Reducing Acidification in Endangered Atlantic Salmon Habitat

Baseline Data Summary

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Introduction

Despite restored access to historic Atlantic salmon (*Salmo salar*) habitat in eastern Maine, population sizes have remained low (USASAC 2017). Most Downeast waters have been identified as acidic (pH <6.5), with headwaters chronically acidic and main stems episodically acidic (Haines et al. 1990; Whiting and Otto 2008). Loss of fish populations due to acidification of surface waters has been well documented in the North Atlantic region (as reviewed by Clair and Hindar 2005; Dennis and Clair 2012). In addition, numerous studies have demonstrated that episodic exposure to low pH can have detrimental, sub-lethal impacts when coinciding with key salmon life stages during snow melt and spring runoff (e.g., Kroglund et al. 2008; Lacroix and Knox 2005; as reviewed by McCormick et al. 1998). Adding lime to acidic waters, through application of agricultural lime or lime slurry, has increased salmon populations in Scandinavia and Nova Scotia (as reviewed by Clair and Hindar 2005; Halfyard 2007; Hesthagen et al. 2011), and has been a recommended restoration action for Maine's acidic rivers and streams (NRC 2004). A 2009 Project SHARE pilot study investigating the efficacy of using clam shells to lime small streams suggested a trend towards improved habitat quality (Whiting 2014). To further investigate the efficacy of this mitigation method, a multi-year liming project in the East Machias River watershed will be conducted in collaboration with the Downeast Salmon Federation (DSF). Clam shells will be spread along treatment reaches both along the stream bottom and along the banks to capture high flow events (when episodic acidity is expected). The project goal is to increase juvenile salmon abundance by application of clam shells to achieve a target pH, and to evaluate changes in the macroinvertebrate community. The first year of the project was used to begin to characterize baseline conditions by monitoring water quality between May and November using continuous monitoring devices and periodic grab samples.

Methods

Four tributary streams to the East Machias River were monitored to collect baseline data (Fig. 1). The East Machias River watershed is typical of coastal eastern Maine, with extensive wetlands resulting in colored waters high in organic materials and low pH, with high summer temperatures (Project SHARE-USFWS 2009). The existing salmon population in the East Machias River system is small (median parr density 3 per habitat unit, $100m^2$), with an estimated 1223±297 parr exiting the system in 2016, and 12 redds observed (USASAC 2017). In 2017, 9 adults returned, resulting in a smolt to adult return rate of 3.4% (Department of Marine Resources, DMR, and DSF data). Richardson Brook and Creamer Brook are both stocked by DMR, and the average fish density is 12 fish/$100m^2$ and 25 fish/$100m^2$ respectively (DMR data). The bedrock geology in the study area is predominantly marine sandstone and slate with some volcanic rocks, especially around Creamer Brook. Continuous monitoring devices provided hourly water quality data that was supplemented by bi-monthly grab samples. Macroinvertebrate samples were collected using rock bags following the DEP protocol (2014) and by DSF staff using kick nets following EPA's Rapid Bioassessment Protocol (Barbour et al. 1999).

Results and Discussion

Weather

Eastern Maine experienced a moderate drought during summer 2017, with precipitation around 50% of normal levels, following a similar drought in 2016 (NOAA 2017). Drought induced low flows have significant impacts on stream water quality and aquatic biota. Low flows

