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Research article

Guiding riparian management in a transboundary watershed through high resolution spatial statistical network models

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ABSTRACT

The United States Environmental Protection Agency and the Houlton Band of Maliseet Indians (HBMI) built a stream temperature spatial statistical network (SSN) model for the Meduxnekeag Watershed. The headwaters of the Meduxnekeag Watershed are in Maine, United States of America and the outlet is in New Brunswick, Canada, creating an additional challenge because many datasets are constrained to political boundaries. The release of the High-Resolution National Hydrology Dataset Plus included transboundary watersheds and enabled creation of fine resolution (1:24,000) SSN temperature models consistent with management scales for riparian buffers. SSN models were developed for July, August, and September median stream temperatures and the growing season maximum (GSM). Fitted SSN models had relatively high R^2 values (0.88–0.96) and all final models included significant parameters for shade-attenuated solar radiation, reference flow, air temperature, and bankfull depth or width. Fitted models predicted stream temperatures during a dry (2010) and wet (2011) year. Monthly models predicted the fewest cold water (<19.0 °C) reaches in July with 28% in the dry and 68% in the wet year. September had >99% cold water reaches, and August results were intermediate between July and September. GSM predictions found 81% of stream reaches could not support salmonid survival (>27.0 °C) in the dry year and 59% of the reaches were warmwater (22.5–27.0 °C) in the wet year. The model was used to predict stream temperatures following restoration scenarios of a forested 30-m or 90-m buffer of stream segments bordered by agricultural or developed land. The restoration scenarios expanded cold water habitat based on monthly median temperatures and decreased the habitat area with GSM above survival thresholds, with little difference in effectiveness of the two buffer widths. These results will guide riparian restoration projects by the HBMI to expand habitat for cold water fishes.

1. Introduction

Stream temperature is a key determinant for the species that occur in a stream network. Stream temperature is impacted by land uses, including urban development (e.g. urban runoff and urban heat island effects), agriculture, water inputs and withdrawals, and damming practices; however, some impacts can be mitigated by maintaining or restoring riparian buffers along the stream corridor. Water temperature models can be applied to predict effects of some restoration practices. However, detailed mechanistic stream/river temperature models used to support development of implementation plans (Boyd and Kasper, 2003; Ecology, 2003) require significant effort to parameterize and calibrate, and are typically applied only to the mainstem of rivers (Butcher et al., 2010; Kennedy and Butcher, 2012; Pelletier, 2002). More recently, mechanistic hydrologic models have been combined with coupled modules (Ficklin et al., 2012a) or models (Sun et al., 2015) describing heat budgets to facilitate application of mechanistic models for stream/river temperature across broader regions. However, in practice, researchers have reduced spatial resolution of the stream networks or level of detail (riparian zone heterogeneity) represented in the models in order to increase spatial extent (Cao et al., 2016; Ficklin et al., 2014a; Yearsley, 2019).

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Recently, spatial statistical network (SSN) models have facilitated prediction of thermal regimes throughout entire medium-resolution stream/river networks across the western United States of America (USA) and New England (NE) and of potential recovery following riparian restoration (Fuller et al., 2019). SSN models can be used to describe the main effects of landscape- and reach-level variables on riverine thermal metrics such as summer monthly average temperatures or 7-day mean daily maxima (7DMDM). SSN models also include measures of spatial autocorrelation in error terms based on Euclidean distance and/or on distance along stream networks that is flow-connected (tail-up variance components) or flow-unconnected (tail-down variance components). Incorporation of spatial autocorrelation error terms, rather than assuming complete independence of all observations, reduces the chance of Type I errors (falsely identifying significant predictors; ver Hoef et al., 2019).

Information on the seasonal variation of thermal regimes from the SSN model can help guide targeted restoration strategies for cold water fisheries such as *Salvelinus fontinalis* (Brook Trout) and *Salmo salar* (Atlantic Salmon). Atlantic Salmon use different portions of a river network during different life stages. Atlantic Salmon migrate as far upstream as possible in the fall to spawn, with ideal spawning habitat for Atlantic Salmon characterized by depths >38 cm and velocities of 31–55 cm/s (Gibson 1993). Suitable temperatures are required for spawning adults, but the timing of migrations has been shifted at least one month earlier over the last few decades due to changes in the phenology of ocean temperatures (Mills et al., 2020). In addition, spawning migrations must be initiated earlier, given potential delays of weeks to months imposed by dams and thermal barriers (Rubenstein et al., 2020). Thus, cold water refuges are required for holding areas during the migration process. While most evidence suggests that subsequent movement of fry and parr in the spring and fall is predominantly downstream, both upstream and downstream dispersal have been recorded in response to differences in habitat suitability. One study in the Freshwater River in southeastern Newfoundland documented the migration of parr to headwaters 4.2 km upstream from the nearest redds (Gibson 1993). In contrast, most recent studies of genetic population structure of Brook Trout in dendritic stream networks demonstrate relatively little movement between areas of preferred habitat in headwater tributaries (Hudy et al., 2010, Kanno et al., 2011), although in the upper Hudson, Bruce and Wright (2018) have found evidence of ongoing migrations among headwater populations both within and between river systems.

SSN models can be used to map cold and coolwater habitat throughout a stream network and efficiently generate predictions for restoration scenarios across broad regions. However, the accuracy of predictions could be limited by the spatial resolution of the underlying stream network used in these models (1:100,000). Predictions for riparian buffer management often focus on management of a 15–30 m riparian corridor, which requires predictions with greater spatial accuracy (Lee et al., 2004). Release of the high-resolution version of NHDPlus (NHDPlus-HR, 1:24,000) has enabled development of SSN models at a resolution scale appropriate for informing riparian buffer management, including the required width and upstream extent for forested buffers to protect thermal regimes (Barton et al., 1985; Bowler et al., 2012). In addition, the NHDPlus-HR dataset has been enhanced to include watersheds that cross international boundaries, extending into Canada (U.S. Geological Survey, 2018).

The Houlton Band of Maliseet Indians (HBMI) partnered with the United States Environmental Protection Agency to expand the NE temperature model into the Meduxnekeag Watershed, a transboundary watershed, to help guide restoration practices by highlighting the areas in the watershed that would benefit the most from riparian restoration. HBMI aims to restore coldwater fisheries habitat (<19 °C) for Brook Trout and to restore enough habitat to reintroduce native Atlantic Salmon to the Meduxnekeag Watershed through restoring riparian vegetation. The Meduxnekeag Watershed case study allows us to explore potential improvements in SSN models applied to the finer-scale NHDPlus-HR, compare to existing SSN temperature models, evaluate stream temperature improvements with a 30-m or 90-m restored riparian buffer, and provide an example of constructing SSN models across international borders. SSN models were developed in the Meduxnekeag Watershed for the median July, August, and September stream temperatures along with the Growing Season Maximum (GSM) to capture both the critical thermal regimes associated with dominance of coldwater, coolwater, and warmwater fish communities (Beauchene et al., 2014), as well as acute events associated with mortality of salmonids (>27 °C, Elliot and Elliot, 1995). The SSN models were applied to predict stream temperatures throughout the watershed for both a dry (2010) and wet (2011) year. Lastly, the models were used to predict stream temperature improvements with a 30-m or 90-m riparian restoration in the agricultural and developed areas in the watershed. The results from the high resolution SSN stream temperature model will help the HBMI maximize stream temperature improvements from limited restoration funds by selecting the stream reaches that would benefit the most from riparian restoration. This includes preferentially restoring stream reaches that shift from warm water to cold or cool water after riparian restoration instead of reaches that remain warm water after restoration.

