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Impacts of small dams on stream temperature

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ABSTRACT

Small, surface-release dams are ubiquitous features of the landscape that typically slow water flow and decrease canopy cover through impounded reaches, potentially increasing stream temperatures. However, reported effects of small dams on water temperature are variable, likely due to differences in landscape and dam characteristics. To quantify the range of thermal effects of small dams, we deployed continuous temperature loggers for one to four years at 30 dam sites across a range of environmental settings throughout Massachusetts (USA). Most dams (67%) warmed downstream waters, with August mean temperatures 0.20–5.25 °C higher than upstream. Downstream temperatures cooled with increased distance from the dam at 68% of sites, such that the warmest temperatures were observed closest to the dam. Where there was both a significant downstream warming effect and cooling pattern (seven sites), elevated temperatures persisted for an average of 1.31 km downstream of the dam. Dams with impoundments that caused the greatest relative widening of the stream channel and those on coldwater streams had the most warming, while streams with short dams in forested watersheds cooled most quickly downstream of the dam. Flow had a homogenizing effect on water temperatures at over half of the sites, whereby summer thermal impacts were more pronounced (e.g., more warming, faster cooling rates) under periods of lower flows. Downstream warming may reduce habitat for coldwater fishes and invertebrates, particularly where dams shift coldwater/coolwater habitat to warmwater. These results suggest that dam removal may mitigate elevated stream temperatures and increase ecosystem resilience in the face of a changing climate via restoration of critical coldwater habitats.

1. Introduction

Stream temperature is fundamentally important to freshwater ecosystems and the aquatic organisms that inhabit them. Through thermal optima and thermal limits, stream temperature drives species distributions of ectothermic aquatic organisms within riverine habitats (Jacobsen et al., 1997; Olden and Naiman, 2010). Anthropogenic factors that alter natural thermal regimes, particularly when coupled with climate-induced temperature shifts, are likely to determine future species distributions and biotic integrity (Isaak et al., 2017). It is critical, therefore, to understand these anthropogenically-driven thermal alterations to better plan future restoration and conservation actions.

Dams are ubiquitous features of the landscape, and are particularly prevalent on New England (USA) streams (Graf, 1999). These anthropogenic structures have been shown to alter riverine thermal regimes, although the effects vary considerably by dam size and type, such as where a dam releases water. Tall (> 15 m, ICOLD, 2011), hypolimnetic-release dams have been well-studied and are known to consistently release unnaturally cold water downstream in the summer when stream temperatures are warm and conversely release unnaturally warm water downstream during the winter (Holden, 1979; Ward and Stanford, 1979; Armitage, 1984). In contrast, smaller (≤ 15 m), surface-release dams show highly variable downstream thermal effects — while some studies have demonstrated downstream warming (Lessard and Hayes, 2003; Saila et al., 2005), others have shown little to no impact of these dams on downstream temperature (Bushaw-Newton et al., 2002; Stanley et al., 2002; Conlon, 2015; Smith et al., 2017). The nation's most comprehensive database of dams, the National Inventory of Dams (NID), currently lists > 90,000 dams in the country (USACE, 2016), while Graf (1993) estimates that when smaller dams are considered,

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there are actually up to two million dams in the USA. This lack of understanding regarding thermal impacts of small dams underscores a critical research need when considering that these smaller dams are less documented, more prevalent, and more poorly studied than their larger counterparts (Graf, 1999; Poff and Hart, 2002; Magilligan et al., 2016).

One such understudied component of small dam impacts are the drivers of observed variability in downstream thermal responses to small dams. Studies that have looked at thermal effects of small dams typically include only a small number of dams (i.e., < three sites, but see Lessard and Hayes, 2003; Santucci et al., 2005), thus limiting the ability to directly compare responses among watersheds and dam types. Studies are also limited in spatial extent of the stream studied; most quantified temperatures only at a single point upstream and a single point downstream of the dam of interest, while only a few (Fraley, 1979; Lessard and Hayes, 2003; Maxted et al., 2005; Bellucci et al., 2011; Dripps and Granger, 2013) measured temperatures at more than one location downstream of the dam.

Given the limited spatial and temporal extents of previous studies, this study aimed to characterize how small dams impact stream temperatures. Specifically, our objectives were to (1) quantify downstream thermal responses to small dams, (2) investigate the relative effect of landscape variables and dam characteristics as drivers of inter-site variation in thermal response, and (3) examine the effects of flow on the intra-site variability in daily summer downstream temperature impacts. To achieve this, we deployed continuous temperature loggers year-round for multiple years at 30 dam sites that represent a range in watershed and dam characteristics. Understanding the factors that drive inter- and intra-site variation in thermal response to small dams can allow managers to improve predictions of stream resilience to a changing climate and identify which dammed streams have the greatest potential for improvement following restoration.

2. Material and methods

2.1. Study area

We assessed the impacts of small dams on temperature at 30 surface-release dam sites in Massachusetts, USA (Fig. 1, Table A). Sites included both human-made dams (n = 27; including run-of-river former mill dams, water supply reservoirs, and winter drawdown dams) and beaver dams (n = 3). These dams were distributed across the state, with terrain ranging from mountainous, high gradient slopes (maximum mean watershed slope of 16%) in the western part of the state to low gradient coastal plains (minimum mean watershed slope of 3%) in the east (Massachusetts Bureau of Geographic Information (MassGIS) Digital Elevation Model 1:5,000). Massachusetts is both heavily forested and one of the most densely populated states in the country (U.S. Census 2010), and the dam site watersheds reflect this spread, with sites ranging from highly forested (95% watershed forest cover) to highly urbanized (28% impervious cover; Table 1, Table B).

Table 1
Minimum, average, and maximum values for the dam, impoundment, and watershed characteristics for the 30 sites.

	Minimum	Average	Maximum
Dam height (m)	0.4	5.3	15.0
Impoundment surface area (ha)	0.1	32.4	261.9
Impoundment volume (m^3)†	200	1,414,318	13,568,280
Impoundment widening‡	1.2	9.9	62.3
Impoundment residence time (hrs)†	0.86	7966.90	66538.52
Impoundment area:watershed area (%)	0.002	2.353	24.752
Upstream temperature (°C)‡	16.27	21.56	25.75
Watershed forest (%)	23.5	66.9	95.4
Watershed impervious (%)	0.1	6.4	27.7
Watershed area (km^2)	0.5	58.4	388.5
Watershed slope (%)	2.7	9.0	16.1
Watershed elevation (m)	23.8	221.1	448.1
Watershed open water (%)	0.0	3.3	24.9
Watershed wetland (%)	0.9	8.4	21.8
Watershed sand and gravel (%)	0.0	20.3	53.1

†Does not include values for the 3 beaver dam sites.
‡Only available for sites with an upstream logger (n = 18).

