures were higher (22.4 °C) than the upstream section (21.4 °C). Downstream temperatures ranged from 21.5 °C to 20.7 °C, with the lowest temperatures generally occurring near DS2 and DS3 and increasing near loggers DS4 and DS5 (Fig. A18.2). This suggests a downstream cooling occurs—potentially due to shading and groundwater inputs—prior to the stream passing through a more open, agricultural area. Downstream warming—the mean difference between upstream and downstream (DS1) daily temperatures—was highest during spring and summer months (Fig. A18.3). Summer downstream warming (July-Sept.) was on average 0.11 °C, with high variability (SD= 0.51; Fig. A18.4), suggesting a small impact on downstream temperatures that varies based on flow conditions and ambient temperatures. Summer stream temperatures warmed with increasing distance downstream from the dam with a linear slope of 0.22 °C/km (Fig. A18.5). Overall, results suggest that Wheelwright Dam has relatively small impacts on downstream temperatures, but impoundment temperature impacts are greater during periods of low precipitation and high air temperatures.

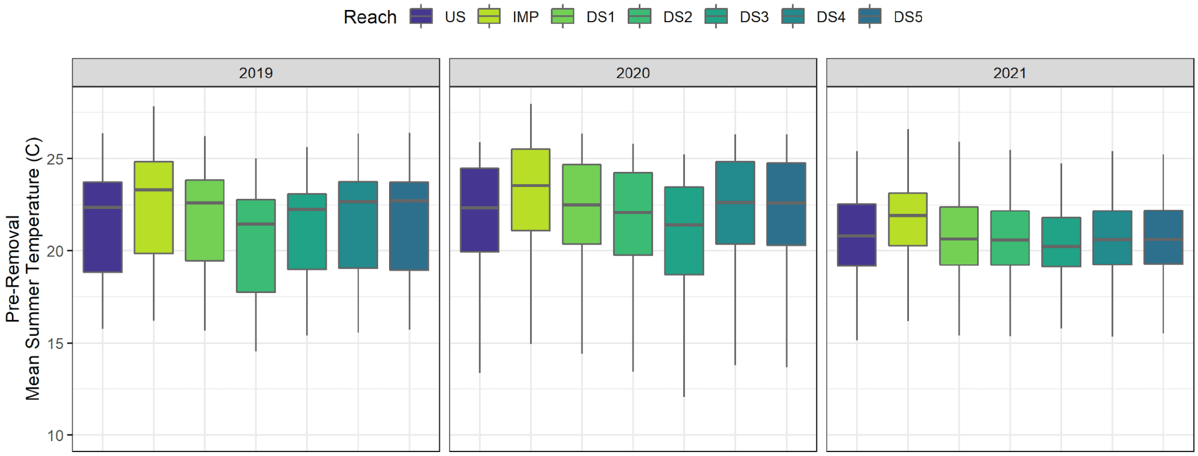


Figure A18.2) Mean summer (July-September) in-stream temperatures at each logger location during 2019-2021. Logger locations are indicated by the following abbreviations: US = upstream, IMP = Impoundment, DS1-DS5 = Downstream 1 through Downstream 5.

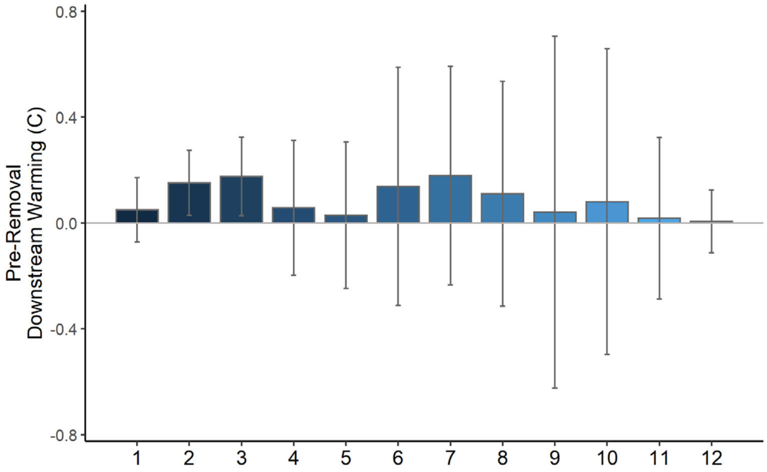


Figure A18.3) Mean downstream warming (i.e., downstream temperature minus upstream temperature) by month, across all years (2019-2021).