2. Methods

The SSN software (ver Hoef et al., 2019) was used to parameterize mixed models of the form

$$Y = X\beta + \sigma_{eu}z_{eu} + \sigma_{tu}z_{tu} + \sigma_{nug}zn_{ug} \quad (1)$$

Where Y = dependent variable, X = matrix of fixed effect independent variables, β = parameter vector for fixed effects, σ = variance component, z = random effect, eu = Euclidean autocorrelation, td = taildown autocorrelation, tu = tailup autocorrelation, and nug = nugget effect. SSN models account for spatial autocorrelation based on both Euclidean distances between sites and the distance between sites along the stream network (either upstream or downstream directions; ver Hoef et al., 2019). The Meduxnekeag SSN model was developed using the existing NE SSN temperature model as guidance (Detenbeck et al., 2016) with the NHDPlus-HR providing stream network flowlines and value-added attributes such as estimated monthly discharge and velocity. The NE SSN model includes fixed effects representing the influence of different heat sources (air temperature, urban heat index), runoff (watershed area, percent impervious cover), groundwater (coarse surficial deposits, soil drainage class), and solar radiation (modified by both topographic and vegetative shade). In addition, the model includes indicators representing the effect of retention time on heat transfers (watershed storage as lakes or reservoirs plus wetlands, adjacent upstream lake or reservoir, discharge, channel slope), and channel morphometry (width to depth ratio) influencing thermal inertia of water bodies (Gu et al., 1998).

The Meduxnekeag SSN model was developed using similar variables as the NE temperature model, with some substitutions made based on binational dataset availability. ArcGIS version 10.5.1 (©ESRI, Redlands, CA) was used for data processing and watershed characterization. The . ssn object, which provides the data framework for an SSN model, was created using ArcGIS toolbox, STARS version 2.0.6 (Peterson, 2017). Lastly, the SSN model was fit using backward stepwise regression and variable substitutions were attempted to improve the model fit. The fitted model was used to predict current and restored temperatures at 3487 prediction points throughout the watershed. SSN R package, version 1.1.13 was used to fit the model and create predictions (ver Hoef, 2018).

2.1. Watershed traits and stream temperature sites

The Meduxnekeag Watershed is 1336 km^2 with its headwaters in northern Maine, USA and its confluence with the Saint John River in New Brunswick, Canada (Fig. 1). Land use in the watershed is 60% forested, 20.4% agriculture, 3.8% developed, and 15.3% lakes and wetlands (Government of Canada, 2010; Homer et al., 2015). The HBMI started monitoring water temperature and water quality in 1995 in the USA portion of the watershed and has continued monitoring until the present day. There were 38 sites on the USA side of the watershed with one or multiple years of monitoring between 2009 and 2017 that were used in this study. Adding new sites was explored in 2018 because spatial statistical network models are more accurate if the existing stream temperature monitoring data used to build the model capture most of the variability throughout the watershed (Jackson et al., 2016; Marsha et al., 2018). Principal Component Analysis was used to select 11 new sites in 2018, including six in Canada and five in the USA headwaters, for a total of 49 temperature sites (see Supplementary Materials).

2.2. Temperature data processing

The HBMI provided stream temperature data from data loggers from 2009 to 2018 for 49 sites at 15- to 30-min increments. Temperature data were checked for quality assurance, including comparing the daily average stream temperature at each site to the daily air temperature from the Houlton International Airport in Houlton, Maine (Menne et al., 2012a, 2012b). Outliers in a regression of water versus air temperature were checked for indications that the temperature logger was exposed to the air or buried in sediment and outliers were removed as needed. Months with less than 90% of the data remaining were removed. The GSM was calculated for each year with both July and August data and