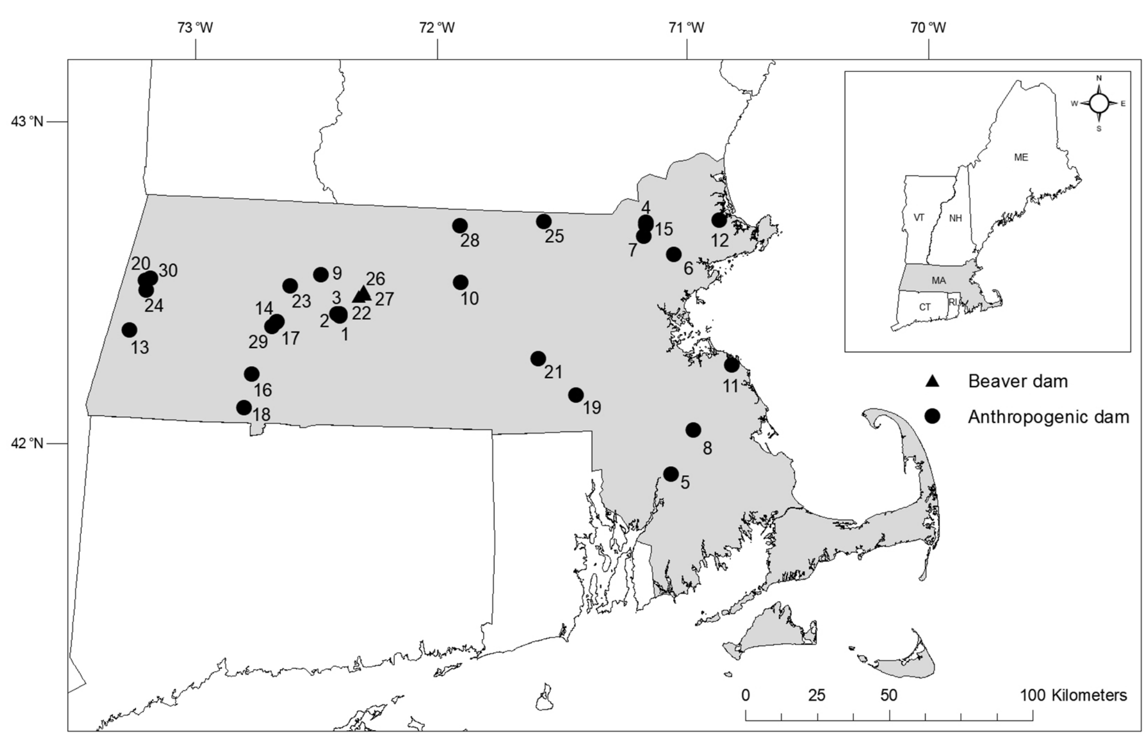

Fig. 1. Thirty dam sites in Massachusetts (northeastern USA) monitored for this study. See Table A for site information corresponding to numbers.

2.2. Study design

We deployed two to six temperature loggers downstream of each dam, with the length of the downstream reach, number of loggers, and spacing between loggers determined by site-specific characteristics, including access. The first downstream logger was installed at the first suitable location (deep pool downstream of the dam plunge pool with suitable bank structure to secure logger) ~35 m downstream of the dam while the most downstream location was upstream of a major confluence, reservoir, or estuary, or just upstream and downstream of an inflowing tributary. In addition to the downstream loggers, sites with a single, main tributary flowing into the impoundment (n = 18) had an upstream reference logger deployed above the influence of the impoundment, and 15 sites had a surface logger deployed within the impoundment near the spillway.

We measured water temperature with HOBO® Water Temp Pro v2 data loggers (U22-001; Onset Computer Corporation, Bourne, MA). Loggers were deployed in white PVC flow-through housings to both physically protect them and shield them from direct solar radiation (Dunham et al., 2005). A National Institute of Standards and Technology (NIST)-certified thermometer was used to ensure that installation locations were representative of each sampling reach. Within free-flowing stream reaches, loggers were deployed in deep pools or runs to ensure submersion throughout summer low flows. Impoundment loggers were deployed near the dam outlet 30 cm below the water surface using a small float anchored to the reservoir bottom to capture the temperature of water spilling over these surface-release dams.

Loggers were deployed year-round beginning in summer 2014 (n = 16), summer 2015 (n = 11), and summer 2016 (n = 3) and set to record temperature every 15 min. There were 16 active sites in the summer of 2014, 26 active sites in the summer of 2015, 20 active sites in the summer of 2016, and 10 active sites in the summer 2017. Each site had a minimum of one summer of data. Logger accuracy was checked annually via an ice bath (Dunham et al., 2005) and loggers were visited biannually (spring and fall) to download data. At each site visit, a spot check temperature reading with a NIST-certified thermometer compared to the continuous logger data ensured accuracy. Temperature data were visually and quantitatively checked using the ContDataQC package in RStudio (RStudio Team, 2016) to identify anomalous points and periods where the logger may have come out of water. Anomalous data were flagged and removed from analyses.

2.3. Landscape variables, dam features, and flow data

We used the U.S. Geological Survey (USGS) application StreamStats (http://streamstats.usgs.gov) to delineate each watershed with the dam as the outlet. For each watershed, several landscape variables were calculated using StreamStats, including: watershed size, mean watershed slope (USGS National Elevation Dataset 2007), mean watershed elevation (USGS National Elevation Dataset 2007), percent forest cover (MassGIS Land Use 2004), percent impervious cover (National Land Cover Dataset 2011), percent open water (MassGIS Massachusetts Department of Environmental Protection (MassDEP) Wetlands 2009), percent wetlands (MassGIS MassDEP Wetlands 2009), the percent underlain by sand and gravel (MassGIS Surficial Geology 2004), and the ratio of the impoundment surface area to the watershed area. Impoundment surface area was measured in ArcGIS 10.3 (Environmental Systems Research Institute, Redlands, CA) from the MassGIS MassDEP Hydrography 1:25,000 layer. Dam heights were obtained through the NID, technical reports, or by measuring the change in elevation from upstream to downstream of the dam in ArcGIS using MassGIS Digital Elevation Model 1:5,000. Impoundment volumes were obtained through the NID or technical reports, or estimated via the average end area method. The average end area method averages the cross-sectional area of the impoundment along the length of the impoundment from the upstream-most extent to the downstream-most extent, which is appropriate for run-of-river dams with fairly consistent widths throughout the impoundment length (Vanoni, 2006). To calculate impoundment widening (only for those sites with a single inflowing tributary and upstream logger), we averaged three evenly-spaced width measurements over the length of the impoundment in Google Earth Pro (version 7.3.2.5487) and divided by the average upstream width, as calculated from field measurements. Upstream temperature, as used in downstream warming models, was the mean August upstream temperature for each site. We estimated hydraulic residence time through the impoundment by dividing the volume of the impoundment by the median August discharge (see methods for estimating daily discharge below) at each dam site for each year a site had data. The presence or absence of an auxiliary spillway (which we defined as anything that bypassed a large amount of water around the main spillway, including fish ladders and significant holes in the dam) was determined based on visual observations in the field.

Daily discharge data was estimated from USGS gages across the state. A suitable gage for each dam site was chosen that was either on the same stream as the dam or on a stream with similar characteristics (e.g., watershed size, geographic proximity) as the dam site. Using this representative gage, we estimated daily discharge for the dammed stream using the drainage area weighting method adapted from Ries (2007) based on a ratio of the gaged and ungaged watershed sizes. In the northeast, given the density of gages and similar regional hydrologic responses, this method has been shown to perform very well for estimating daily discharge at ungaged sites (Patil and Stieglitz, 2012).

2.4. Data analysis

From 15-minute temperature data, we calculated daily mean temperatures, and used those to calculate mean monthly temperatures for each logger throughout the study period. We calculated a mean monthly magnitude of downstream temperature change from all dam sites with data for > 80% of the month (i.e., 23–24 days of record for the month) for each month of the year. A *t*-test for each month determined temperature change magnitudes that were significantly different than 0.

To quantify downstream thermal responses to dams (Objective 1), we calculated the magnitude of both impoundment and downstream temperature change relative to upstream using August temperatures. We focused on August because this was one of the three summer months (i.e., the "worst-case" for thermal effects of dams) with the highest temperatures and largest effects of dams (Fig. 2), and the month that had the most complete data across all sites. *Impoundment temperature change magnitudes* were calculated as the daily difference between the impoundment logger and the upstream logger, whereby positive numbers indicated warmer values within the impoundment relative to upstream. *Downstream temperature change magnitudes* were calculated as the daily difference between a logger located 40–180 m downstream of the dam (to avoid potential groundwater influx from head immediately downstream of the dam) and the upstream logger, and similarly, positive numbers indicated warmer values downstream compared to upstream. To avoid potentially inflated type I error rates due to autocorrelation in daily data, we selected out a random subset of days (Zwiers and von Storch, 1995) from the daily August data, and used days as replicates in a paired *t*-test to determine temperature change magnitudes (both within the impoundment and downstream of the dam) that were significantly different from 0 at each site. We bootstrapped these *t*-tests 10,000 times to avoid data loss or skewed values due to subsampling. Sites without upstream or impoundment loggers were not included in these analyses.