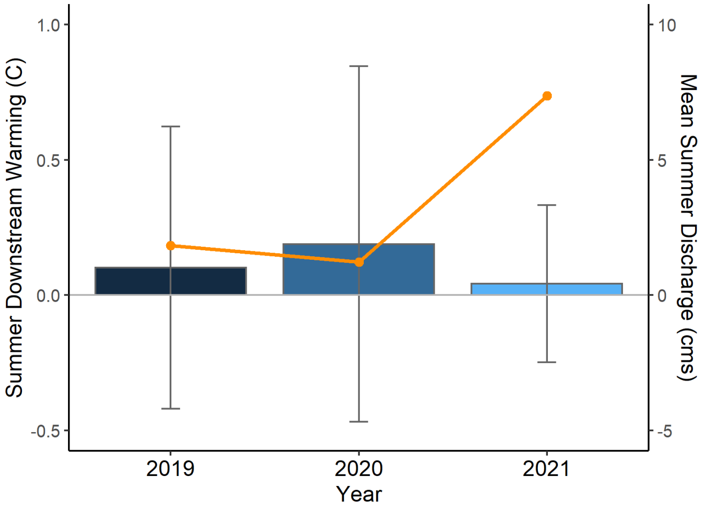


Figure A18.4) Summer (July-September) downstream warming (i.e., the difference between upstream and downstream temperatures ± SD; blue bars) and estimated mean summer discharge orange line).

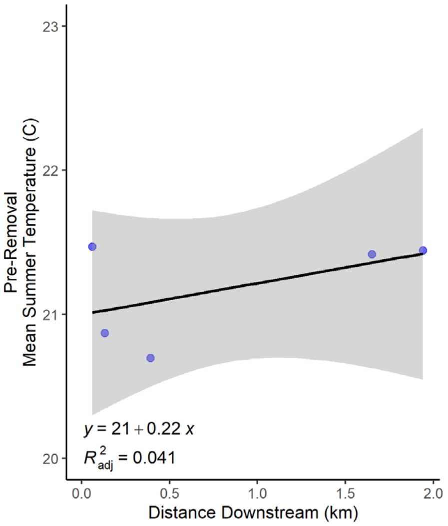


Figure A18.5) Mean summer temperature for each downstream logger (DS1-DS5) relative to the distance from the dam. The black line represents the mean slope of linear temperature decay downstream of the dam and the shaded grey area represents the 95% confidence interval.

Dissolved oxygen (DO)

Average surface DO within the impoundment of Wheelwright Dam (6.88 mg/L) was slightly lower than both the upstream (7.62 mg/L) and downstream (7.57 mg/L) section across all years. Differences among stream sections were variable across years monitored (Fig. A18.6). For example, in 2020, low precipitation and high temperatures may have resulted in lower DO within both the upstream and downstream sections. Higher-than-normal precipitation in 2021 may have led to slightly higher DO within the impoundment. Daily ranges downstream were generally higher than upstream ranges (1.12 mg/L), decreasing slightly in the impoundment (0.97 mg/L) and with the smallest daily range found in the downstream section (0.57 mg/L; Fig. A18.7). Larger daily ranges typically indicate more plant and algal growth, as high rates of oxygen production during daytime photosynthesis and oxygen consumption via nighttime respiration result in larger daily oxygen fluxes (Diamond et al. 2021). The upstream section is sinuous and flows through several wetland complexes, so the high daily range may be reflective of that habitat. The upstream and downstream sections never experienced DO less than 5 mg/L (Fig. A18.8), a threshold below which waters may be considered impaired for DO (MassDEP 2016). Similar to thermal impacts, the average dissolved oxygen impact of Wheelwright Dam is small, but may be exacerbated by warm, drought years.