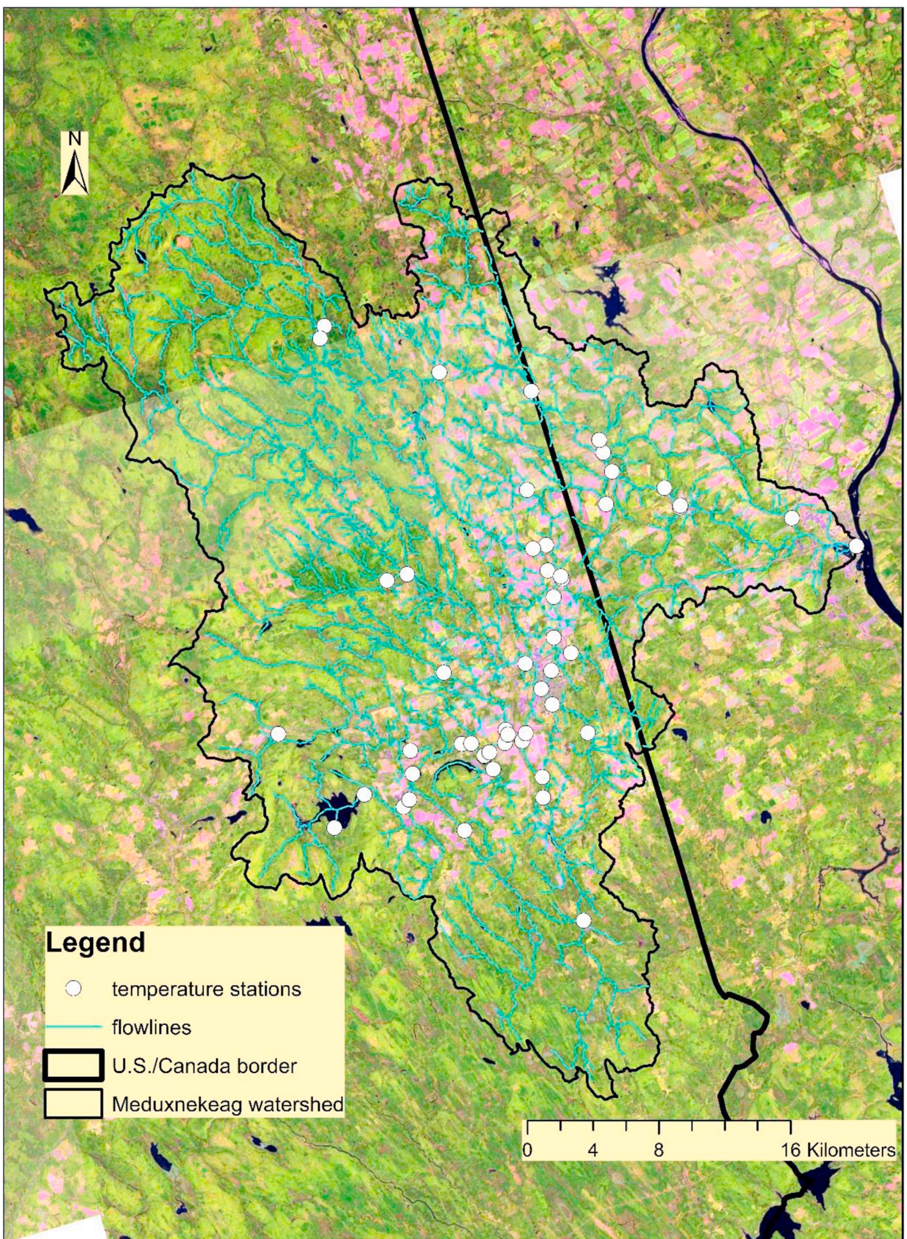

Fig. 1. Location of transboundary Meduxnekeag River watershed as a tributary to the Saint John River in northern Maine, USA and New Brunswick, Canada with predominance of forested land cover in headwaters. The underlying Landsat 8 natural color images from September 14, 2018 illustrate the predominance of forested land cover in the headwaters and temperature monitoring stations are overlaid as filled circles.

the median monthly stream temperature was calculated for July, August, and September.

To avoid pseudoreplication, only one year of data was used to represent each site when fitting the model; the year of interest was chosen randomly. Input variables that change between years, e.g., air temperature and discharge, were matched to the observation year selected for water temperature. The July model was built with data from 37 sites that were all in the USA. The August model was built with 49 sites, with seven in Canada. The September model was built with 37 sites with six sites in Canada. Lastly, the GSM model was built with 36 sites that were all in the USA.

2.3. Characterizing upstream drainage areas

The SSN model was built by first characterizing the upstream area of the 49 temperature monitoring sites for 2009 through 2018 (Fig. 1). Watershed parameter data sources that differed between the USA and Canada are listed in Table 1. All parameters with a single data source have the data source identified in the text below.

NHDPlus HR data were used to determine the mean annual discharge, mean annual velocity, site elevation, and local slope (U.S. Geological Survey, 2018). The total upstream area stream length, drainage density, and U.S.G.S 10-85th percentile main channel slope were calculated using Arc Hydro (ESRI, 2019) with data from NHDPlus HR. Additionally, squared and cubed terms for main channel slope were tested for significance because in the NE model, the temperature response to main channel slope was found to be nonlinear.

Stream characteristics, including stream width, depth and width to depth ratios, were calculated using equations from Bent and Waite (2013) based on the upstream drainage area:

$$\text{Bankfull width (ft)} = 15.0418 \left[\text{Drainage area } \left(\text{mi}^2\right)\right]^{10.4038} \tag{2}$$

$$\text{Bankfull mean depth (ft)} = 0.9502 \left[\text{Drainage area } \left(\text{mi}^2\right)\right]^{10.296} \tag{3}$$

Bent and Waite (2013) equations using slope were also considered, but global imagery from Google Earth indicated that equations without slope better estimated the stream width.

Stream/river temperature is influenced by the relative contributions of upstream inputs, runoff, lateral flow, and groundwater, each of which has a different temperature signature. Groundwater influences were indicated using both the global baseflow recession coefficient (Beck et al, 2013, 2015) and by determining the percentage of well drained soils in the watershed (Table 1). The percentage of the upstream watershed with excessively drained soils was calculated along with the percentage of the watershed with excessively and somewhat excessively drained soils.

Table 1
Data sources that differed between the USA and the Canadian side of the watershed.

Parameter	Country	Data sources
Percent well drained soils	USA	Soil Survey Geographic Database (Soil Survey Staff, 2019)
	Canada	National Soil Database (Government of Canada, 2002)
Watershed storage	USA	United States National Wetland Inventory (U.S. Fish and Wildlife Service, 2018)
	Canada	Government of New Brunswick (Department of Environment and Local Government, 2018).
Percent developed land	USA	2011 National Land Cover Dataset (Homer et al., 2015)
	Canada	Canada Open Government 2010 Land Use raster (Government of Canada, 2010).
Reference flow	USA	Miller et al. (2018), USGS gage station (#1018035), NHDPlus HR flowlines
	Canada	USGS gage station (#1018035), NHDPlus HR flowlines

The waterbodies shapefile from NHDPlus HR was used to determine if there was a lake or reservoir in the upstream catchment of the sampling site. Only waterbodies over 0.01 km^2 were included and global imagery was used to confirm that the upstream waterbody had open water. Lake or reservoir depth of the upstream waterbodies was calculated using the R package *lakemorpho*, version 1.1.1 (Hollister and Stachelek, 2017). Only two of the monitoring sites had a lake or reservoir upstream of them, which created a spurious correlation with the USA/Canada dummy variable because both lakes were in the USA. Instead of focusing only on lakes and reservoirs, the Meduxnekeag SSN model included a variable of the maximum upstream water depth, as either a lake, reservoir or maximum stream depth, in the upstream catchment of the sampling site. Watershed storage was also calculated as the percentage of the total drainage area covered by lakes, reservoirs, and wetlands (Table 1).

The Meduxnekeag is a mostly rural watershed and only two monitoring sites had any potential urban heat island effects, which created autocorrelated variables. Instead, percent developed area in the last 500 m of the watershed, in the last 1000 m of the watershed, and the total upstream watershed were calculated (Table 1).

The median monthly July, August, and September air temperatures from 2009 to 2018 were calculated using the minimum and maximum monthly air temperatures from Daily Surface Weather and Climatological Summaries (Daymet) (Thornton et al., 2018a). Additionally, median annual air temperatures for the upstream drainage area were calculated from the minimum and maximum annual air temperature from Daymet annual summaries (Thornton et al., 2018b). The GSM was always in July or August and was determined as the maximum monthly air temperature for the upstream drainage area from Daymet from 2009 to 2018. An interaction term was also calculated between monthly air temperature of GSM and stream width to depth ratio as an indicator of thermal inertia of deeper water (Gu et al., 1998).

The reference flow was determined for July, August, September and the GSM from 2009 to 2018. NHDPlus HR includes the mean annual discharge for each flowline for the period 1970 to 2000. The reference flow dataset in the USA from Miller et al. (2018) based on NHDPlus v2 was used to determine the percent difference between each sampling month and year as compared to the mean annual average discharge from 1970 to 2000. The calculated percent difference was used to estimate the reference flow for all NHDPlus HR flowlines from 2009 to 2015. The Miller et al. (2018) data stopped at 2015. To account for the 2016 to 2018 data, the 2015 reference flow data were adjusted based on data from the U.S.G.S. gage station (#1018035) on the Meduxnekeag River. Reference flow and gaging station data for July–September 2010 and 2011 were highly correlated ($r^2 = 0.75$). This meant that if the August 2018 U.S.G.S. discharge at the gage station was only 50% of the discharge in August 2015, the Miller et al. (2018) data for August 2015 would be multiplied by 0.5 to estimate the August 2018 data.