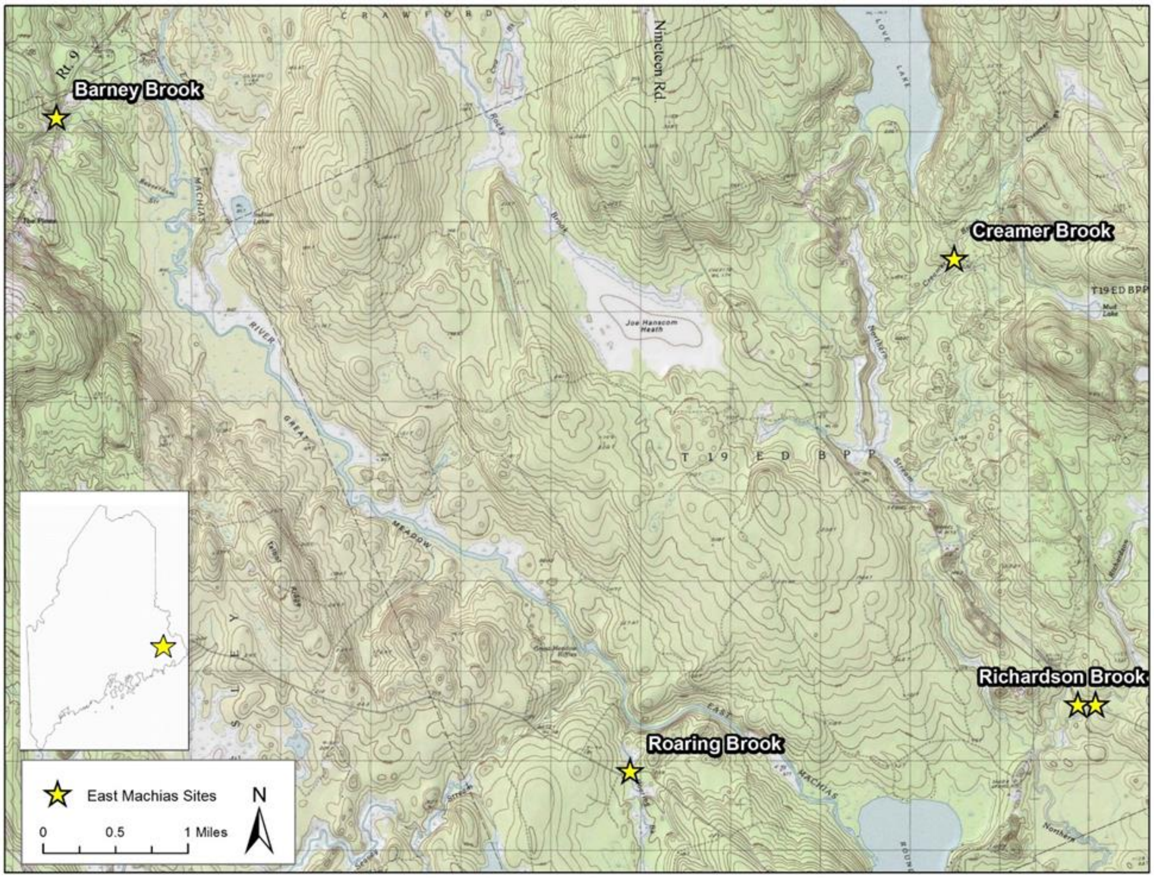

Figure 1. Map of the five study sites on four tributaries to the East Machias River. On Richardson Brook, samples were taken upstream and downstream of the road.

can reduce fish mobility, potentially trapping them in isolated pools where they could experience higher temperatures and lower dissolved oxygen, and reducing foraging opportunities. The influence of cold groundwater during low flows may reduce stream temperature.

pH

For the majority of the sampling period, the pH values in the study area remained above the state water quality criterion of 6.0 and above the threshold of 5.4, where no adverse impacts to salmon are expected (Fig. 2; Haines et al. 1990; 38 MRS Section 464.4.A.5; Stanley and Trial 1995). Barney Brook is the only circumneutral stream in the study, with a mean pH of 6.5 ± 0.3, possibly due to the underlying limey protolith which may give it a higher buffering capacity than the marine volcanics in the rest of the study area (MGS 2017). A significant decline of up to 1.5 pH units occurred after more than 150 mm of rain fell in 48 hours in late October (Fig. 2). Organic acids from leaf drop may have contributed to the low pH values. Stream pH did not recover for at least a month, likely resulting in sub-lethal stress and potentially mortality (Baker et al. 1996; Henriksen et al. 1984; Lacroix and Knox 2005; Magee et al. 2003). The pH ranges observed in these Downeast streams are similar to those observed in other eastern Maine streams (Haines et al. 1990) and higher than in Norway and Nova Scotia (Clair et al. 2004; Halfyard 2007; Hesthagen et al. 2011). Following the addition of lime, Nova Scotia streams achieved pH values comparable to the ones studied here (Halfyard 2007). Although eastern Maine streams are not chronically acidic, as in Norway and Nova Scotia, episodic acidification following rain events in the fall and spring can be just as harmful to salmon populations.