In addition to magnitude variables, we also calculated *daily downstream decay rates* for each day in August and averaged over the month to determine a mean monthly pattern between temperature and distance downstream of each dam in the study. The decay rate was calculated as the slope of the linear regression between the mean

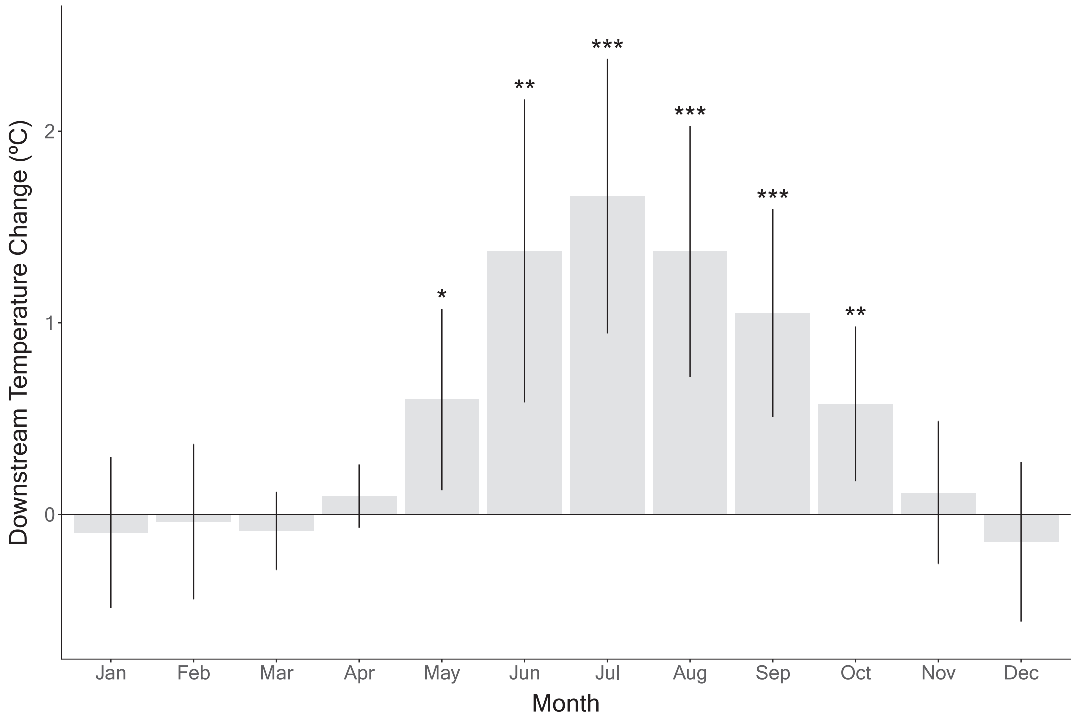

Fig. 2. Mean monthly downstream temperature change magnitudes across all sites for Jun 2014–Sep 2017. Error bars represent the 95% confidence interval and asterisks represent temperature change magnitudes that were significantly different from 0 based on a *t*-test for each month. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

temperature value of each downstream logger and the logger's distance from the dam. For sites with a surface impoundment logger, we included impoundment temperature in the decay rate regression. We used an ANOVA to determine if decay rates were different than 0.

When a site had significant downstream warming and a significant negative decay rate (i.e., cooling), we estimated the extent of downstream warming (i.e., thermal footprint). To do this, we divided the warming magnitude by the absolute value of the decay rate and calculated the distance at which the downstream temperature would equal the upstream temperature.

We additionally classified the upstream and downstream reaches into thermal classes based on thresholds established in Connecticut (USA) by Beauchene et al. (2014), who defined three classes based on mean July temperatures: coldwater (< 18.45 °C), coolwater (18.45–22.30 °C), and warmwater (> 22.30 °C). We used the upstream logger and a logger 40–180 m downstream (i.e., the loggers used to calculate downstream temperature change magnitudes) and averaged across each July of data for each logger to directly utilize these Beauchene et al. (2014) thermal classes.

We used univariate linear mixed effects regression models to determine how landscape and dam characteristics (Table 1) affect differences in downstream thermal response at the 27 human-made dams (Objective 2). All continuous predictor variables were Z-score standardized. First, we regressed the mean August downstream temperature change magnitude (n = 36) and mean August downstream linear decay rate (n = 56) as response variables in individual mixed effects models (with a random effect for site) against each of the landscape and dam characteristics separately. In determining the variables to include in further additive models, we dropped highly correlated variables (those with Pearson correlation coefficients > 0.7), and with the "corvif" function (Zuur et al., 2009), we further dropped variables with a variance inflation factor (VIF) > 3.0 in a stepwise process until all remaining predictor variables had VIF values < 3.0. We then tested a series of separate linear mixed effects models for each of the two response variables against additive combinations of landscape variables and dam characteristics as predictors. Site and year were included as random effects in each model. We used a maximum of three predictor variables (not including the random effects) for each response variable to avoid overfitting the models. Akaike information criterion corrected for small sample size (AICc; Burnham and Anderson, 2002) was used to determine the best supported model (the model with the lowest AICc was best supported). We used a Welch's ANOVA to test for significance between decay rates downstream of sites with and without an auxiliary spillway as the test is not sensitive to highly unequal variances between groups.

For assessing the effect of flow on thermal responses (Objective 3), we regressed the mean daily response variables (daily downstream temperature change and daily downstream decay rate) against daily summer (22 June–21 September) discharge from USGS gages. We used generalized least squares fitted models with a first-order correlation structure to accommodate non-independence in the daily data and log-transformed daily discharge to satisfy normality assumptions. All analyses were performed in R version 3.3.1 (R Core Team, 2016). Results were considered significant if $p < 0.05$.

3. Results

3.1. Downstream thermal responses to small dams (Objective 1)

The magnitude of downstream temperature changes were highly variable across months. The greatest downstream warming occurred from June–September (Fig. 2). There was a moderate amount of warming in May and October, and no significant differences between upstream and downstream temperatures from November to April (Fig. 2).

All but one of the 13 impoundments (92%) with both an impoundment and an upstream logger were warmer than upstream waters. Impoundments with significant warming magnitudes were on average 1.62 °C (range: 0.19–5.72 °C) higher than upstream temperatures. Warm impoundment surface waters translated to warmer downstream temperatures relative to upstream at the majority (67% of 18 sites) of sites (Fig. 3). At these 12 sites, temperatures were

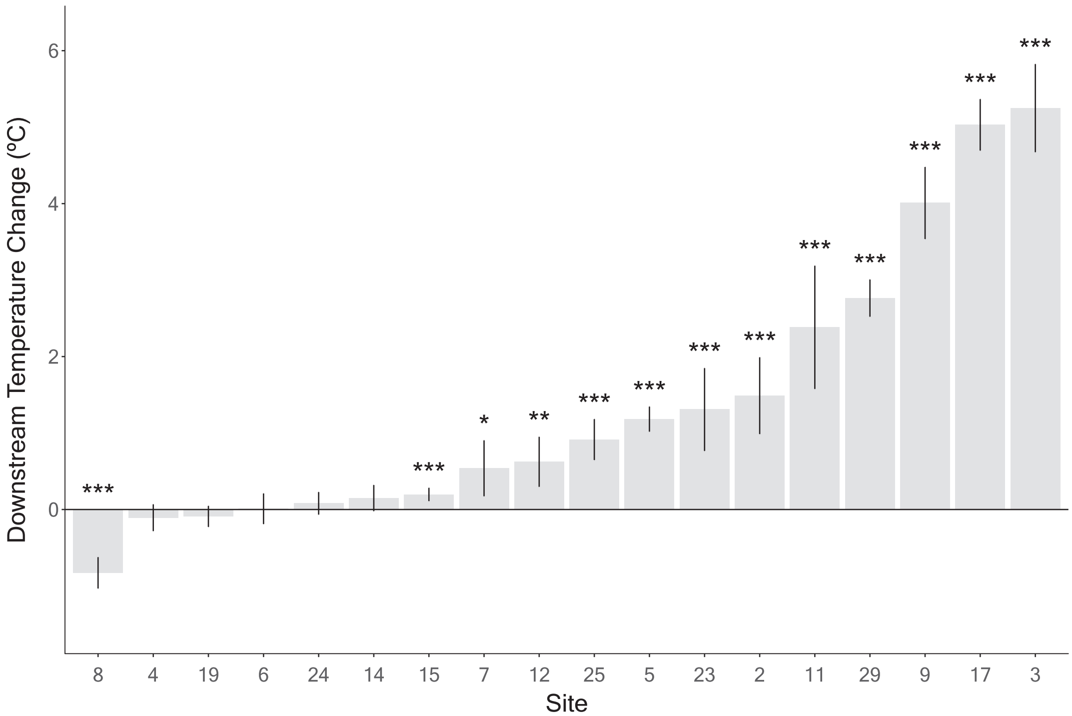

Fig. 3. Variation in mean daily August downstream temperature change by site (see Table A for site information corresponding to numbers). Error bars represent the 95% confidence interval and asterisks represent significant downstream temperature differences from 0 based on bootstrapped paired *t*-tests at each site. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

0.21–5.24 °C (average = 2.14 °C) warmer than upstream temperatures. Five sites had statistically similar temperatures above and below the dam, and one site had cooler temperatures downstream of the dam (Fig. 3). Throughout the study, 89% (16 of 18) of sites experienced the same directionality of response, while only two sites experienced a shift in response direction among years. The one site with cooling and the five sites with no difference exhibited that relationship each August of data we had at the site. Of the 12 sites with downstream warming, 10 experienced warming each August, while two sites had no significant warming in one of the years.