The shade. xls VBA-based tool developed for the Washington State Department of Ecology (https://ecology.wa.gov/Research-Data/Data-resources/Models-spreadsheets/Modeling-the-environment/Models-tools-for-TMDLs) was used to calculate the % shade from vegetation for 20,842 stream segments that were spaced every 80 m throughout the network. Shade model input parameters included the site elevation from NHDPlus HR, stream segment aspect from the ArcGIS linear directional mean tool, the stream width and depth from Bent and Waite (2013), and angle of the horizon at 90°, 180°, and 270° using the Whitebox toolbox in ArcGIS (Lindsay, 2016). Stream segments in waterbodies or wide areas of the stream were measured using the waterbodies shapefile from NHDPlus HR. Vegetation zones were created for each stream segment on both the left and right bank. The vegetation zones were non-overlapping stream buffers with each zone being 10 m wide. The Hansen Global Forest Change dataset (Hansen et al., 2013) was used to determine the % canopy cover along each vegetation zone. On the USA side of the watershed the LandFire Environmental Vegetation Height dataset was used to determine the average vegetation height for each zone (U.S.

Department of Interior, 2017a, U.S. Department of Interior, 2017b). The Canadian side had limited high resolution digital surface models available near the watershed (Government of Canada, 2017). These areas were used to estimate the current average vegetation height in each land use classification, which were then used to estimate the average vegetation height for the vegetation zones in the watershed on the Canadian side. The shade model was run for all stream segments in the Meduxnekeag for July, August, and September using the Oregon Department of Environmental Quality (ODEQ) shade calculation method adjusted for % cloudiness using data from EarthEnv (Wilson and Jetz, 2016).

The shade-attenuated solar radiation (SASR) of each shade point was calculated using equation (4):

$$SASR = \left(1 - \left(\frac{\%\ shade\ from\ vegetation}{100}\right)\right) * potential\ solar\ radiation \quad (4)$$

Potential solar radiation under clear skies was calculated from the ArcMap (©ESRI, Redlands, CA) Area Solar Radiation tool. The ArcMap solar radiation area tool enables the user to calculate global solar radiation (direct + diffuse) over a geographic area for specific time periods, accounting for atmospheric effects, site latitude and elevation, steepness (slope) and compass direction (aspect), daily and seasonal shifts of the sun angle, and effects of shadows cast by surrounding topography, based on methods from the hemispherical viewshed algorithm developed by Fu and Rich (2002). The average SASR was then calculated for several upstream buffers based on stream travel time or distance including 1 h, 2 h, 3 h, 1 km, 2 km, 3 km, 4 km, 5 km, 10 km, and the entire upstream buffer, using methods of Fuller et al. (2019). Travel buffers accounted for the distance upstream 'as the fish swims,' meaning it included the sinuosity of the stream flow path. Both distance upstream and travel time are used to account for the nonequilibrium nature of stream temperature, that is, stream temperatures do not instantly equilibrate to solar exposure and overlying air temperature for a given reach. A parcel of water is continually changing in temperature as it moves downstream. Travel time is more directly related to residence time of surface water within the stream than a simple distance measurement. Mean annual travel time was calculated based on mean annual reach velocity and reach length values in NHDPlus HR. The edges shapefile in the SSN object was used to construct a network in ArcMap, and upstream buffer polygons were defined using the service analysis function in Network Analyst using stream length or travel time to define impedance in routing upstream from observation or prediction points.

Many of the variables that were used to build the SSN model had different data sources between the USA and Canadian parts of the watershed (Table 1). To account for this, a dummy variable indicating if the site was in Canada or not was included as a potential parameter in the model along with the percent of the upstream site watershed area that was in the USA.

2.4. Fitting the model

The SSN models were fitted using a backwards stepwise regression method by removing the parameter with the highest p-value one at a time. Independent variables were standardized before fitting models to enhance comparability of regression coefficients and to reduce collinearity among predictors (including squared, cubed, and interaction terms with simple main effects). In general, the model with the best Akaike's Information Criteria (AIC) value was selected, although model bias and root mean square prediction error (RMSPE) were also considered in selecting the best model (Burnham and Anderson, 1998). Next, parameters that were represented multiple ways, for example the percent upstream development in the last 500 m of the watershed and the percent upstream development of the entire watershed, were substituted and the model with the lowest AIC was selected. Next, results from all shade buffers were substituted and the buffers with the lowest AIC for the median monthly stream temperatures and the GSM were selected, 3 h travel time and 1 km travel distance, respectively. Lastly, possible interaction terms were added in and the autocorrelation model was selected by trying all possible combinations of autocovariance error functions in the SSN package. Autocovariance functions can be based on Euclidean distance, distance along the flow network regardless of flow direction, and distance along the flow network consistent with flow direction. The model with the lowest AIC (within 3 units of the lowest AIC model) that contained at least one tailup component (reflecting flow-connected covariance) was selected. Temperature of upstream reaches influence downstream reaches but, except in cases of flow reversals, the reverse is not true.

2.5. Restoration scenarios

Two possible restoration scenarios for reducing stream temperature throughout the Meduxnekeag included restoring the riparian vegetation in agricultural and developed areas throughout the watershed for 30-m or 90-m buffer widths. The effects of this restoration were simulated by selecting the stream segments with >25% agriculture and/or development in the vegetation zones, non-overlapping stream buffers with each zone being 10 m wide, that were used in the shade model. For the 30-m restoration scenario, any segments with >25% agriculture and/or development in the 30-m buffer had the original percent canopy cover and vegetation height in that zone replaced with restored values. The restored values were 100% canopy cover and 17.5 m vegetation height, the same values that were seen in currently fully forested areas in the Meduxnekeag Watershed. In the 90-m restoration scenario, any segments with >25% agriculture and/or development in any of the nine vegetation zones had the original percent canopy cover and vegetation height in all nine vegetation zones replaced with restored values. For both restoration scenarios, any segment with medium density development only had the first vegetation zone restored if the medium development occurred in the first three vegetation zones. If the development occurred between the fourth and ninth zones, the vegetation zones were restored between the stream and first occurrence of medium density development. This assumes that areas between buildings and the stream would be restored, but that buildings themselves would not be removed and replaced with vegetation.

The stream segments that were selected for restoration had the percent shade from vegetation recalculated using the shade model. The restored mean shaded-solar radiation was then recalculated for the selected travel buffers from the fitted models (3 h and 1 km).

2.6. Watershed prediction points

NHDPlus HR catchments were used to create 3487 prediction points throughout the watershed with a prediction point 10 m upstream of each catchment's pour point. These prediction points were used to model the expected stream temperature throughout the watershed under current conditions, along with 30-m and 90-m restored conditions. A wet (2011) and dry (2010) year were selected for modeling the stream temperature predictions based on the Palmer Drought Severity Index (NOAA, 2019) and reference flow conditions throughout the watershed. Predictions were generated using air temperature and discharge input data for July, August, and September of 2010 and 2011.