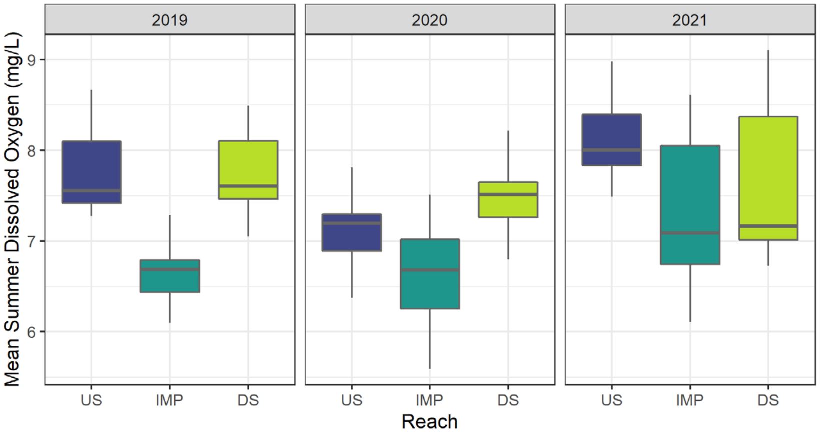


Figure A18.6) Mean summer (July-September) dissolved oxygen concentrations in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2019-2021.

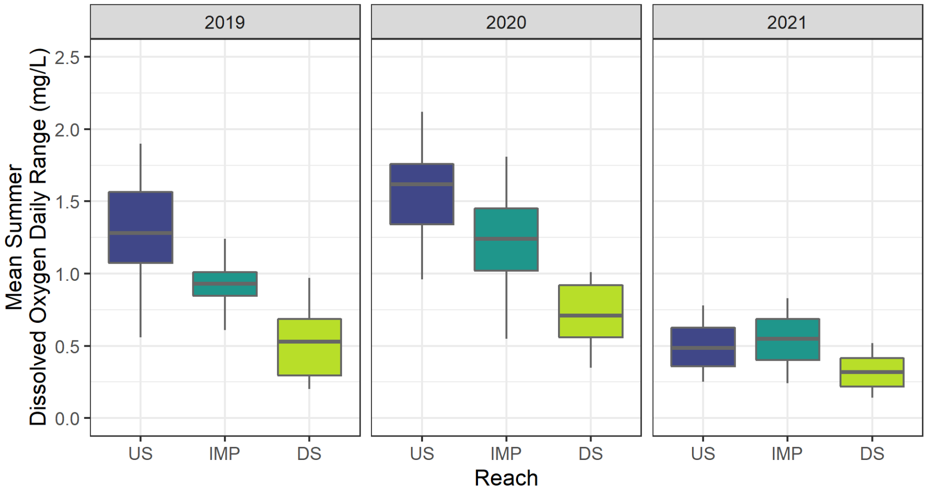


Figure A18.7) Mean summer (July-September) daily range of dissolved oxygen levels in upstream (US), impoundment (IMP) and downstream (DS) stream sections from 2019-2021.

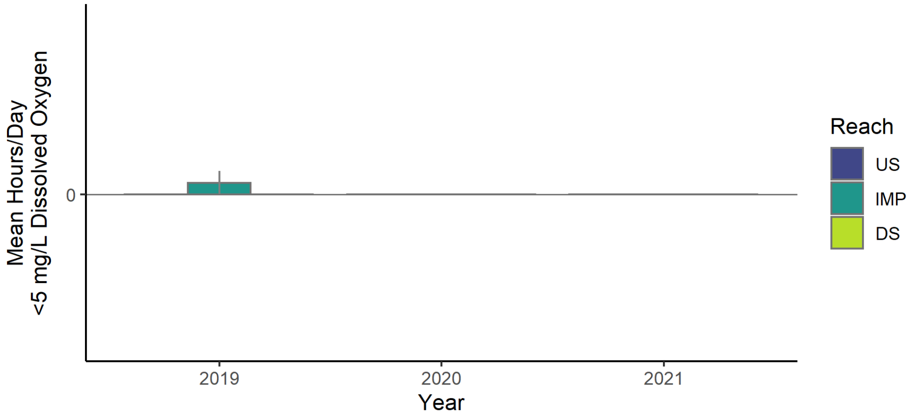


Figure A18.8) Mean and standard error (SE) hours per day that upstream (US), impoundment (IMP) and downstream (DS) stream sections spent below 5.0 mg/L, a threshold below which waters may be considered impaired for DO (MassDEP 2016). Most stream sections, except the impoundment in 2019, did not experience any time with DO < 5 mg/L.