Using the July mean thermal classifications developed in Beauchene et al. (2014) on the upstream reaches, there were two coldwater (< 18.45 °C), six coolwater (18.45–22.30 °C), and nine warmwater (> 22.30 °C) sites in this study (Fig. 4). Downstream reaches were either coolwater (n = 4) or warmwater habitat (n = 13); no sites had coldwater habitat downstream of the dam. Both upstream coldwater sites transitioned to coolwater downstream, and four of the six upstream coolwater sites transitioned to warmwater habitat downstream. Two coolwater and all nine warmwater sites experienced no difference in classification between upstream and downstream (Fig. 4). No dams in this study shifted temperatures to a cooler thermal class downstream.

Nineteen of 28 sites (68%) had temperatures cool significantly with distance downstream of the dam in at least one August of the study. The fastest (i.e., minimum) cooling rate observed was −9.43 °C/km, while the slowest (i.e., maximum) cooling rate was −0.43 °C/km (average = −3.53 °C/km). Three sites had temperatures increase with increasing distance downstream of the dam (average warming rate = 3.62 °C/km), and six sites did not experience a significant downstream decay pattern. Across the four years of August data (2014–2017), 75% of sites maintained the same directionality of response, while 25% experienced inconsistent directionality among years (e.g., cooling one year, no decay pattern the next). All six of the sites without a downstream pattern, 13 of 19 sites with a negative decay (i.e., cooling), and two of three sites with a positive pattern (i.e., downstream warming) exhibited such relationships every August of the study. The three beaver dam sites (sites 22, 26, and 27) did not exhibit a consistent pattern, as one site had temperatures significantly cool with distance, one experienced significant increases in temperature downstream with distance, and one site did not have a significant relationship between downstream temperatures and distance.

Seven sites (of 16 sites with an upstream logger) had both significant warming and a significant cooling rate downstream of the dam that together could determine the thermal footprint of the dam (Table 2). Warming magnitudes at these seven sites ranged from 0.54 °C to 5.25 °C (average = 2.46 °C), with cooling rates ranging from −4.32 °C/km to −0.64 °C/km (average = −3.02 °C/km). Using these values, the estimated distance to recovery at these seven sites ranged from 0.28 to 4.47 km, with an average downstream thermal footprint of 1.31 km (Table 2).

3.2. Drivers of inter-site variation (Objective 2)

The dams in this study varied widely in features and physical settings. Dams were an average of 5.3 m high (range: 0.4–15.0 m) and their impoundments had an average surface area of 32.4 ha (range: 0.1–261.9 ha) and an average volume of 1,414,318 m^3 (range: 200–13,568,280 m^3; Table 1, Table B). For the 18 sites with a single tributary, the average upstream August temperature was 21.56 °C (range: 16.27–25.75 °C) and impoundments were, on average, 9.9 times (range: 1.2–62.3 times) wider than the width of the upstream reach. The average watershed was 58.4 km^2 (range: 0.5–388.5 km^2) in size, 221.1 m (range: 23.8–448.1 m) above sea level, and had 66.9% (range: 23.5–95.4%) forest cover (Table 1, Table B).

Downstream temperature change magnitude was positively predicted by dam height, impoundment volume, impoundment widening, impoundment residence time, impoundment area:watershed area, and watershed forest cover (Table 3). The average upstream August temperature, watershed impervious cover, watershed size, and watershed sand and gravel had negative relationships with temperature change (Table 3). Nine of the 15 predictors had Pearson correlation coefficients > 0.7 and VIF values > 3.0, and thus only six predictors were included in additive models. The best supported model explaining

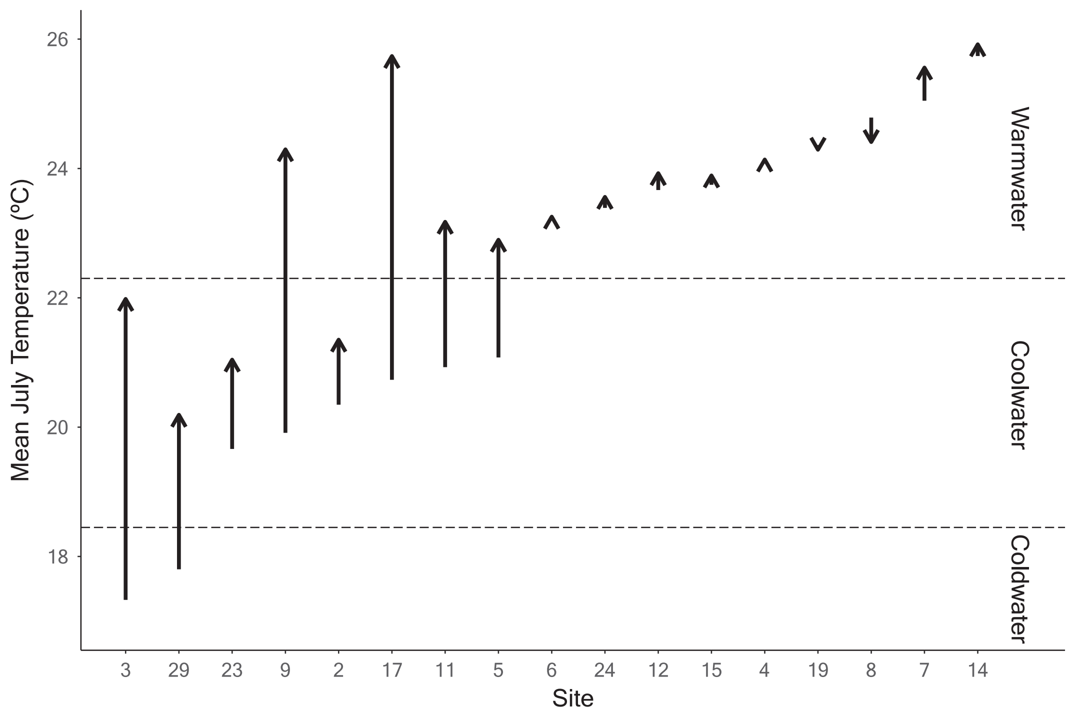

Fig. 4. Change in mean July temperature from upstream to downstream at each dam, with the direction and length of each arrow representing the direction and magnitude of change, respectively. Dashed lines separate coldwater (< 18.45 °C), coolwater (18.45–22.30 °C), and warmwater (> 22.30 °C) classifications based on Beauchene et al. (2014).

Table 2
Predicted thermal footprint (distance to recovery of upstream temperatures given observed downstream decay rates) for seven sites with both significant warming and subsequent cooling patterns with distance downstream of the dam.

Site	Warming (°C)	Decay rate (°C/km)	Footprint (km)
7	0.54	−1.93	0.28
5	1.18	−3.72	0.33
23	1.31	−3.75	0.34
2	1.49	−4.32	0.35
3	5.25	−4.10	1.35
9	4.72	−2.65	2.04
29	2.76	−0.64	4.47
Mean	2.46	−3.02	1.31

downstream temperature change magnitude included impoundment widening (positive) and upstream temperature (negative) with random effects for site (variation = 0.295) and year (variation = 0.784; Table 4, Fig. 5).