2.7. Predicted extent and distribution of habitat for Atlantic Salmon

Thermal regime classes for Atlantic Salmon habitat suitability were defined based on the upper range of optimum temperatures (19 °C) for feeding or survival of Atlantic Salmon early fry and parr, the maximum temperature for feeding by parr (22.5 °C), and the lower threshold for salmonid survival during acute temperature events (27 °C) (Danie et al., 1984; DeCola, 1970; Elliott, 1991; Elliott and Elliott, 1995; Jensen et al., 1989). These cutoffs are like those separating regimes supporting coldwater, coolwater, and warmwater fish communities in Connecticut, so we refer to these as coldwater, coolwater, and warmwater regimes (Beauchene et al., 2014). These thresholds were used to map and quantify extent and distribution of habitat for Atlantic Salmon for each month or GSM conditions for wet and dry years both with and without implementation of riparian buffer restoration.

3. Results

3.1. Fitted models

Final selected models for each month and for the GSM are summarized in Table 2. Fitted SSN models were of good quality with relatively high r^2 values (0.88–0.96), root mean square prediction errors less than 1 °C for monthly models and slightly greater than 1 °C (1.2 °C) for GSM, and low bias (−0.08 to 0.02 °C). Final fitted SSN model parameters shared many common elements across models for monthly median and GSM temperatures (Table 2). All models included significant parameters for shade integrated over 3 h travel time (monthly models) or 1 km upstream (GSM model), reference flow, monthly average or GSM air temperatures, and bankfull depth or width. Other predictors that were statistically significant in a subset of models included elevation, local gradient or squared channel slope, baseflow recession coefficient, ln maximum depth upstream, latitude, and country. Based on magnitude of regression coefficients, channel morphometry had the strongest influence on median and GSM temperatures, followed by air temperature or elevation; reference flow, SASR or maximum upstream depth, and slope variables. Some nonlinear responses were observed for August mean temperatures, with squared terms for main channel slope and reference flow. Although a few interaction terms appeared in regressions, none of these were statistically significant.

3.2. Predicted temperature regimes for dry (2010) and wet (2011) years

Predicted thermal regime extent and distribution varied by both year and month. The predicted thermal regimes for July 2010 and 2011 by reach length meters were predominantly cold (28 and 68%, respectively) and coolwater (57 and 28%, respectively; Fig. 2a and b; KML map). Predominance of cool versus coldwater regimes switched between the dry year (2010) and wet year (2011), with a much greater extent of coldwater reaches in the wet year. In the dry year, coldwater reaches were mainly in headwater streams, while in the wet year, cold water regimes extended downstream to some but not all second-order reaches. Warmwater regimes were almost entirely restricted to the mainstem except for short segments downstream of lakes or reservoirs. In August, the extent of coldwater regimes expanded in both 2010 and 2011, while the extent of warmwater reaches diminished to only 4 and 1.5%, respectively (Fig. 2c and d). In September, the coldwater regime expanded in both years to cover over 99% of reach lengths throughout the entire Meduxnekeag watershed. The GSM predicted the most temperature restricted habitat with 81% of stream reaches unable to support salmonid survival (>27 °C) in a dry year and 59% of stream reaches categorized as warmwater habitat during a wet year (Fig. 2e and f; KML map).

3.3. Predicted effects of riparian restoration

The predicted effectiveness of riparian restoration on thermal regimes differed little between 30-m riparian restoration and 90-m riparian restoration scenarios but did vary widely among months. Extent of coldwater reaches in July increased from 28% to 45% with 30 m zone restoration and to 52% with 90 m restoration in 2010 and from 68% to 77% (30 m) to 79% (90 m) in 2011 (Fig. 3a and b; KML map). Extent of coldwater reaches was predicted to be even greater in August for both the dry year 2010 (66% with 30 m, 73% with 90 m) and the wet year 2011 (82% 30 m and 85% 90 m). Riparian restoration would ameliorate GSM as well, reducing no survival reaches from 81% to 70.8% with 30 m buffer restoration and to 65% with 90 m buffer restoration in 2010, and from 30% to 25% with 30 m buffer restoration and to 23% with 90 m buffer restoration in 2011. However, riparian restoration could only increase cold + coolwater refugia during GSM to 2.4–3.2% of reach

Table 2
Regression coefficients and model statistics associated with the final fitted models to predict July, August, and September average water temperatures, and the GSM based on standardized predictors. RMSPE = root mean square prediction error. ***p < 0.001, **p < 0.01, *p < 0.05.

	Model statistics and coefficients	July	Aug	Sept	GSM
	Intercept	21.8***	20.2***	15.9***	27.9***
	Longitude			0.95	
	Latitude			−1.00**	−0.53
	Baseflow recession coefficient	−0.98**			0.94
	Gradient	−0.60*			−0.96 (*)
	Main channel slope				
	Main channel slope^2		−0.58***	−0.17	0.69
	Ln (maximum upstream depth)	1.21***		1.16**	
	Channel depth	1.01***		1.85***	3.25***
	Bankfull width		3.26***		
	Watershed storage			−0.61	
	Elevation		1.58*		2.57***
	Location of site in Canada		−1.64*	−1.83***	
Vary with time	Monthly air temperature	1.78***	2.30***	2.22***	
	GSM air temperature				1.56**
	Reference_flow (monthly)	−1.72***	−2.21***	−1.34***	
	Reference_flow (growing season average)				−1.58**
	Reference flow^2		1.52*		
	3 h upstream SASR	0.98***	1.21**	0.47	
	1 km upstream SASR				1.27*
	Maximum growing season air temperature x width: depth ratio				−0.97
	Baseflow recession coefficient x Main channel slope				0.28
	Reference flow (monthly) x Air temperature (monthly)	1.20			
	AIC:				
	Spatial Autocovariance Error Term:	LinearSill.tailup Gaussian.Euclid	Epanech.tailup Gaussian.Euclid	LinearSill.tailup	LinearSill.tailup
	Generalized r^2	0.96	0.89	0.91	0.88
	RMSE (° C)	0.5	0.9	0.9	1.2
	Bias (° C)	−0.1	<0.1	−0.1	<0.1