Macroinvertebrates

At this site, we found that the Wheelwright Dam had localized impacts on macroinvertebrate assemblages within the impoundment, with smaller impacts on downstream taxa. For example, the percent of taxa (unique organisms) classified as coldwater (thermal optimum <18 °C) was much lower within the impoundment (2.3%) as compared to upstream (6.7%) and downstream (7.2%) sections, and warmwater taxa (>20 °C) followed a similar pattern. In general, coolwater (18-20 °C) taxa dominated all sections at this site. We also observed a reduced percentage of pollution-sensitive taxa within the impoundment (3.6%) than in the upstream (23.7%) or downstream (26.8%) sections (Fig. A18.9). The most pollution-tolerant taxa were found within the impoundment (53.8%), which was dominated by amphipods (scuds), Odonata (e.g., damselflies), and chironomids (midges). The Hilsenhoff Biotic Index (HBI), which estimates the overall pollution tolerance weighted by the relative abundance of each taxa (Hilsenhoff 1988), also indicated more pollution-tolerant taxa within the impoundment relative to flowing water sections (Fig. A18.10), and downstream had a lower HBI than upstream. The total number of taxa (taxa richness) and the diversity, which incorporates both richness and abundance of taxa, were both lowest within the impoundment (Fig. A18.10). Functional traits—feeding behavior and movement habits, for example—allow us to link environmental conditions to the abundance and diversity of the different functional groups sampled. In the impoundment, we observed a lower proportion of taxa that feed by "filtering" and "scraping", like some caddisflies (Trichoptera) and riffle beetles (Elmidae), which may reflect reduced flow velocities and a lack of hard substrates on which periphyton may grow (Fig. A18.11). In the impoundment, we also found a higher percentage of taxa that burrow and sprawl on sediment and a lower percentage of clingers than both flowing-water sections, reflecting the shift to stagnant waters and to finer sediment and organic matter (Fig. A18.11).

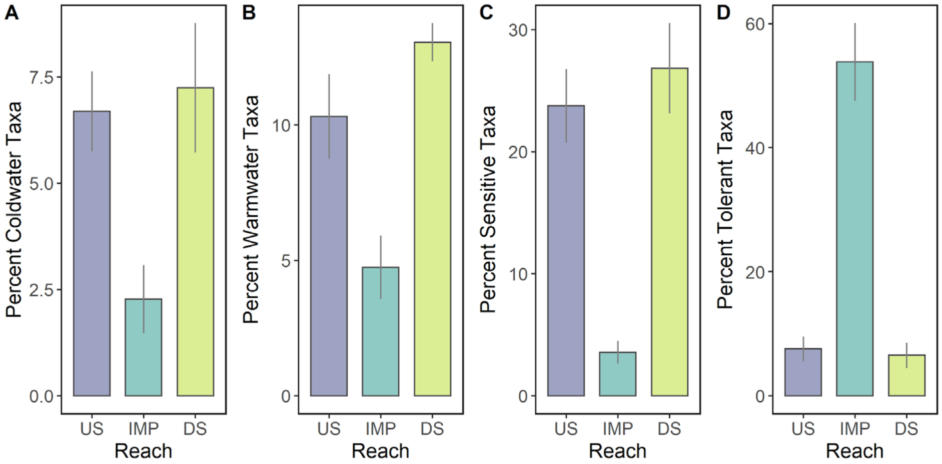


Figure A18.9) Mean percent of macroinvertebrate taxa by A) coldwater, B) warmwater, C) sensitive, and D) pollution-tolerant found within each sample in upstream (US), impoundment (IMP), and downstream (DS) stream sections.