Two continuous variables significantly predicted downstream decay rates across all sites (Table 3). Impoundment surface area was positively related to downstream decay rates, while watershed forest cover had a negative relationship. At the subset of sites with an upstream logger (n = 15), downstream decay rates were negatively predicted by the impoundment widening ratio, such that sites with a larger increase in impoundment wetted width experienced faster cooling rates downstream. The presence of an auxiliary spillway also had a significant effect on decay rates, whereby sites with an auxiliary spillway had slower downstream decay rates than those without (Welch's F (1,45.787) = 15.833, $p < 0.001$). We excluded nine highly-correlated predictors from the mixed effects models and tested combinations of the remaining four. Downstream decay rates were best explained by a model consisting of watershed forest cover (negative), dam height (positive), and impoundment surface area (positive) with a random effect for site (variation = 0.799) and year (variation = 0.184; Table 4, Fig. 6). The model without surface area was equally well supported ($\Delta AIC_c = 0.8$).

3.3. Influence of flow on daily summer intra-site variation (Objective 3)

Mean daily discharge had a significant effect on daily downstream temperature change magnitudes at 11 of 18 sites in this study (Fig. 7, Table C). Ten of these 11 sites experienced reduced warming magnitudes under higher flows. Seven sites experienced more warming during lower flow periods (Fig. 7a); these were all sites with significant downstream warming. Four sites experienced greater downstream cooling magnitudes during lower flows (Fig. 7b, Table C); these sites, with the exception of one site that experienced downstream warming, were comprised of sites that had either significantly cooler downstream temperatures (n = 1) or non-significantly different downstream temperatures (n = 2). Seven sites did not experience a significant effect of flow on temperature change.

Mean daily discharge significantly affected mean daily downstream decay rates at 20 of 28 sites (Table C), while eight sites did not experience an effect of flow on daily decay patterns. Higher flows resulted in a more thermally homogenous downstream reach, such that sites exhibited little/no change in temperature with increasing distance downstream of the dam during higher flow periods (Fig. 7c-d, Table C). At most of these sites (n = 17), temperature cooled faster downstream of the dam during lower flows (Fig. 7d), while temperatures increased more rapidly with distance under lower flows at three sites that did not experience overall downstream cooling patterns (Fig. 7c). Similar to the overall patterns, there was no consistent directionality in the relationship between downstream decay rates and discharge at the three beaver dam sites.

4. Discussion

4.1. Thermal responses and associated ecosystem impacts

The highest August water temperatures were consistently observed in impoundments rather than free-flowing reaches, a finding similar to

Table 3
Results of the single parameter models between each of the predictor and response variables tested in this study. Predictor variables were scaled to report relative and comparable effects on the response variables across all parameters and included a random effect for site. Bold font indicates significant differences at $p < 0.05$. R^2 represents the model's marginal R^2.

	Downstream temperature change			Downstream decay		
Variable	Estimate	R^2	p	Estimate	R^2	p
Dam height	**0.91**	**0.22**	**0.022**	0.39	0.02	0.405
Impoundment surface area†	0.42	0.05	0.324	**1.08**	**0.15**	**0.011**
Impoundment volume†	**0.84**	**0.19**	**0.031**	0.78	0.08	0.080
Impoundment widening†‡	**1.62**	**0.69**	**< 0.001**	**−0.91**	**0.30**	**0.013**
Impoundment residence time†	**1.11**	**0.38**	**< 0.001**	0.05	0.00	0.913
Impoundment area:watershed area	**1.36**	**0.48**	**< 0.001**	0.70	0.06	0.122
Upstream temperature‡	**−1.16**	**0.43**	**< 0.001**	0.03	0.00	0.915
Watershed forest	**1.11**	**0.33**	**0.002**	**−1.04**	**0.14**	**0.011**
Watershed impervious†	**−1.11**	**0.33**	**0.002**	0.76	0.07	0.088
Watershed area†	**−1.19**	**0.37**	**< 0.001**	0.36	0.02	0.446
Watershed slope	0.80	0.16	0.071	−0.31	0.01	0.526
Watershed elevation	0.75	0.14	0.096	0.00	0.00	0.988
Watershed open water†	−0.84	0.18	0.067	0.80	0.08	0.083
Watershed wetland	−0.74	0.13	0.098	0.34	0.01	0.482
Watershed sand and gravel	**−0.82**	**0.17**	**0.049**	0.27	0.00	0.568

†Predictor variable was log-transformed for analyses.
‡For decay relationships, variable was only available and tested for sites with an upstream logger (n = 18).

Table 4
Model output from the top models ($\Delta AIC < 2.0$) explaining the variation in downstream temperature change and downstream decay rates. All models included random effects for site and year.

Model	AIC_c	ΔAIC_c	Marginal-R^2	Conditional-R^2
Downstream temperature change				
Impoundment widening + Upstream temperature	106.4	0.0	0.74	0.94
Downstream decay				
Watershed forest + Dam height + Surface area	264.8	0.0	0.33	0.45
Watershed forest + Dam height	265.5	0.8	0.28	0.47

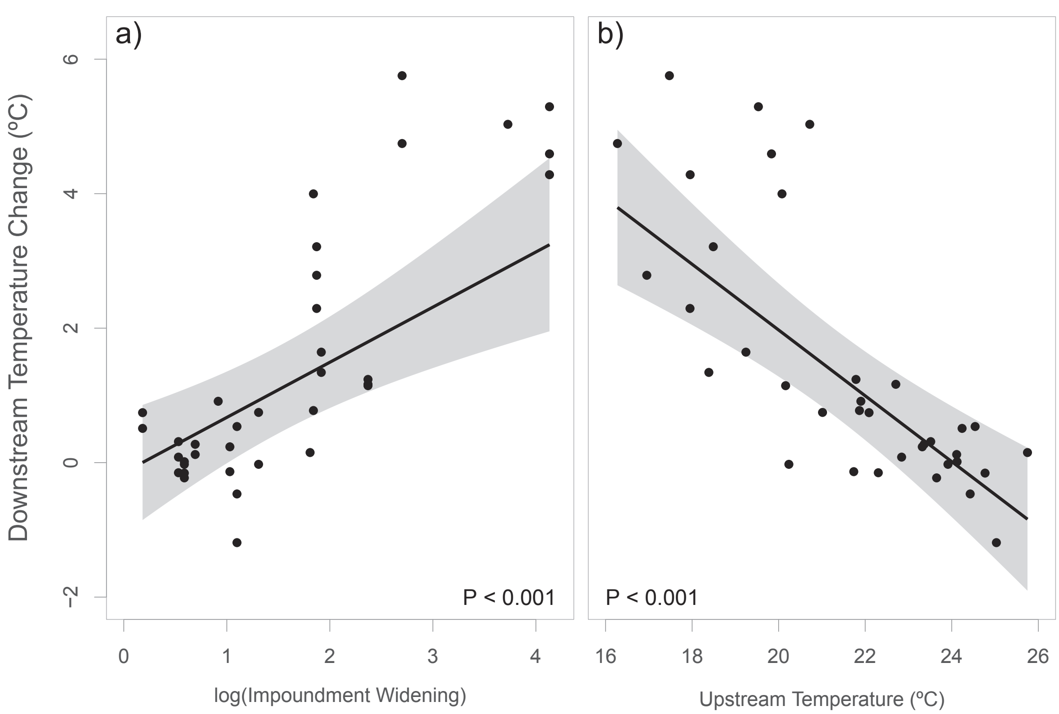

Fig. 5. Downstream temperature change magnitudes were best explained by an additive linear mixed effects model of (a) impoundment widening (log-transformed) and (b) the upstream average temperature with random effects for site and year. Dark lines are the mean response for each covariate and shaded polygons represent the 95% confidence interval about that mean (i.e., panel (a) is the relationship between impoundment widening and downstream temperature change while holding upstream temperature at its mean value).