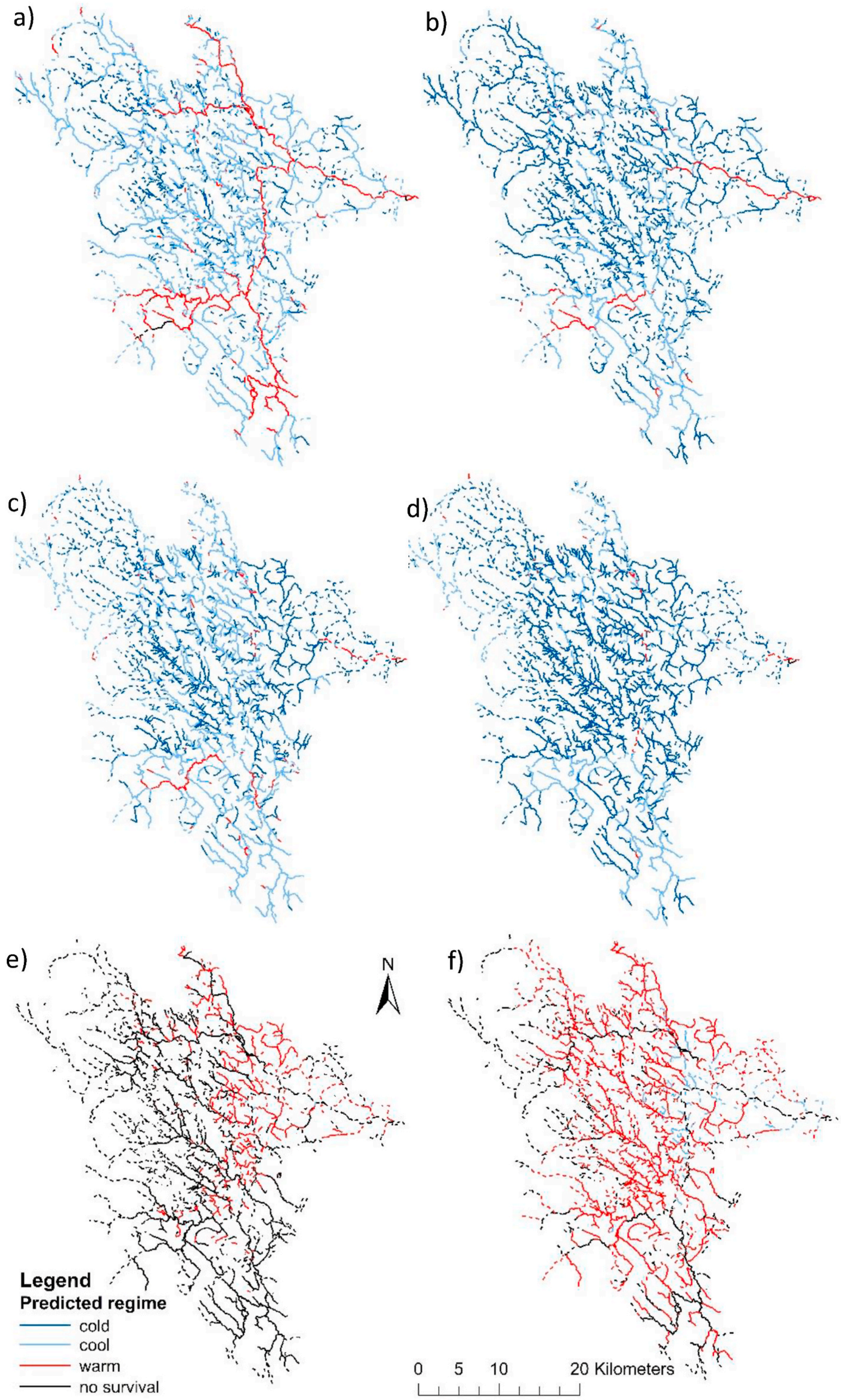

Fig. 2. Predicted thermal regimes for stream reaches in the Meduxnekeag watershed for a) July 2010, b) July 2011, c) August 2010, d) August 2011, e) 2010 GSM, and f) GSM. Dark blue lines = coldwater regime (<19 °C), Light blue lines = coolwater regime (19–22.5 °C), Red lines = warmwater regime (22.5–27 °C), Black lines = beyond survival (>27 °C). Dashed lines represent reaches with greater uncertainty for predictions (predictors <90% of minimum or > 110% of maximum values of predictor variables for observation points). See Supplemental KML Maps for high resolution images.

length in the dry year 2010 and to 19.4–24.2% of reach length in the wet year 2011. Coldwater refugia would be restricted to headwater reaches (Fig. 3c and d; KML map).

4. Discussion

4.1. Comparison of Meduxnekeag SSN with other stream temperature models

The Meduxnekeag SSN model using NHDPlus HR provides unique capabilities in comparison to other models developed for this region, and to SSN temperature models developed for other regions. Relatively few stream temperature models have been applied to watersheds in

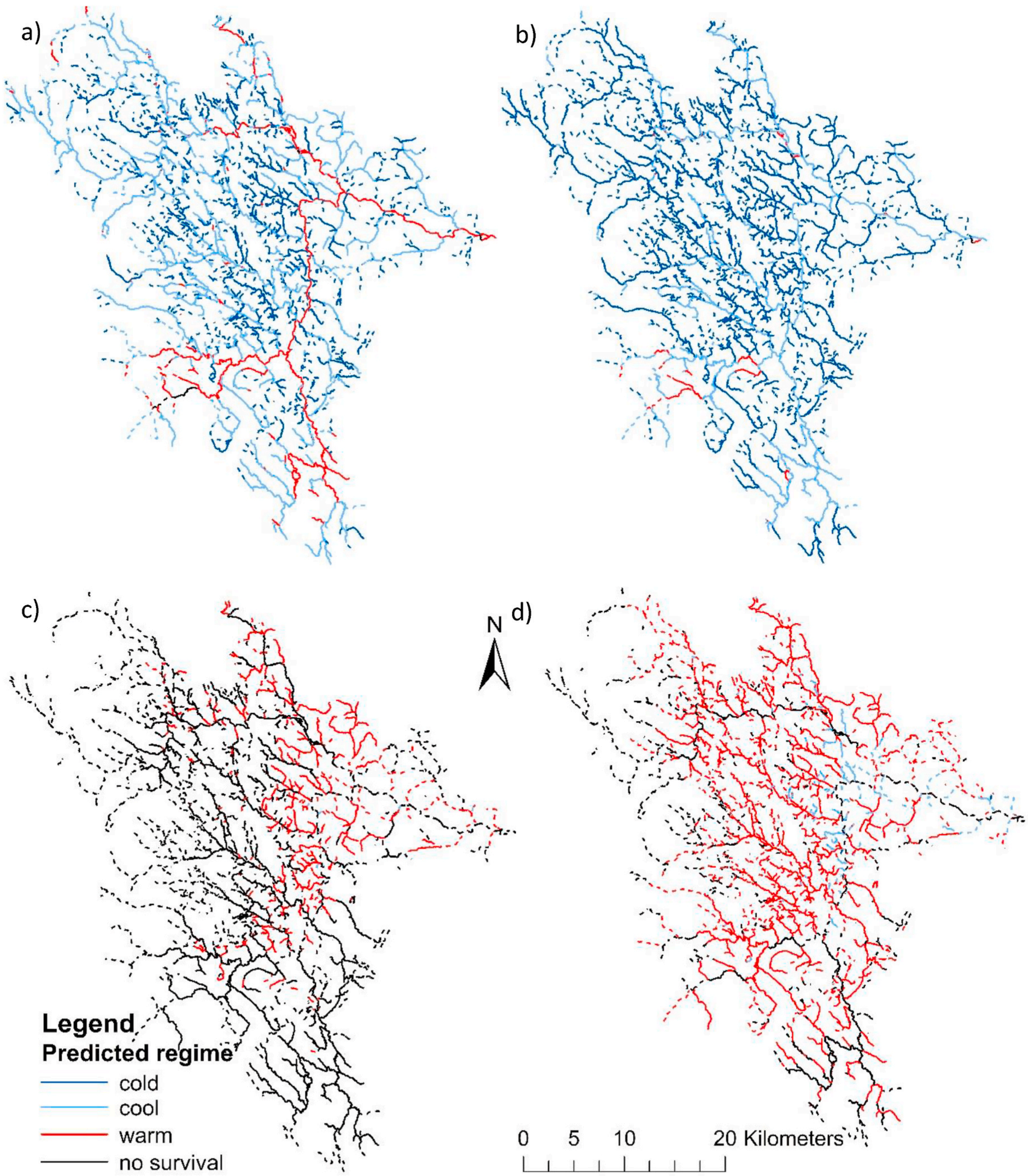

Fig. 3. Predicted thermal regimes for stream reaches in the Meduxnekeag watershed following restoration of 30 m riparian buffer zones for a) July 2010, b) July 2011, c) 2010 GSM, and d) 2011 GSM. Dark blue lines = coldwater regime (<19 °C), Light blue lines = coolwater regime (19–22.5 °C), Red lines = warmwater regime (22.5–27 °C), Black lines = beyond survival (>27 °C). Dashed lines represent reaches with greater uncertainty for predictions (predictors <90% of minimum or > 10% of maximum values for observation points). See Supplemental KML Maps for high resolution images.