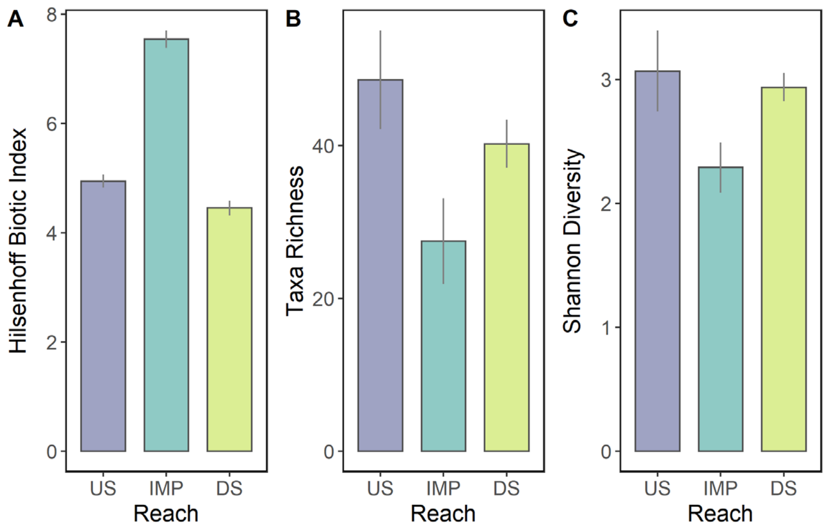


Figure A18.10) Mean macroinvertebrate biotic metric A) Hilsenhoff Biotic Index, B) total taxa richness, and C) Shannon diversity found in upstream (US), impoundment (IMP), and downstream (DS) sections.

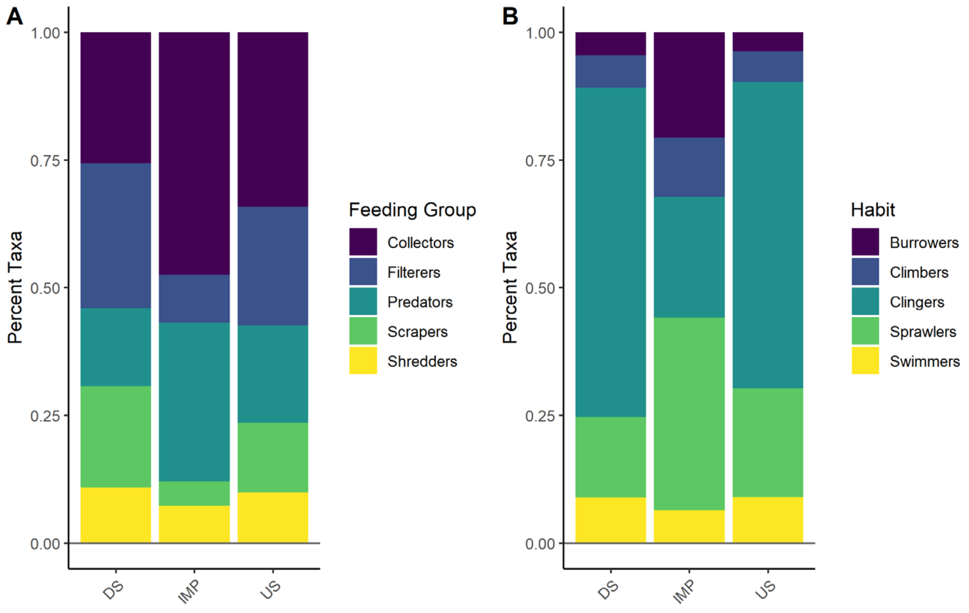


Figure A18.11) Percent of macroinvertebrate taxa by functional trait groups A) feeding group, and B) habit in upstream (US), impoundment (IMP), and downstream (DS) stream sections. See Table A2.1 in Appendix 2 for information on feeding groups and habit categories.

Table A18.1. Averages of key ecological parameters before dam removal in each stream section (± 1 standard deviation).

Ecological Parameter	Upstream Before	Upstream[†] After	Impoundment Before	Impoundment After	Downstream Before	Downstream After
Stream Temperature (C)	21.4 ± 2.8	-	22.4 ± 3.1	-	21.5 ± 2.8	-
Dissolved Oxygen (mg/L)	7.6 ± 0.6	-	6.9 ± 0.6	-	7.6 ± 0.6	-
Hilsenhoff Biotic Index[††] (HBI)	4.9 ± 0.3	-	7.5 ± 0.5	-	4.5 ± 0.3	-

[†] Temperature from first downstream logger (DS1) only. [††] Higher HBI indicates a greater relative abundance of pollution-tolerant macroinvertebrate taxa and suggests poorer water quality.