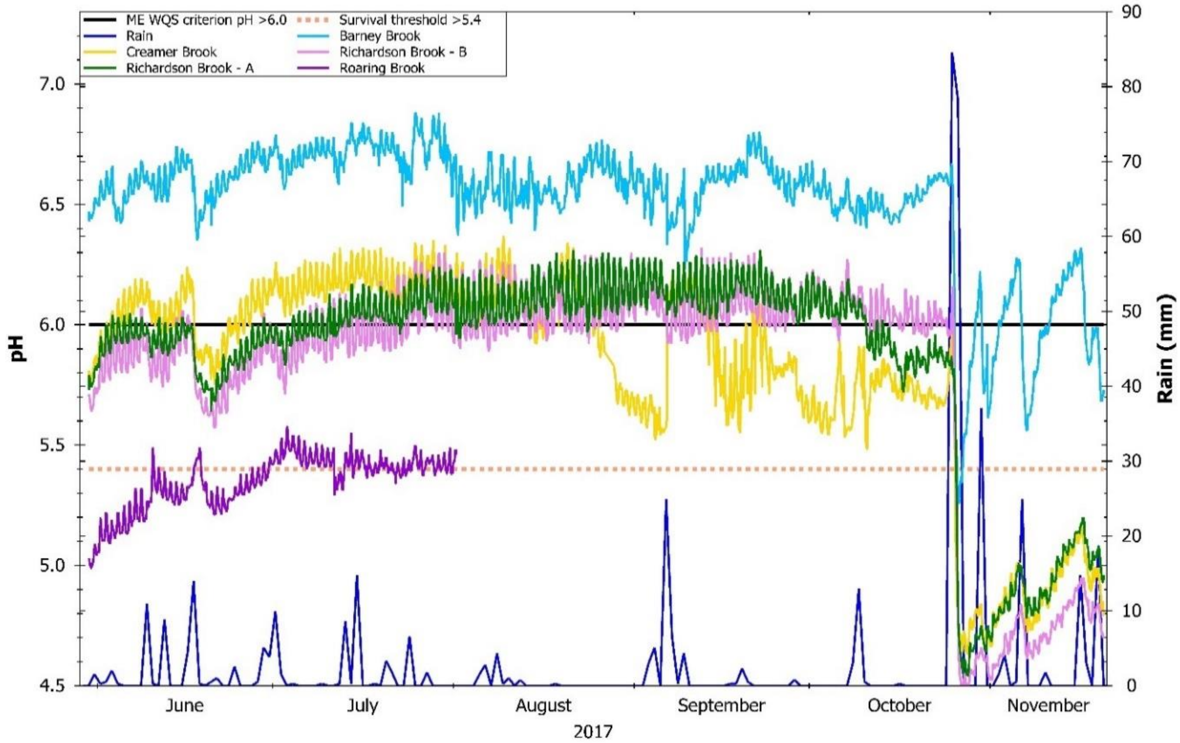

Figure 2. Hourly pH and local rainfall. Roaring Brook had no flow by August 1. Rainfall data from Weather Underground station KMEALEXA2. Survival threshold from Stanley and Trial 1995 and Haines et al. 1990.

<u>Stream Temperature</u>

Temperatures remained below the threshold for optimal growth of 20°C for the majority of the study (Fig. 3; EPA 1986). The stress threshold of 22.5°C was exceeded only 9% of the time (Elliott and Hurley 1997; Stanley and Trial 1995). The maximum temperature for salmon survival of 27°C was never exceeded, and temperatures remained within or below the 16-19°C preferred temperature range for 70% of the spring and summer (Stanley and Trial 1995). Recovery from thermal stress is likely feasible in the study streams due to the relatively short