Maine or New Brunswick, and with the exception of the NE SSN (Detenbeck et al., 2016), most of these focus on air temperature as the main predictor so do not explicitly incorporate the influence of shading, groundwater inputs, or discharge variability on stream temperature (Caissie et al., 2005, 2017; Chenard and Caissie, 2008), and thus cannot be used to predict effects of management actions influencing those drivers. Most of the previous SSN models developed for temperature focus on watersheds in the western half of the USA (Isaak et al., 2017) and predict conditions for hydrologic frameworks at a scale of 1:100, 000. Unlike the NorWeST SSN models, which rely on canopy coverage as predictors of shade, the calculation of SASR in the Meduxnekeag SSN model takes into account the influence of clouds and topographic shading, and can be used to estimate the effects of fine-scale buffer management on solar exposure to streams and effects on stream temperature. The Meduxnekeag SSN model also extends the NE SSN model by taking into account the effect of stream velocity (and temperature equilibration) on longitudinal zones of shade influence.

The Meduxnekeag SSN models performed well in comparison to the NE SSN model, with lower RMSE values (0.52–0.94 °C for monthly medians as compared to 1.4–1.5 °C, 1.2 °C for GSM as compared to 1.6 °C) and higher r^2 values 0.88–0.96 as compared to 0.41–0.43 (Detenbeck et al., 2016). In addition, the finer spatial resolution of the Meduxnekeag SSN model allowed us to evaluate effects of buffer width (30 versus 90 m), as well as upstream extent of buffers influencing thermal regimes (3 h travel time or 1 km). The 1-km range of influence is somewhat lower than earlier estimates of 2.5 km for shading range of influence by Barton et al. (1985) for southern Ontario streams, but travel times may differ between the two regions. Barton et al. did find that the influence of upstream shade diminished between 1 and 2.5 km upstream.

The Meduxnekeag SSN models contained a similar suite of variables as the NE and western USA SSN models, including effects of air temperature, SASR, local gradient or main channel slope, groundwater indicators (baseflow recession coefficient in place of soil properties), and maximum upstream lake or reservoir depth. The NE SSN model included both squared and cubed terms for main channel slope but only the squared term was included in the Meduxnekeag model, based on goodness of fit. Fullerton et al. (2015) have described asymptotic patterns of temperature along longitudinal gradients in large rivers. In Maine and the Meduxnekeag, coarse surficial deposits are less common and more patchily distributed, with eskers and alluvial deposits occurring in the downstream portion.

For the Meduxnekeag SSN model, mean baseflow recession constant was a better predictor of stream temperatures than were soil characteristics related to infiltration rates. The Meduxnekeag SSN also detected effects of discharge on median stream temperatures, while the discharge effect appears in NE SSN models only for prediction of stream temperature ranges, not median values, and appears in western USA SSN models, but usually as a less influential predictor (Isaak et al., 2017). However, analysis of monitoring data for stream temperatures in the Pacific Northwest has demonstrated that discharge accounted for approximately half (52%) of the inter-annual variation in summer temperatures from 1980 to 2009 (Isaak et al., 2012). The western USA SSN models include drainage area as a surrogate for stream size but do not attempt to factor out effects of individual morphometry variables. Neither width nor depth appeared as significant predictors in the NE SSN models, but either width or depth appeared as significant and influential predictors in the Meduxnekeag SSN models. However, the width: depth ratio had a negative effect on GSM in the NE model, consistent with the positive depth effect in the Meduxnekeag SSN. Lake, reservoir, and wetland storage was a significant predictor for the NE SSN model but not for the Meduxnekeag SSN, possibly due to the low range of variability for this attribute across the Meduxnekeag watershed (see PCA results).

The Meduxnekeag SSN included additional positive effects of elevation not detected in the NE SSN model. Normally elevation is associated with a decrease in temperature due to the adiabatic effect on air temperatures, which in turn affects water temperatures. However, the adiabatic effect on air temperature should have been accounted for in the Daymet equations used to interpolate air temperatures between observations to create a continuous grid Thornton et al., 1997. With one exception, adiabatic rates estimated by the geographically weighted regressions of Detenbeck et al. (2016) tended to increase over time between 1985 and 2010. For the year 2010, July maximum air temperatures extracted from Daymet grids for prediction points decreased at a rate of 7.87 °C per 1000 m elevation as compared to an average rate of 6.56° per 1000 m elevation based on the 2010 geographically weighted regression results of Detenbeck et al. (2016; Detenbeck, personal communication). Thus, the positive elevation effect included in the Meduxnekeag SSN model could reflect a bias correction factor to adjust air temperatures upward for higher elevations. The greater incidence of groundwater seepage sites associated with the mainstem along lower portions of the Meduxnekeag (as indicated by thermal infrared imagery) could also contribute to an elevation effect (Culbertson et al., 2014).

The positive signs associated with bankfull depth variables in the Meduxnekeag SSN model were also unexpected. In the NE SSN model, width: depth ratio interactions with air temperature had a positive effect on water temperatures because shallower depths are associated with more rapid warming, but the width: depth ratio was not a significant term in the Meduxnekeag SSN models. For the Meduxnekeag SSN model, both bankfull width and depth were estimated as a function of watershed area using Bent and Waite's (2013) equations, supplemented by measurements of instream water body widths, so it may be difficult for the model to actually distinguish between width and depth effects. In addition, watershed area in Meduxnekeag subbasins is negatively correlated with base flow index, so greater bankfull widths and depths could also be associated with lower base flow index values and thus higher water temperatures.

4.2. Current study limitations and potential improvements

The SSN models created for the Meduxnekeag Watershed met our needs with good accuracy, provided useful insights on the location of cold water refuge areas, and allowed us to make useful predictions of the potential effects of riparian restoration to inform management actions. However, SSN models do have limitations. Predictions outside of the range of observations used to develop the model are inherently more uncertain. In addition, although most of the types and directions of effects on stream temperature suggested by the SSN models were consistent with theory, there were some exceptions, which could increase the uncertainty of projections to future conditions under climate change. Some of these anomalies could probably be resolved with improved input data.