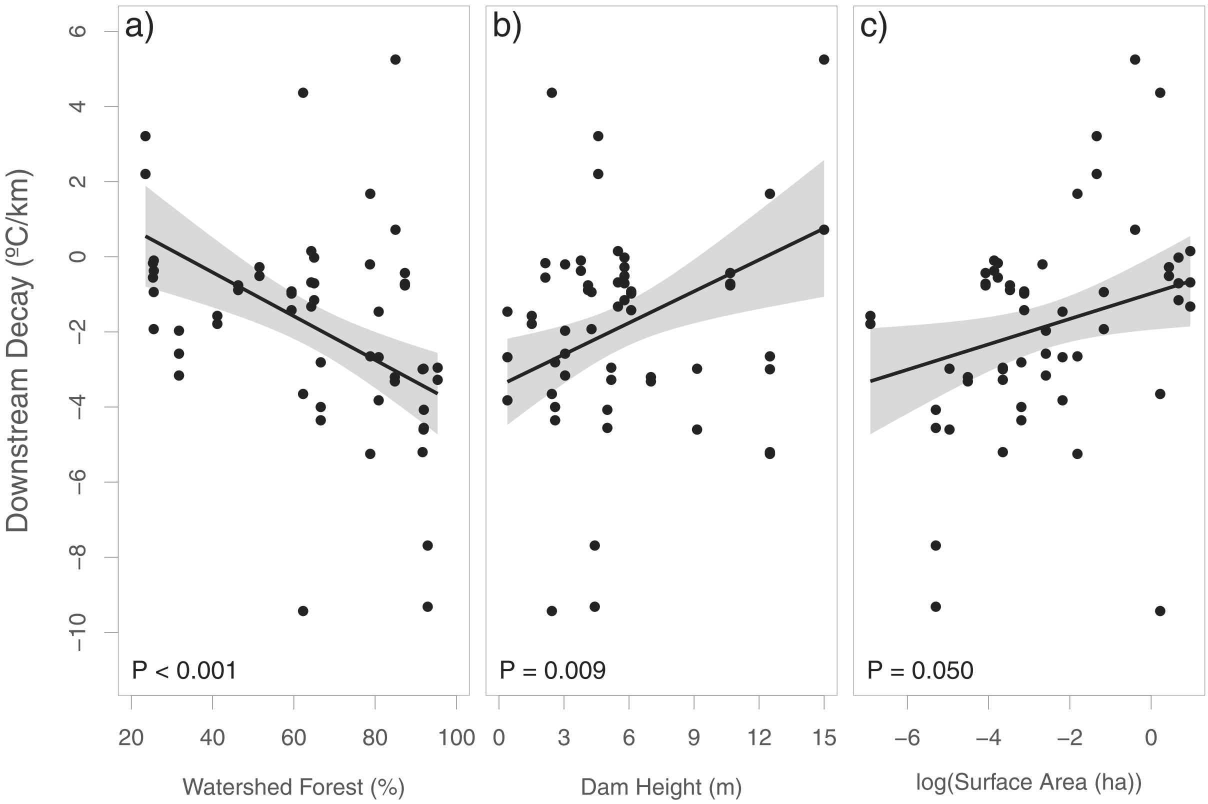

Fig. 6. Decay rates were best explained by an additive linear mixed effects model of (a) watershed forest, (b) dam height, and (c) surface area of the impoundment (log-transformed) with a random effect for site and year. Dark lines are the mean response for each covariate and shaded polygons represent the 95% confidence interval about that mean.

results from other studies (Maxted et al., 2005; Santucci et al., 2005; Dripps and Granger, 2013). The elevated water temperatures in the impounded areas created by dams were dramatically warmer (up to 5.4 °C) than upstream reference reaches. Wider impounded reaches experience more proportional solar radiation than shaded stream reaches (Dripps and Granger, 2013), and the loss of riparian shading leads to substantially higher temperatures (Brown and Krygier, 1970; Swift and Messer, 1971). Moreover, the reduced flow rates in impoundments result in increased residence times in this already-warm lentic environment, further contributing to higher temperatures compared to lotic reaches (Sinokrot and Gulliver, 2000).

The warm impoundment surface waters caused warmer downstream temperatures at 67% of these small, surface-release dams. The return to a flowing stream, an increase in riparian shading, and a potential reconnection to cold groundwater inflows likely caused the less consistent thermal effect downstream as compared to the impoundments. Downstream temperatures were up to 5.3 °C warmer than upstream reaches — values that approached previously reported warming magnitudes > 6.0 °C (Maxted et al., 2005; Dripps and Granger, 2013). These high temperatures persisted for long distances downstream (up to 4.47 km), and many sites did not experience recovery to upstream temperatures. Other observations in the literature documented temperatures persisting from 0.5 to 3.4 km downstream of small dams in Michigan, Connecticut, and South Carolina (Lessard and Hayes, 2003; Bellucci et al., 2011; Dripps and Granger, 2013), with one study (Fraley, 1979) reporting elevated temperatures persisting in a large river > 50 km downstream of a surface-release dam in Montana. For many dammed streams, thermal recovery is not possible due to close proximity to downstream reservoirs or the stream emptying into larger rivers or estuaries.

The increased temperatures caused by dams in summer months likely carry biological impacts for impounded areas and downstream ecosystems in our study. Most directly, warming can change species distributions and shift temperatures out of the thermal conditions that many aquatic ectotherms have evolved in (Allan, 1995). Several prior studies have demonstrated decreased abundances of coldwater fish species and increased abundances of warmwater species downstream of surface-release dams that experience a downstream warming effect (Lessard and Hayes, 2003; Bellucci et al., 2011). Fish species data were not collected in this study; however, 75% of cold-/coolwater sites experienced a shift from a cooler thermal class upstream to a warmer class downstream of the dam (i.e., coldwater to coolwater or coolwater to warmwater), suggesting a change in fish community composition favorable to warmwater species. Macroinvertebrate assemblages are also driven by temperature, and downstream warming may explain the shifts to lower-quality macroinvertebrate communities observed below small dams (Lessard and Hayes, 2003; Santucci et al., 2005; Bellucci et al., 2011). Additionally, elevated temperatures will facilitate greater rates of metals uptake (Dijkstra et al., 2013), potentially lead to an increased prevalence of harmful algal blooms (Przytulska et al., 2017), and increase decomposition rates (Martinez et al., 2014), thus altering energy availability throughout the aquatic food chain.

Water temperature changes downstream of dams in this study were large throughout summer months (June–September), but did not persist into the winter months, consistent with the findings of Dripps and Granger (2013). There was also warming in May and October, albeit not as pronounced as the summer, but from November through April there were no differences between upstream and downstream temperatures across our sites. This pattern of warming closely matches the periods of leaf-on and leaf-off for deciduous trees in the region, likely because when the canopy was most full, it provided the greatest relative shading effect compared to the wider and less shaded impoundment (Dripps and Granger, 2013). During the leaf-off months (e.g., November–April), there is little shade provided to any reach of the stream; therefore, the