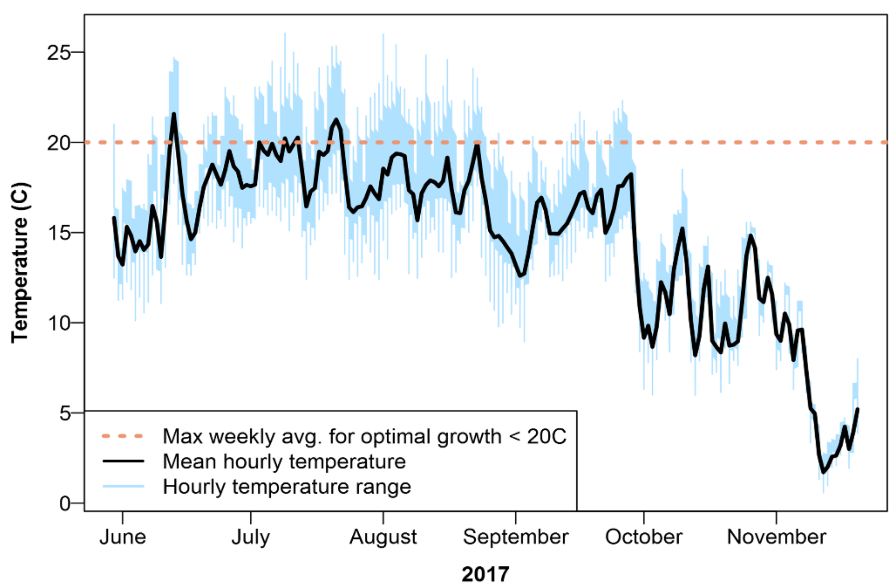

Figure 3. Mean hourly temperature across all study sites.

duration of stressful temperatures, in addition to the diel fluctuations providing a nightly temperature refuge. Thermal stress is not expected to play a significant role during episodic acidity events in the study area.

Dissolved Oxygen (DO)

DO levels were within a healthy range for fish and aquatic life, in addition to the preferred range for salmon of >6-7 mg/L for the majority of the study period (Stanley and Trial 1995). However, during extreme low flows DO decreased below both the Maine Water Quality Standard of 7 mg/L as well as EPA's threshold for acute impairment of 5 mg/L (38 MRS Section 465.2.B; EPA 1986). These minima persisted for on average 8 hours, with the longest duration of 40 hours. DO minima coincided with the warmest temperatures as well as with low flows, increasing stress and possibly preventing fish movement to refugia, if any existed nearby.

Acid Neutralization Capacity (ANC)

ANC remained above the threshold of acid sensitivity of 50 μeq/L in all but two samples (Fig. 4; Driscoll et al. 2001), and above both the Norwegian 20-30 μeq/L critical limits for salmon in all samples (Baker et al. 1990; Lien et al. 1996; Kroglund et al. 2002). Higher ANC gives greater buffering capacity and correlates with higher pH (lower acidity). Relatively low ANC values in the study streams indicate a deficit of buffering materials in the watershed, due to thin soils (Potter 1982), allowing volatile swings in pH after rain inputs and increasing the