Potential improvements in the temperature monitoring strategy for the Meduxnekeag to support SSN model development include addition of sample sites to extend the range of predictor variables covered. In particular, the headwater reaches in the lower portion of the Meduxnekeag appear to be critical refuge areas, particularly during peak air temperature events in dry years, but many of these reaches had attributes outside of the range of existing monitoring stations. In 2018, sampling did not begin until mid-July, so it would be helpful to do additional monitoring, particularly at new stations to cover the full month. Inclusion of some paired sites at confluences (upstream on both branches and downstream on the mainstem) would improve the estimation of spatial autocorrelation error terms (Marsha et al., 2018).

Better definition of channel morphometry effects may require explicit measurements of channel features at temperature stations rather than reliance on regional prediction equations based solely on watershed area. Historical logging and log transport practices in the Meduxnekeag probably led to widening of stream channels beyond conditions for reference systems (Peabody and Mitchell, 2005). Finally, while selection of sites to fill in the gaps along PC axes of variation was an efficient means of covering PC space, it may have led to problems in cases where correlated variables (e.g., watershed area, stream depth and width, and baseflow index) are expected to have confounding effects. Thus, it would be helpful to also include the rarer combinations of key variables such as baseflow index and watershed area if these exist (high watershed area and low BFI or low watershed area and high BFI) to tease out channel morphometry and BFI effects (see Jackson et al. (2016) for alternative site selection strategy).

Direct measurements of air temperatures and creation of local predictive equations for air temperature based on elevation to interpolate between sites would also be useful. This might eliminate the anomalous positive elevation effects appearing in the Meduxnekeag SSN models if these do represent a bias correction factor for Daymet air temperature predictions.

Our results were limited in that the SSN models only predicted monthly medians or GSM. Maps of habitat suitability based on GSM present dire predictions for the future of Atlantic Salmon in the Meduxnekeag. Broadening the modeling effort would provide more information on the long-term persistence of fish populations, particularly given the wide distribution of apparently lethal temperatures during midsummer in dry years. Mortality for coldwater fish species depends not just on magnitude of temperature exposure, but also diurnal variation and duration of high temperature events across days (Barton et al., 1985 [trimean weekly maxima <22 °C], Beauregard et al., 2013; Beitinger et al., 2000; Butryn et al., 2013; Kratzer and Warren, 2013;

Wehrly et al., 2007). For example, Butryn et al. (2013) determined that metrics based on a combination of magnitude and duration were better predictors of locations where Brook Trout did not occur or infrequently occurred (e.g., 2 of 17 years) than standard metrics such as monthly means or 7-day means of daily maxima. Sites in Vermont streams without Brook Trout had median stress events (>22 °C) that exceeded 4 h and 0.4 °C average magnitude. At the population scale, persistence depends on the number of consecutive years with adverse conditions (Kanno et al., 2015). Kanno et al. (2015) determined that low flows in 3 years of every 5 were a good indicator of Brook Trout population failure to persist. Ultimately, the suitability of thermal regimes across the watershed network to ensure population persistence could be evaluated with a spatially-explicit bioenergetics or individual-based population model such as HexSim (Schumaker, 2016).

4.3. Management implications

The Meduxnekeag SSN model was created at a management level scale and can be used to guide on-the- ground restoration practices in the Meduxnekeag Watershed by prioritizing stream reaches with the largest thermal benefit (reduced stream temperature) from riparian restoration. The results from the SASR distance and travel buffers also suggests that stream temperature improvements are contingent on continuous upstream buffers. The riparian buffer zone of influence was approximately 3 h based on time of travel for monthly median temperatures or 1 km upstream for GSM. This suggests that restoration strategies should prioritize areas that create continuous buffer sections over creating a patchwork of improved buffer areas that are shorter than the zone of influence. Thermal improvements from restoration were seen throughout the watershed, but portions of the mainstem remained warmwater habit during high temperatures and during dry conditions. This suggests that restoration of headwater reaches near the mouth of the Meduxnekeag and along the mainstem will be critical for producing coolwater refugia during extreme temperature events.

The restoration scenarios suggested that most of the thermal benefits are accrued through restoration of the 30-m zone adjacent to streams. The modeled restoration scenarios accounted for development by only restoring the first 10 m of buffer in areas with development, instead of an entire 30- or 90-m buffer. The Meduxnekeag Watershed has very little development overall including very few buildings within the riparian zone. Instead, riparian restoration will focus on areas were the riparian buffer has been impacted by agricultural practices. The restoration scenarios were based on the current forest height and cover that is commonly found in the Meduxnekeag Watershed, suggesting that the restoration benefits could be captured by using current vegetation in the watershed through planting new vegetation or allowing the buffer to naturalize over time.

Beyond stream shading through riparian restoration, the Meduxnekeag SSN model identified other thermal regime predictors that are amendable to management actions to restore coldwater habitat in short or intermediate time scales. This includes improving midsummer baseflows particularly during drought years through reducing water withdrawals and/or consumptive water use. Additionally, restoring historical channel morphometry to reduce channel widths (Field, 2010), expected to be widened through previous logging, would both improve shade and increase water depth. Lastly, given the influence of upstream lakes or reservoirs on thermal habitat immediately downstream, consideration should be given to the nature of releases from dams from warmer epilimnion or cooler hypolimnion waters.

Ideally, management strategies should consider the implications of climate change. Summer baseflows in eastern Maine are particularly low compared to the rest of NE in both wet and dry years (Detenbeck, 2018). The 3-in-5 year low flow statistic, an indicator of Brook Trout population persistence, has been steadily increasing for eastern Maine over the past 30 years but longer term projections are unknown (Detenbeck, 2018).

5. Conclusions

An SSN stream temperature model was created for the Meduxnekeag Watershed case study using the NHDPlus HR hydrography framework (1:24,000) to provide sufficient spatial resolution for informing riparian buffer restoration practices. The Meduxnekeag SSNs produced high quality predictions at the management level scale in spite of the challenges associated with using transboundary data sources to describe landscape conditions. The best predictors of effects of solar radiation on stream temperatures were based on estimates of upstream shading delimited by 3 h stream travel time (monthly medians) or 1 km (GSM). Most of the predicted improvements from riparian restoration accrued for the 30-m width buffer restoration, with limited additional improvements in coldwater habitat for the 90-m buffer width. In current conditions, habitat for coldwater fisheries were limited to headwater tributaries during extreme temperature events in a dry year with low flows but could be expanded with riparian restoration in agricultural areas. The Meduxnekeag SSN model will guide future riparian restoration projects by highlighting the stream reaches that show the greatest improvements in cold and coolwater habitat from riparian restoration.

Credit author statement

Stephanie Figary: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing, Visualization; Naomi Detenbeck: Supervision, Project administration, Validation, Writing - original draft, Writing - review & editing, Visualization; Cara O'Donnell: Conceptualization, Investigation, Data curation, 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 associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jenvman.2020.111585.

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Data statement

Data associated with figures in this manuscript will be available via a query accessible at this url: https://edg.epa.gov/metadata/catalog/main/home.page within a few months of publication.

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