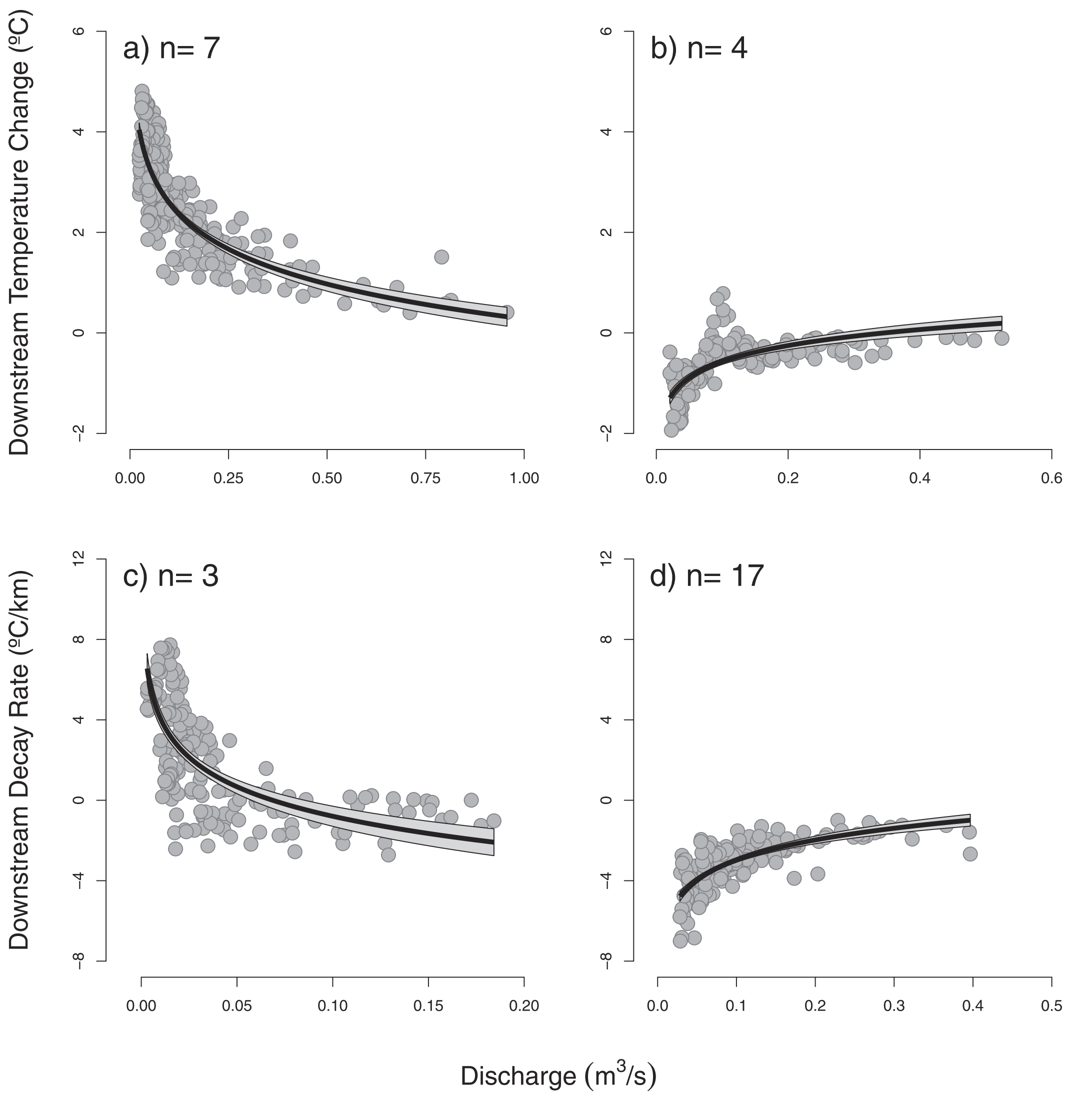

Fig. 7. Examples (based on a single site) of four patterns of significant relationships between flow and temperature change magnitudes (a–b) and downstream decay rates (c–d), including both positive and negative relationships for each response variable. Dark lines are the mean response between each response variable and flow and shaded polygons represent the 95% confidence interval about that mean. N indicates the number of sites exhibiting each pattern.

disparity between the upstream shaded reaches and open impoundment canopy is temporarily eliminated, and warming is not experienced until leaf-on begins again in the spring. While thermal impacts and the resulting likely biotic impacts were strongest in the summer, warming downstream of these dams during the shoulder seasons (spring, fall) may still carry implications for aquatic organisms. For example, fall spawning species such as brook trout experience reduced annual survival (Letcher et al., 2015) and lower growth rates (Xu et al., 2010) with warmer fall temperatures. Additionally, warmer temperatures can lead to earlier insect emergence in the spring (DeWalt and Stewart, 1995), even when those differences are relatively small (~1.5 °C; Cheney et al., 2019) and well within the range of observed impacts in this study.

4.2. Factors explaining variation in thermal responses

We observed wide variation in the downstream responses to small, surface-release dams, with results from this study paralleling those reported in the literature (Fig. 8), where temperature changes downstream of small dams ranged from a minimum of −1.0 °C (i.e., downstream cooling; Lessard and Hayes, 2003) to a maximum of +6.6 °C (i.e., downstream warming; Maxted et al., 2005). Our strongest predictor of warming magnitude was impoundment widening, suggesting that the loss of riparian shade and increased exposure to solar radiation may have the largest effects on downstream temperature. Those dams with the most downstream warming generally were on smaller, forested headwater streams, while higher order rivers in larger, more urbanized watersheds exhibited smaller effects on downstream temperatures. These results support the hypothesis of Jones (2010) that, all else equal, headwater stream dams would have a larger warming effect than dams on larger rivers. Stream temperature is a function of the amount of energy in a volume of water (Poole and Berman, 2001; Caissie, 2006), and small stream reaches with a lower thermal capacity immediately downstream of a dam are likely more susceptible to warming from a single input (e.g., an impoundment) introducing relatively large amounts of warm water. Coldwater streams also have a larger potential to be warmed by a single input of warm water, likely explaining why upstream temperature was such a strong predictor of the magnitude of temperature change downstream of a dam. The negative relationship between the percentage of a watershed underlain by sand and gravel and downstream warming suggests that streams with less groundwater inputs were more susceptible to warming from dams (Randall, 2001). Lastly, larger impoundments with tall dams, large volumes of impounded water, long residence time, and

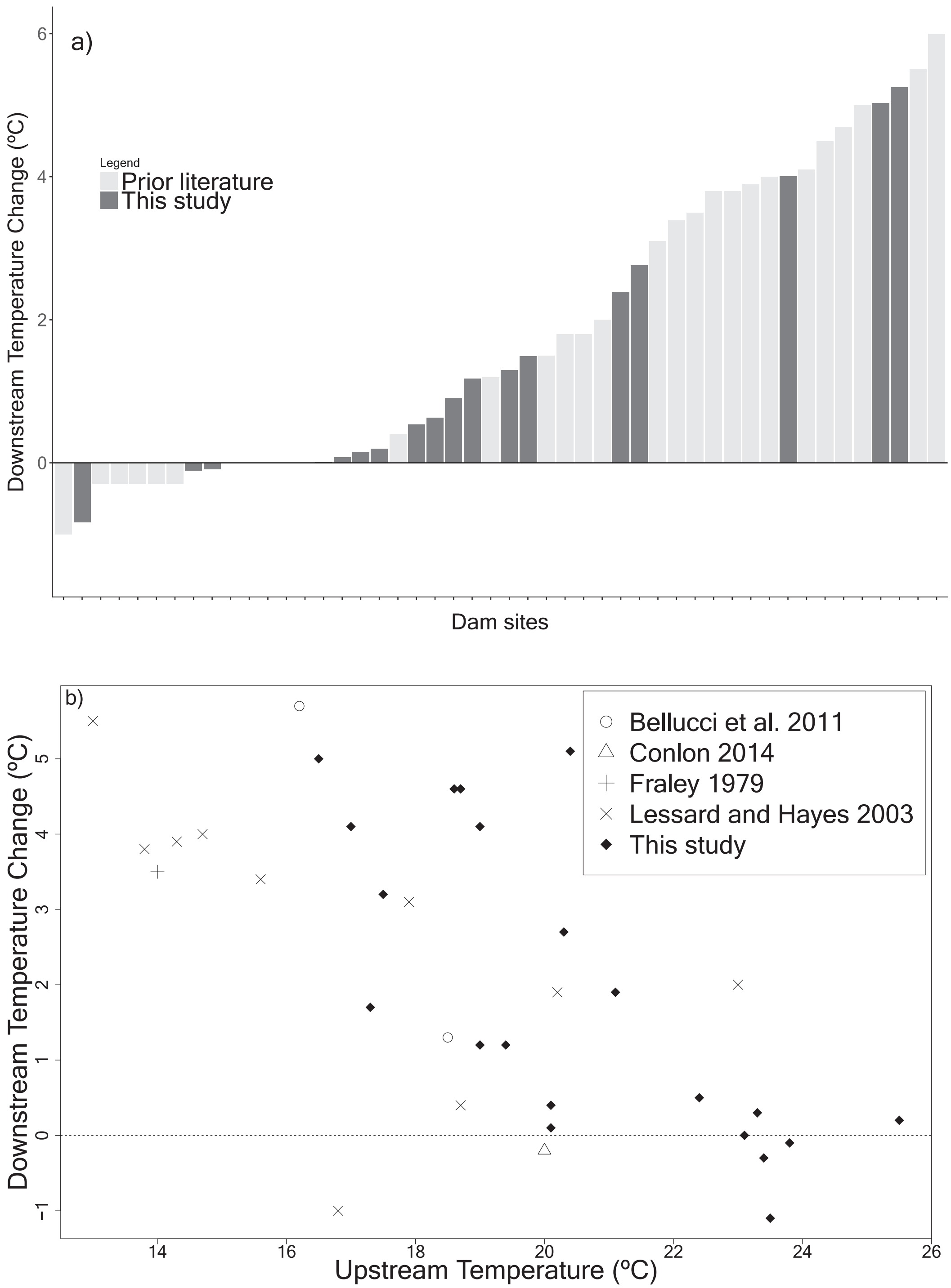

Fig. 8. Comparing the results from this study to those of the previously reported literature, with (a) a bar plot of downstream temperature change for the collective prior literature (30 sites; light gray bars) and this study (18 sites; dark gray bars). Several sites (e.g., Bushaw-Newton et al., 2002; Stanley et al., 2002) were only reported to have no difference (i.e., no number values provided) and are plotted as a bar of 0 °C (no change) height. Panel (b) plots temperature change magnitudes by upstream temperature, where upstream data was reported in the literature.

surface areas that encompassed a larger percentage of the watershed had higher downstream warming magnitudes. Previous studies have suggested that the impounded area and residence time can influence the extent of downstream warming (Bushaw-Newton et al., 2002); however, this study is the first to provide quantitative evidence based on differences among dam sites about impoundment characteristics that influence warming.