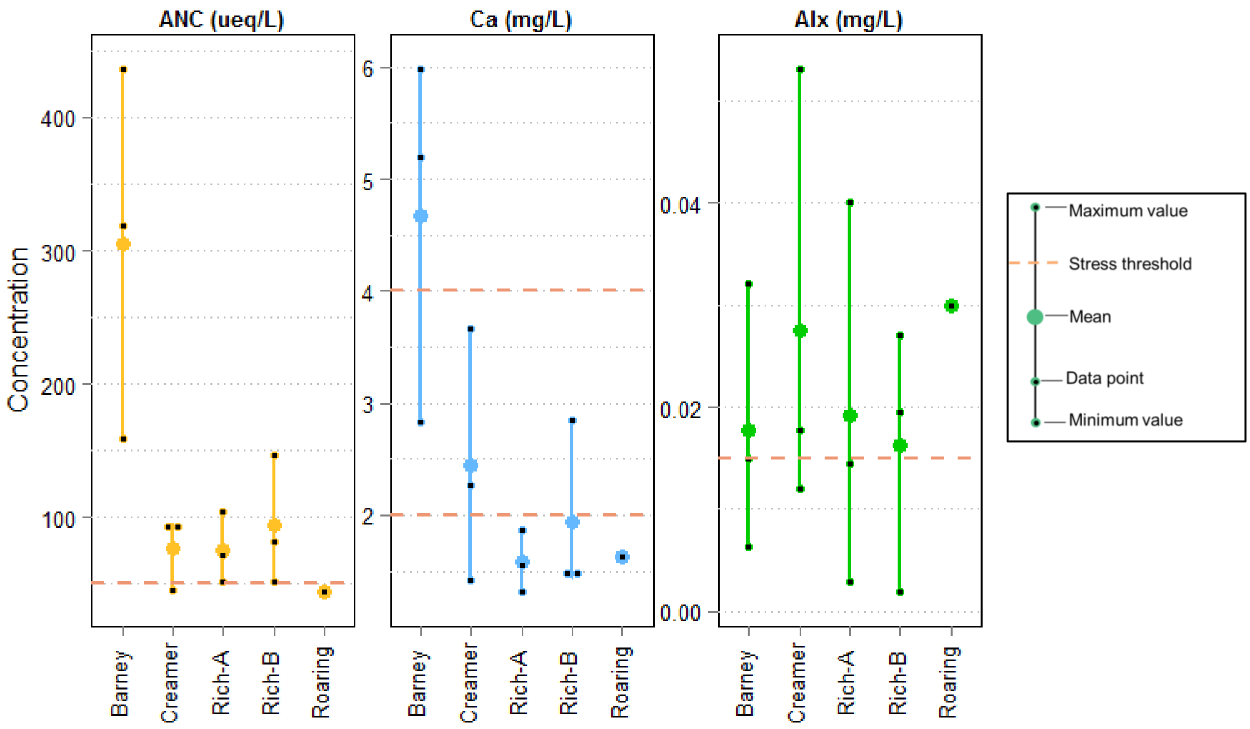

Figure 4. Acid neutralization capacity (ANC), calcium (Ca) and exchangeable aluminum (Alx). n = 3 except for Roaring Brook, n =1. ANC stress threshold of <50 μeq/L from Driscoll et al. 2001. Calcium stress thresholds of <4 mg/L from M. Whiting (pers. comm.) and <2 mg/L from Baker et al. 1990 and Baldigo and Murdoch 2007. Alx stress threshold of >0.015 mg/L from EIFAC as cited in Dennis and Clair 2012. Small dots represent data points, large dots represent means.

potential for salmon mortality (MacAvoy and Bulger 1995). Although low, ANC values are often higher in Maine than in Nova Scotia, indicating a greater buffering capacity in the study streams (Clair et al. 2004; Dennis and Clair 2012; Halfyard 2007). Due to the low buffering capacity, if liming mitigation is pursued, it is expected that the system would revert to the pre-treatment acidified state relatively quickly if mitigation ceased (Halfyard 2007).

Calcium

Calcium was below the survival threshold of 2 mg/L at all sites except for Barney Brook (Fig. 4; Baker et al. 1990; Baldigo and Murdoch 2007). Only Barney Brook had calcium levels above the suggested threshold of 4 mg/L to prevent deformities (M. Whiting pers. comm.). Calcium was higher than in Nova Scotia, including the limed West River (Clair et al. 2004; Halfyard 2007). Low calcium coincided with low pH and high aluminum. Calcium buffers the detrimental impacts of exchangeable aluminum (Alx) by increasing the efficiency of ion regulation (Baldigo and Murdoch 2007; MacDonald et al. 1980), however this buffering capacity decreases when calcium concentrations are below 1 mg/L at pH 6.5, and around 2 mg/L Ca when pH is <6.5 (Wood et al. 1990). It is expected that some buffering of Alx is likely occurring in the study streams (Baker et al. 1990; Wood et al. 1990).

Exchangeable Aluminum (Alx)

The range of Alx observed in this study is similar to data from other cool ecosystems underlain by a range of geological types (Haines et al. 1990), however values were lower than in Nova Scotian and Norwegian streams, and similar to limed Norwegian streams (Dennis and Clair 2012; Hesthagen et al. 2011). For protection of aquatic life, including macroinvertebrates, the European Inland Fisheries Advisory Commission (EIFAC) recommends that exchangeable aluminum should not exceed 0.015 mg/L at pH 5.0-6.0, even for short durations (Howells et al. 1990 as cited in Dennis and Clair 2012; Kroglund and Staurnes 1999; McCormick et al. 2009). All streams except for Barney Brook exceeded this criterion (Fig. 4), but only when flows were high and pH was near 6.0, when aluminum solubility (and therefore toxicity) is reduced (Dennis and Clair 2012; Driscoll et al. 2001). However, all streams fell below a pH of 6 periodically, for a total of about half the study period, especially following the late October rain event. The abundance of acid-sensitive species decreases when Alx is >72 μg/L and pH is ≤5 (Driscoll et al. 2001). These conditions may occur in the study streams during rainfall driven episodic events when buffering capacity is reduced due to dilution of calcium and DOC (Clair and Hindar 2005; Dennis and Clair 2012; Haines et al. 1990). The risk of salmon mortality in the study streams due to high Alx concentrations is unlikely except during high discharge events (Baldigo and Murdoch 2007; Haines et al. 1990), however sub-lethal stress may decrease smolt tolerance to saltwater (Kroglund and Staurnes 1999; McCormick et al. 2009; Monette et al. 2008; Staurnes et al. 1995). Compared with Norwegian rivers, reduced salmon populations are expected at all streams except for Barney Brook, based on pH and Alx (Kroglund et al. 2002).

Dissolved Organic Carbon (DOC)

DOC is a strong determinant of fish mortality (for brook trout, Baldigo and Murdoch 2007) and can be used as an indicator of organic acidity to determine the role of anthropogenic activity in acidic streams (Garmo et al. 2014). Downeast streams, including those studied here, are highly colored, with relatively high organic content due to wetlands and coniferous forests (Haines et al. 1990). DOC increased with precipitation and runoff, coinciding with low pH.

Above pH 5.5, and at DOC concentrations greater than 2.0-5.0 mg/L, DOC can buffer against the toxic impacts of exchangeable aluminum, by binding the aluminum into inert organic complexes (Baldigo and Murdoch 2007; Kroglund et al. 2008; Tipping et al. 1991). DOC values in Maine are lower than most streams in Nova Scotia (Clair et al. 2004; Dennis and Clair 2012), possibly due to differences in the underlying bedrock. More data are needed to determine the relative impact of anthropogenic acidification versus organic acidity from wetlands.

Macroinvertebrates

The study streams attained Maine's highest aquatic life water quality classification (Class A; Davies et al. 2016). The dominant taxa were mayflies and caddisflies that most often occur in cool springs and streams, usually in areas of little current, such as were found in the low flow conditions this year. Mayflies are considered to be the most sensitive group of aquatic insects to acidity (Weiderholm 1984) and represented half of the generic richness, suggesting a healthy macroinvertebrate assemblage requiring good water quality. Rainfall driven decreases in acidity below pH 5 may have a detrimental impact on any acid-sensitive macroinvertebrates present, although the most critical period for macroinvertebrates is likely emergence, so species that reproduce in the fall and spring would be most affected (Bradley and Ormerod 2002; Weiderholm 1984). However, as episodic acidity events have been occurring for decades, the macroinvertebrate assemblage in Downeast streams may be tolerant to low pH pulses. Salmon are thought to be opportunistic feeders, changing their diet to the most abundant prey available, so changes in macroinvertebrate abundance may have a stronger impact on salmon than changes in composition (Scott and Crossman 1973 as cited in Stanley and Trial 1995).

Conclusion

The results of the first year of monitoring indicate that under moderate baseflow conditions, water quality is decent for salmon but deterioration of water quality during high-discharge, high acidity events could lead to sub-lethal stress or even mortality. More stormflow and winter samples are needed to better predict fish community status during stressful low pH, high Alx, low buffering capacity circumstances (Baker et al. 1996). All streams experienced episodic acidification due to precipitation events. Cumulative sub-lethal stress is likely causing detrimental impacts to salmon due to the combined impact of low pH and aluminum toxicity. Exposure to physiological stressors, such as changes in salinity and acidity, has been shown to reduce anti-predatory behavior in smolts (Handeland et al. 1996), in addition to increasing residence time in estuaries, an area of high smolt predation. Salmon are more susceptible to these negative impacts if further stress events occur during the recovery period (3+ days) following acidic events (Magee et al. 2003). The most sensitive life stages to acidity are alevins (from hatch to swim up) which are present in the study area from March through June, and smolts (especially as they out migrate), which are present from April through June. This time range also coincides with snow melt, when streams become episodically acidic, increasing the severity of detrimental impacts to salmon. By decreasing exposure to acidity, smolt survival may increase during their seaward migration. As clam shells are added to the target area, monitoring efforts will continue for at least five years to determine the efficacy of using this approach to mitigate acidity.

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