The range of cooling rates downstream of dams was also highly variable among sites, as some experienced little to no change in temperature with distance, while others experienced rapid cooling with distance that approached the reported rate of −10 °C/km in Maxted et al. (2005). Unimpacted streams generally warm with increasing distance downstream (Vannote et al., 1980), with reported warming values of 0.6 °C/km in small streams (Zwieniecki and Newton, 1999) and 0.09 °C/km in larger rivers (Torgersen et al., 2001). Thus, the rapid cooling rates observed downstream of dams in this study are particularly notable. Sites with large impoundments (e.g., large surface area and large volume of water impounded) generally had slower downstream decay rates than those with smaller impoundments. Forest cover was also indicative of a stream's downstream cooling rate, suggesting that forested riparian areas are critical for recovery from increased temperatures caused by dams. Sites with the greatest widening also experienced faster cooling rates, which may be driven by a greater amount of downstream 'narrowing' and subsequent greater increase in riparian cover as the stream returns to its natural width below the dam.

Most streams in this study did not exhibit static thermal responses to dams throughout the summer, but instead experienced daily variations in response to changes in daily discharges. Dam effects were generally more pronounced during periods of lower flow, while there was a homogenizing thermal effect throughout the study reach with increasing discharge levels. During low flow periods, an impoundment is likely receiving the greatest amount of solar insolation and experiencing the greatest warming (Fuller and Peckarsky, 2011). At the same time, during low flow there is a reduced volume of water in the downstream reach with a subsequent decreased ability to buffer against warm thermal inputs from an impoundment (Poole and Berman, 2001; Caissie, 2006). However, as seen in Kanno et al. (2014), groundwater inputs could have larger relative cooling effects during low flows, which may explain some variability in responses across sites. These daily relationships between flow and temperature effects from dams suggest that interannual variability in air temperature and precipitation (e.g., extreme heat, drought) may also influence thermal responses.

4.3. Applications for river restoration and monitoring

The number of dam removals in the United States has been increasing exponentially and if current trends continue, an estimated cumulative US$10.5 billion will be spent on the practice by 2050 (Grabowski et al., 2018). However, removing dams remains costly and time-consuming, meaning that models and methods for prioritizing restoration efforts (e.g., Hoenke et al., 2014) are critical to optimize the use of limited resources. The variation in thermal response to small dams identified within this study underscores the need to consider site and landscape characteristics when prioritizing thermal benefits via dam removal. As cold, headwater streams generally experienced the largest and most negative thermal effects from damming, targeting dams on smaller, forested streams should maximize thermal benefits from dam removal. Alternatively, practitioners aiming to restore coldwater habitat may target dams where upstream conditions are suitable for coldwater species, but downstream temperatures are warmed above thermal limits for coldwater species. Lastly, given that the most pronounced dam effects were observed under the lowest flows, a stream's susceptibility to low flows is another consideration for prioritization.

In addition to dam removal, other restoration practices may help to minimize impacts of dams. Reducing the volume of impounded water behind a dam and increasing spillage during summer months via notching or partial dam breaching may reduce thermal impacts. One impoundment within this study had been dewatered, and this was the only site that did not experience warming through the impounded reach, and the only site with cooler downstream waters. Finally, maintaining or re-establishing riparian cover is commonly used as a restoration approach to increase riparian habitat, stabilize banks, and maintain cooler stream temperatures via shading (Osborne and Kovacic, 1993; Beechie et al., 2010). Forested riparian areas are especially useful downstream of dams in small headwater streams, where warming impacts were largest and shade could provide the greatest cooling effect to recover natural, pre-dammed (i.e., upstream) temperatures.

Currently, fewer than 10% of dam removals are monitored scientifically, with water quality receiving far less attention than other parameters (e.g., biological or geomorphic; Bellmore et al., 2017). This lack of study had left large gaps in our collective understanding regarding stream thermal impacts and predicted responses to dams and dam removal. The relationships between dam and watershed characteristics and warming identified here can help managers estimate the thermal impacts of a given dam. For those who wish to confirm these estimated impacts with field data collection, temperature monitoring efforts in temperate ecosystems should be focused during warm summer months and periods of lower flows to identify the "worst case" effect of a dam. In most cases, a single month of continuous summer data should be sufficient to quantify the impacts of a dam, although we acknowledge that years with extreme drought or heat may show anomalous responses in thermal responses to dams. Monitoring for a full summer may provide greater insights into if and how the downstream response changes as a function of flow events, and if the site is particularly susceptible to the additive effects of the dam and lower flows. The Gulf of Maine's Stream Barrier Removal Monitoring Guide calls for monitoring temperature at a minimum of one location upstream of the impoundment (reference), within the impoundment, and downstream of the dam (Collins et al., 2007). However, to better understand the spatial extent of thermal alterations, additional loggers can be deployed downstream of the dam until a thermal barrier is reached to more completely capture a stream's warming response from a dam.

5. Conclusions

Review papers (e.g., Bednarek, 2001) define a consensus warming effect below surface-release dams, but discount the large variation in warming magnitudes and the reality that not all dams warm downstream temperatures. Here, we showed that the widening of the impoundment (as a presumed surrogate for exposure to solar radiation) relative to the upstream reach, upstream temperature, and basin size are critical factors in determining the extent of dam-induced thermal impacts, and are therefore useful in identifying dams that likely cause the largest thermal impacts. Given that 67% (12 of 18) of the dams in this study had downstream warming, it is likely that of the 14,000 dams in New England (Magilligan et al., 2016), over 9000 may be increasing stream temperatures and collectively thermally altering thousands of kilometers of stream length in the region. To further understand and better predict the impacts from dams to stream temperature across the region, the data from this study will be incorporated into and help refine the Spatial Hydro-Ecological Decision System statistical temperature model (https://ecosheds.org; Letcher et al., 2016; SHEDS Development Team, 2020). Predicted changes in regional climatic conditions (Hayhoe et al., 2008) will likely reduce coldwater habitat in the northeastern United States in the future and carry negative implications for aquatic organisms adapted to and dependent upon coldwater habitat (Chambers et al., 2017). While some bottom-release dams may provide refugia to coldwater-adapted species (Olden and Naiman, 2010), in contrast, run of river dams (such as those in this study, which are far more numerous) appear to be having the opposite effect, and are likely exacerbating and accelerating the loss of critical coldwater habitat. These impacts are particularly important in the context of a warming climate with more variable precipitation, where coldwater headwater habitats are likely to be squeezed from below by warming temperatures and from above by increased frequency of droughts and floods. Management actions, such as removal of high-impact (i.e., high-warming) dams, are key to maintaining critical coldwater habitats and increasing resilience to current and future ecosystem changes.

CRediT authorship contribution statement

Peter A. Zaidel: Methodology, Formal analysis, Investigation, Visualization, Writing - original draft, Writing - review & editing. **Allison H. Roy:** Conceptualization, Methodology, Writing - review & editing, Project administration. **Kristopher M. Houle:** Writing - review & editing, Funding acquisition. **Beth Lambert:** Conceptualization, Funding acquisition. **Benjamin H. Letcher:** Methodology, Writing - review & editing. **Keith H. Nislow:** Conceptualization, Methodology, Writing - review & editing, Funding acquisition. **Christopher Smith:**

Methodology, Investigation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.106878.

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